WELCOME TO ICAP 2014

On behalf of the organizing committee and the Joint Quantum Institute, we would like to welcome you to the 24th International Conference on Atomic Physics, held at the historic Mayflower Renaissance Hotel in downtown Washington, D.C.

Following in the tradition of previous ICAPs, the conference includes an outstanding program of invited speakers covering a broad range of atomic physics topics such as:

Ultracold Bose and Fermi gases

Ultracold molecules

Fundamental atomic tests and measurements

Precision measurements, atomic clocks and interferometers

Quantum information and simulations with atoms, ions, and photons

Rydberg gases

Hybrid quantum systems and artificial atoms

Ultrafast phenomena

The program includes plenary sessions with 47 invited speakers, including 10 “hot topic” talks. There are more than 450 posters, distributed over three sessions on Monday, Tuesday, and Thursday. Included in this book are abstracts for the invited speakers and the contributed posters, as well as a list of exhibitors who will be presenting throughout the conference.

We hope you enjoy the conference and your stay in our city.

Gretchen Campbell and Trey Porto

Co-Chairs, ICAP 2014

WELCOME TO ICAP 2014

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INVITED SPEAKERS

Monday, 4 August 2014 8:30 am – 8:45 am

Welcome Remarks

Monday, 4 August 2014 8:45 am – 10:15 am

Nobel Prize Session

Chair: W. Phillips

D. Wineland "Quantum control of trapped ions at NIST" (45) p.32

S. Haroche "Quantum control of trapped photons with Rydberg atoms" (45) p.32

Monday, 4 August 2014 10:45 am – 12:30 pm

Quantum Gases I

Chair: F. Chevy

T. Esslinger "Bands with a twist and quantum sized steps" (45) p.33

R. Grimm "Efimov and beyond: New developments in few-body physics with ultracold bosons and fermions" (30) p.33

Z. Hadzibabic "Uniform Bose gases" (30) p.34

Monday, 4 August 2014 2:15 pm – 4:00 pm

Artificial Atoms

Chair: D. Meschede

J. Wrachtrup "Quantum Spin Sensors" (45) p.34

E. Waks "Coherent control of light-matter interactions in a semiconductor nanophotonic device" (30) p.35

M. Hafezi "Photons in synthetic gauge fields" (30) p.35

INVITED SPEAKERS

Tuesday, 5 August 2014 8:30 am – 10:15 am

Molecules
Chair: W. Bakr

P. Julienne "Universality in Cold Molecular Collisions" (45) p.36

B. Gadway "Studying the dynamics of a long-range interacting spin system of ultracold polar molecules" (30) p.37

M. Zeppenfeld "Generating cold ensembles of polyatomic molecules" (30) p.37

Tuesday, 5 August 2014 10:45 am – 12:30 pm

Quantum Gases II
Chair: M. Lewenstein

C. Chin "Roton-Maxon Excitation of Bose Condensates in a shaken optical lattice" (45) p.38

Y. Takahashi "Quantum simulation using ultracold ytterbium atoms" (30) p.38

S. Chen "Generation and Exploration of Spin-Orbit coupled Bose Gas" (30) p.39

Tuesday, 5 August 2014 2:15 pm – 4:00 pm

Fundamental Atomic Tests
Chair: A. Derevianko

D. DeMille "ACME: A Search for the Electron's Electric Dipole Moment" (45) p.40

K. Blaum "Fundamental tests of nature and a high-precision measurement of the atomic mass of the electron" (30) p.41

M. Kasevich "Precision Inertial Sensing Using Atom Interferometry" (30) p.41

INVITED SPEAKERS

Wednesday, 6 August 2014 8:30 am – 10:15 am

Ultrafast Science
Chair: J. Ahn

U. Keller "Attosecond ionization dynamics" (45) p.42

N. Dudovich "Resolving and manipulating attosecond processes via strong-field light-matter interactions" (30) p.43

C. Geddes "Laser plasma accelerators and photon sources" (30) p.43

Wednesday, 6 August 2014 10:45 am – 12:30 pm

Rydberg Atoms
Chair: A. Gorshkov

T. Pohl "Many-body physics with Rydberg atoms and quantum light" (45) p.44

S. Hofferberth "Rydberg quantum optics in dense ultracold gases" (30) p.44

A. Browaeys "Experimental investigations of resonant dipole-dipole interaction between cold atoms" (30) p.45

INVITED SPEAKERS

Thursday, 7 August 2014 8:30 am – 10:15 am

Quantum Calculation — Chair: I. Novikova

J. Taylor “Quantum sensing and simulation with light and matter” (45) p.46

A. Aspuru-Guzik "Quantum Information and Quantum Computation for Chemistry" (30) p. 46

A. White "Photonic Quantum Simulation" (30) p.47

Thursday, 7 August 2014 10:45 am – 12:30 pm

Precision Measurements — Chair: M. Safronova

K. Eikema "Ramsey-comb spectroscopy: high power and accuracy combined" (45) p.48

A. Ludlow "Ultra-precise atomic timekeeping with the optical lattice clock" (30) p.48

E. Peik "Optical clocks based on strongly forbidden electronic and nuclear transitions in trapped ions" (30) p.49

Thursday, 7 August 2014 2:15 pm – 4:20 pm

Hot Topics I — Chair: I. Spielman

U. Schneider "An Aharonov-Bohm interferometer for determining Bloch band topology" (25) p.50

L. Fallani "SU(N) fermions: multicolor physics and orbital magnetism" (25) p.51

F. Ferlaino "Dipolar physics with ultracold atomic magnets" (25) p.52

P. Cappellaro "Quantum control strategies for imaging and spectroscopy" (25) p.52

J. Doyle "Detecting the Chirality of Molecules using Buffer-gas Cooling and Phase Sensitive Three-wave Mixing" (25) p.53

INVITED SPEAKERS

Friday, 8 August 2014 8:30 am – 10:15 am

Bose Gases
Chair: M. Inguscio

J. Dalibard "The uniform 2D Bose gas, in and out of equilibrium" (45) p.54

Y. Shin "Geometric Hall Effect in a Spinor Bose-Einstein Condensate" (30) p.55

S. Stringari "Superstripes in spin orbit coupled Bose-Einstein condensed gases" (30) p.55

Friday, 8 August 2014 10:45 am – 12:30 pm

Quantum Simulation/Ions/Molecules
Chair: B. Odom

P. Zoller "Quantum Simulation of Dynamical Gauge Fields with Cold Atoms" (45) p.56

E. Hudson "Sympathetic cooling of molecules with laser-cooled atoms" (30) p.57

M. Köhl "Direct photonic coupling of a semiconductor quantum dot and a trapped ion" (30) p.57

Friday, 8 August 2014 2:00 pm – 3:45 pm

Hybrid Quantum Systems
Chair: P. Treutlein

A. Rauschenbeutel "Breaking the mirror symmetry of spontaneous emission via spin-orbit interaction of light" (45) p.58

C. Regal "Two-atom quantum interference in tunnel-coupled optical tweezers" (30) p.58

O. Painter "Phonon counting experiments in cavity-optomechanics" (30) p.59

INVITED SPEAKERS

Friday, 8 August 2014 4:00 pm – 6:05 pm

Hot Topics II

Chair: S. Gupta

J. Reichel "Creating entanglement in an ensemble of 40 atoms using quantum feedback and quantum Zeno dynamics in a fiber cavity" (25) p.59

M. Oberthaler "Detection of entanglement of non-gaussian atomic states and upscaling of atomic squeezing to large atom numbers" (25) p.60

P. Richerme "Simulating quantum many-body dynamics with trapped atomic ions" (25) p.61

D. Hall "Dirac Monopoles in a Synthetic Magnetic Field" (25) p.61

V. Vuletic "Very Attractive Photons" (25) p.62

Monday Poster Session

Bose Gases

Mon-001	The *p*-orbital Bose-Einstein condensation of two-species mixture in a bipartite square optical lattice - *Liu*
Mon-002	Dynamics of ultracold atoms in amplitude-modulated parabolic lattices - *Yamakoshi*
Mon-003	Novel quantum phenomena of atomic quantum gas in a shaken optical lattice - *Ha*
Mon-004	Direct observation of chiral order in double layer superfluid - *Ewerbeck*
Mon-005	Effective preparation of atomic condensates in excited bands of an optical lattice by standing-wave pulses - *Zhou*
Mon-006	Tunneling-Induced Restoration of the Degeneracy and the Time-Reversal Symmetry Breaking in Optical Lattices - *Sowinski*
Mon-007	Using Tilted, Modulated Lattices to Implement Novel Hamiltonians - *Burton*
Mon-008	Bosons in optical lattices: beyond the Bose-Hubbard Hamiltonian - *Carbonell-Coronado*
Mon-009	Ultracold Atoms in a Tunable Optical Kagome Lattice - *Barter*
Mon-010	Bose-Einstein condensation of ultra-cold atoms in a frustrated, triangular optical lattice - *Mathey*
Mon-011	Magnetometric Probe of an Ultra-cold Spinor Gas - *Higbie*
Mon-012	Quantum dynamics of spin waves using ultracold atoms - *Fukuhara*
Mon-013	Quantum control of a many-body system in a spin-1 Bose-Einstein condensate - *Hoang*
Mon-014	Investigation of Kibble-Zurek quench dynamics in a spin-1 ferromagnetic BEC - *Anquez*
Mon-015	Metastable Spin Texture of Spin-1 Bose-Einstein Condensates in a Ring Trap - *Kunimi*
Mon-016	Dipolar ultracold atoms in a double well trap - *Vernac*
Mon-017	Quantum phases in an asymmetric double-well optical lattice - *Paul*
Mon-018	Experiments with BECs in a Painted Potential: Atom SQUID, Matter Wave Bessel Beams, and Matter Wave Circuits - *Boshier*
Mon-019	Observation of Solitonic Vortices in Bose-Einstein Condensates - *Donadello*
Mon-020	Ring Dark Solitons in Toroidal Bose-Einstein Condensates - *Toikka*
Mon-021	One dimensional atomic rings with barriers: a Luttinger liquid approach to precision measurement - *Ragole*
Mon-022	Finite-Temperature Effects in ring-shaped Bose-Einstein condensates - *Edwards*
Mon-023	Investigation of Critical correlations in an ultracold Bose gas by means of a temporal Talbot-Lau interferometery - *Chen*
Mon-024	Collective modes of a two-dimensional quantum gas - *Merloti*
Mon-025	Measurement-based control of many-body systems - *Heck*
Mon-026	A novel experiment for coupling a Bose-Einstein condensate with two crossed cavity modes - *Leonard*
Mon-027	Heat Capacity of a Bose-Einstein condensate measured through Global variables - *Telles*

Mon-028 Probing the excitation spectrum of a ring-shaped Bose-Einstein Condensate - *Wang*

Mon-029 Dynamics of coupled mixtures in optical lattices - *Reeves*

Mon-030 Superfluid Atomtronic Circuits - *Eckel*

Mon-031 Emergence of coherence in a 2D uniform Bose gas - *Chomaz*

Few Body Interactions and Collisions

Mon-032 Three-body recombination of helium atoms from ultracold to thermal energies: classical trajectory vs. quantal calculations - *Pérez-Ríos*

Mon-033 Field dependent studies of inelastic scattering properties in an ultracold mixture of lithium and metastable ytterbium - *Roy*

Mon-034 Measurements of Na - Na^+ total collision rate - *Goodman*

Mon-035 Dynamics of gas phase Ne*-ND_3 Penning ionization at low temperatures - *Jachymski*

Mon-036 Few-body interactions in an ultacold Bose-Fermi mixture - *Jiang*

Mon-037 Collisional Properties of Ultracold Radium Isotopes - *Dammalapati*

Cooling and Trapping of Atoms and Ions

Mon-038 Very low power two-photon absorption in cold ^{87}Rb atoms using an optical nanofiber - *Gokhroo*

Mon-039 A nanostructured tapered optical fiber for cold atom trapping - *Nic Chormaic*

Mon-040 Laser cooling with three-level cascade transitions: calculations for group I and II atoms and prospects for tests with calcium - *Cruz*

Mon-041 Atomic Interactions with a Bichromatic Field: Stimulated Emission and Laser Cooling - *Singh*

Mon-042 Dynamics of Polychromatic Optical Forces for Deceleration of Atoms and Molecules - *Galica*

Mon-043 Laser Cooling without Spontaneous Emission - *Corder*

Mon-044 Localized Interactions between Laser-cooled Atoms and Optical Near-field - *Ichinoseki*

Mon-045 Surface Science with Trapped Ions - *Noel*

Ultracold Mixtures and Molecules

Mon-046 Towards a MOT of CaF - *Hemmerling*

Mon-047 Magnetic Slowing, Optical Loading and Magnetic Trapping of CaF and K - *Kozyryev**

Mon-048 Laser cooling and slowing of CaF molecules - *Hambach*

Mon-049 MM-Wave Spectroscopy and Determination of the Radiative Branching Ratios of ^{11}Bh for Laser Cooling Experiments - *Truppe*

Mon-050 Magneto-Optical Trapping of a Diatomic Molecule - *Norrgard*

Mon-051 Towards ultracold LiK ground-state molecules - *Debatin*

Mon-052 Dual Component ^{87}Rb and ^{41}K Bose-Einstein condensates in configurable optical potentials - *Neely*

Mon-052 Mixtures of Bose-Fermi superfluids - *Chevy*

Mon-054 Designing an ultracold Yb-Li mixture with controllable interactions - *Schaefer*

Mon-055 High-Resolution Spectroscopy of Trilobite-Like States of $^{85}Rb_2$ - *Carollo*

Mon-056 The creation of ultracold RbCs molecules in the rovibrational ground state - *Cornish*

Mon-057 Thermalization and progress to degeneracy in a mixture of rubidium-87 and ytterbium - *Vaidya*

Intense Fields and Ultrafast Phenomena

Mon-058 Electron Dynamics and Terahertz Emission in Two-Color Photoionization - *You*

Mon-059 Electron-Rescattering from Ar and Xe induced by Intense Laser Filed: Above Threshold Ionization and Rydberg Excitation - *Ding*

Mon-060 Benchmark H_2 few-cycle photoionisation measurements and laser intensity calibration with percent-level accuracy - *Sang*

Mon-061 Ionisation of metastable states of neon using few-cycle light fields - *Calvert*

Mon-062 Characterisation of intense few-cycle laser pulses from photo-ionisation of atomic hydrogen - *Wells*

Mon-063 Strong-field ionization of helium by elliptically polarized light in attoclock configuration - *Ivanov*

Mon-064 Improving conversion efficiency of high harmonic generation with gas mixtures - *Sayraç*

Mon-065 Signatures of field-induced intramolecular quantum interference in high-order harmonic generation by laser-irradiated homonuclear diatomic(s) - *Usachenko*

Quantum Optics and Cavity QED

Mon-066 Coherent population trapping (CPT) coupled by magnetic dipole interactions - *Han*

Mon-067 High Conversion Efficiency in the Resonant Four-Wave Mixing Process - *Lee*

Mon-068 Dynamics of strongly interacting photons in waveguides: a generalized input-output formalism - *Caneva*

Mon-069 Coherent population trapping in a two field cavity-QED system: Semiclassical Theory - *Zou*

Mon-070 Coherent coupling of hybrid alkali vapor through spin-exchange collisions - *Katz*

Mon-071 Observation of Paired Superradiance - *Uetake*

Mon-072 Cavity QED in the Recoil Resolved Regime - *Klinder*

Mon-073 Nonequilibrium phase transitions in periodically-driven cavity QED systems - *Mori*

Mon-074 Strong atom-light interactions in 1D photonic crystals - *Goban*

Mon-075 Crossover from Lasing to Photon Bose-Einstein condensation by Photon Gas Thermalization - *Schmitt*

Mon-076 Fiber cavity-based photon-ion interfaces - *Maiwald*

Mon-077 Building a hybrid quantum system of neutral atoms coupled to a superconducting circuit - *Grover*

Mon-078 Atom induced cavities and tunable long-range interactions between atoms trapped near photonic crystals - *Douglas*

Mon-079 2-D spectrum of an optical microcavity coupled to a few atoms - *Lien*

Mon-080 Graphene plasmons quality factors - *Jablan*

Mon-081 Single-photon second-order nonlinear processes in graphene - *Manzoni*

Mon-082 Room temperature coherent population trapping with nuclear spins in diamond - *Jamonneau*

Mon-083 Coherent spin control of a nanocavity-enhanced qubit in diamond - *Chen*

Mon-084 Size-dependence of radiation power thermally emitted from a microparticle - *Tachikawa*
Mon-085 Experimental Realization of Environment Assisted Speed Up of the Quantum State Evolution in the Open Quantum System - *Yan*
Mon-086 Modal decomposition and control of higher-order modes in silica nanofibers - *Fatemi*

Quantum Information

Mon-087 Entanglement Generation in a Multi-Qubit System Coupled to Heat Bath - *Pegahan*
Mon-088 Quantum storage based on the control field angular scanning - *Zhang*
Mon-089 Time-Continuous Bell Measurements - *Vasilyev*
Mon-090 A Monte Carlo wavefunction method for semiclassical simulations of spin-position entanglement - *Billington*
Mon-091 Individual Addressing of Trapped Ions with MEMS-based Beam Steering - *Crain*
Mon-092 Quasiparticle engineering and entanglement propagation in a quantum many-body system - *Hempel*
Mon-093 Femtosecond Ramsey interferometry for atomic qubit state measurement - *Lee*

Quantum Simulation

Mon-094 Quantum Simulation of Unphysical operation with a Trapped Ion - *Zhang*
Mon-095 Propagation of information in long-range interacting quantum lattice system. - *Gong*
Mon-096 Single phonon addition to thermal mechanical motion of trapped ion - *Slodička*
Mon-097 Quantum Computing with Ba and Yb Ion Chain - *Zhou*
Mon-098 Ultrafast entanglement of trapped ions - *Neyenhuis*

Rydberg Atoms

Mon-099 Population transfer collisions involving nD Rydberg atoms in a CO_2 optical dipole trap - *Kondo*
Mon-100 Aggregation of Rydberg excitations in a dense thermal vapor cell - *Urvoy*
Mon-101 Design and simulation of a cold Rydberg atom production and detection system. - *Mojica-Casique*
Mon-102 3-body resonant interaction in cold Cs Rydberg atoms - *Faoro*
Mon-103 Quantum simulations of biochemical processes with Rydberg atoms - *Wüster*

Spectroscopy, Atomic and Molecular Structure

Mon-104 Molecular alignment measured with photoelectron ionization yields - *Kaya*
Mon-105 Investigating (*R*)-3-methylcyclopentanone Conformers using Temperature Dependent Raman Spectroscopy - *Al-Basheer*
Mon-106 Time-sliced 3D momentum imaging of photofragmentation H_2^+ - *Kaya*
Mon-107 A new method to measure photoexcitation cross-sections with a Gaussian laser beam questions the photodetachment cross-section of H^- - *Vandevraye*
Mon-108 Weakly bound $^{87}Rb_2(5s_{1/2}+ 5p_{1/2})1_g$ molecule: Hyperfine interaction and improved LeRoy-Bernstein analysis including nonlinear terms - *Jelassi*
Mon-109 Observation of the $X^1\Sigma^+$ and $C^1\Sigma^+$ States of NaD Molecules - *Whang*
Mon-110 Resonance transition in atoms passing through a magnetic grating - *Hatakeyama*

Mon-111 Lifetime of a Spin State in an Isolated Rydberg Ion - *Tan*

Mon-112 Non-Resonant Correlation Spectroscopy in Cold Atoms: Extracting the Correlation Information of Light Sidebands - *Kumar*

Mon-113 Driving Rydberg-Rydberg transitions with an amplitude-modulated optical lattice - *Moore*

Mon-114 Towards multi-photon Raman scattering with higher excited levels of rubidium atoms in a warm ensemble - *Parniak*

Mon-115 Probe-intensity dependence of velocity-selective polarization spectroscopy at the rubidium D_2 manifold - *Ramírez-Martínez*

Mon-116 Methods for Characterizing the Dispersion of Passive Optical Cavities using a Femtosecond Optical Frequency Comb - *Kyriacou*

Mon-117 Coherent interactions between matter and radiation in neutral hydrogen clouds in the interstellar medium - *Rajabi*

Precision Measurements and Fundamental Tests

Mon-118 Sensitivity improvements to the YbF electron electric dipole moment experiment - *Devlin*

Mon-119 Improved Limit on the Electric Dipole Moment of the Electron - *Baron*

Mon-120 Measuring the Electron Electric Dipole Moment with Trapped Molecular Ions - *Grau*

Mon-121 Mercury Monohalides as Candidate Molecules for Electron Electric Dipole Moment Searches - *Prasannaa V*

Mon-122 Precision Experiments with Multiply-ionized Atoms in Compact Ion Traps - *Hoogerheide*

Mon-123 Precision spectroscopy of atomic hydrogen for a new determination of the Rydberg constant and the proton charge radius - *Beyer*

Mon-124 Progress on a separated-oscillatory-field microwave measurement of the n=2 Lamb shift of atomic hydrogen - *Vutha*

Mon-125 Unshielded Radio-Frequency Magnetometer - *Keder*

Mon-126 Experimental Test of Quantum Jarzynski Equality with a Trapped Ion - *An*

Mon-127 Free Spin Precession as a Tool for Testing Fundamental Physics - *Fan*

New Experimental and Theoretical Techniques

Mon-128 High-Performance Parallel Solver for 3D Time-Dependent Schrodinger Equation for Large-Scale Nanosystems - *Gaynullin*

Mon-129 Time of Flight Mass Spectrometer for Molecular Ion Trapping - *Petricka*

Mon-130 Coherent Stern–Gerlach momentum splitting on an atom chip - *Margalit*

Mon-131 Phase space tomography using an atom chip with random and engineered fragmentation potentials - *Zhou*

Mon-132 Injection locking of a high power ultraviolet laser diode for laser cooling of ytterbium atoms - *Hosoya*

Mon-133 A deterministic laser-cooled source of single Si ions for solid state qubits - *Ronald*

Mon-134 Room-Temperature Microwave Saturation Spectroscopy of Nitrogen-Vacancy Ensembles in Diamond - *Kehayias*

Mon-135 Diamond Magnetometry of Superconducting Thin Films - *Waxman*

Mon-136 A single frequency tunable laser near 1000 nm for spectroscopic applications - *Huang*

Atomic Clocks

Mon-137 Hyperfine structure in ${}^{229}{}_{g}\mathrm{Th}^{3+}$ as a probe of the ${}^{229}{}_{g}\mathrm{Th} \rightarrow {}^{229}{}_{m}\mathrm{Th}$ nuclear excitation energy - *Beloy*

Mon-138 A search for ultra-low energy nuclear isomer state of Thorium-229 -- New method using synchrotron radiation X-ray source-- - *Yoshimura*

Mon-139 Towards a measurement of the nuclear isomer transition in Thorium-229 - *Stellmer*

Mon-140 Search for optical excitation of the low-energy nuclear isomer of Th-229 - *Peik*

Mon-141 ${}^{229}\mathrm{Th}$ and ${}^{232}\mathrm{Th}$ Optical Spectroscopy System for Nuclear Frequency Standard - *Krasavin*

Mon-142 Improving atomic clocks using coherence preserving measurements - *Bertoldi*

Mon-143 Development of an ultra-stable universal synthesiser for state-of-the-art frequency metrology - *Johnson*

Mon-144 Towards Optical Clocks and Coherent Frequency Transfer in Sweden - *Zelan*

Mon-145 TACC - Trapped Atom Clock on a Chip - *Deutsch*

Mon-146 Compact Frequency Standard with Cold Atoms: Transportable System - *Müller*

Mon-147 Decoherence time of Ramsey fringes observed in a cesium atomic fountain clock - *Nakamura*

Tuesday Poster Session

Fermi Gases

Tue-001	Half metallic antiferromagnetic ordering of cold fermions induced by resonant tunneling - *Noda*
Tue-002	New Quantum Simulation with Multi-component Fermi Gases - *Pagano*
Tue-003	Ultracold Dysprosium gases: towards a topological superfluid - *Dreon*
Tue-004	Breakdown of Landau's Fermi liquid theory in a Strongly Interacting Fermi Gas - *Drake*
Tue-005	Diffusion of spin in a unitary Fermi gas - *Smale*
Tue-006	Exploring the phase diagram of a strongly interacting 2D Fermi gas - *Zürn*
Tue-007	Experimental studies of an interacting 2D Fermi Gas - *Peppler*
Tue-008	Production of a degenerate fermi gas of chromium - *Vernac*

Bose Gases

Tue-009	ZNG – Theory for Dipolar Quantum Gases - *Veljić*
Tue-010	Dynamics of spinor condensates in a microwave dressing field - *Zhao*
Tue-011	Non-Equilibrium Dynamics of Component Separation in a Binary Bose Gas - *Proukakis*
Tue-012	Nonlinear interferometric scaling from spin-mixing density oscillations - *Mahmud*
Tue-013	Kinetic Model of a Finite Temperature Multi-Component Condensate - *Edmonds*
Tue-014	Mapping the phase diagram of spinor condensates via adiabatic quantum phase transitions - *Jiang*
Tue-015	Fast thermalization and Helmholtz oscillations of an ultracold Bose gas - *Papoular*
Tue-016	BEC dynamics with solitons and vortices - *de Freitas Smaira*
Tue-017	Production of Two Species Superfluid to Study Quantum Turbulence and Vortices. - *Farias*
Tue-018	Coherent matter wave propagation with BECs in toroidal guiding potentials for atom interferometry and ATOMTROMICS based quantum simulators - *Birkl*
Tue-019	Towards producing atomic circulations in a toroidal trap in a Rb87 Bose-Einstein condensate - *Chen*
Tue-020	A continuous atom laser extracted from sodium condensates using two-photon Raman transition - *Murakami*
Tue-021	Observation of a reduced damping rate of collective oscillations of a quasi-1D Bose-Einstein condensate - *Yuen*
Tue-022	Spin dynamics in a two dimensional quantum gas - *Pedersen*
Tue-023	Vortex Pair Annihilation in Two-Dimensional Superfluid Turbulence - *Kwon*
Tue-024	Bethe ansatz approach to prethermalization in a coherently split 1D Bose gas - *Kaminishi*
Tue-025	Enhanced scattering in a Bose-Einstein condensate and a measurement of the heat capacity. - *Bons*
Tue-026	Atom chip based ultracold potassium for testing microwave and RF potentials - *Ziltz*
Tue-027	Experimental Investigation Of Quantum Turbulence in a Trapped Superfluid - *Tavares*

Tue-028 Thermodynamics With Global Variables For a Trapped Bose Gas - *Bagnato*
Tue-029 Bose-Einstein Condensation of ^{86}Sr - *Reschovsky*

Quantum Simulation

Tue-030 Non-equilibrium wave-packet dynamics in 1D optical lattices - *Tacla*
Tue-031 A Dissipative Quantum Many-Body System with Long-Range Interactions - *Mottl*
Tue-032 Dissipative Transport in a Many Body Quantum System - *Santra*
Tue-033 Ballistic Atom Pumps - *Byrd*
Tue-034 The effects of phase noise on the delta-kicked rotor - *Hoogerland*
Tue-035 Dynamics of atoms in bilayer optical lattices, and adiabatic state preparation - *Langer*
Tue-036 Observation of a disordered bosonic insulator from weak to strong interactions - *D'Errico*
Tue-037 Particle-hole entanglement of ultracold atoms in an optical lattice - *Ng*
Tue-038 Quantized Scattering from an Oscillating Barrier for Atomic Quantum Pumps - *Pyle*
Tue-039 A Dynamic, Ultra-Slow Optical-Matter Wave Analog of Event Horizon - *Zhu*
Tue-040 Breaking of time-reversal symmetry during coherent transport in disordered media - *Müller*
Tue-041 Superexchange Mediated Dynamics of Anti-Feromagnetic Order in an 2D Optical Lattice - *Koller*
Tue-042 Optimally Shaped Gates for Trapped Ion Chains - *Choi*
Tue-043 Quench dynamics in ion chains with variable-range interactions - *Buyskikh*
Tue-044 Quantum Simulation and Many-Body Physics with 2D Ion Crystals in a Penning Trap - *Bohnet*
Tue-045 Tunable spin-spin interactions and entanglement of ions in separate wells - *Wilson*
Tue-046 Experimental Developments towards studying Quantum Dynamics in Trapped Ions - *De Munshi*
Tue-047 Implementing scaleable remote ion-photon entanglement - *Graham*
Tue-048 Preparation of High NOON State of Phonon in a Trapped-ion System - *Zhang*

Ultracold Mixtures and Molecules

Tue-049 A microwave trap for sympathetic cooling of polar molecules - *Dunseith*
Tue-050 Towards a Three Dimensional Magneto-Optical Trap for Diatomic Molecules - *Hummon*
Tue-051 A cryogenic buffer-gas BaH beam for molecular laser cooling and ultracold fragmentation - *Tarallo*
Tue-052 Photoassociation spectroscopy of RbYb in a conservative trap - *Goerlitz*
Tue-053 Continuous formation of rovibronic ground state RbCs molecules via photoassociation - *Shimasaki*

Cooling and Trapping of Atoms and Ions

Tue-054 Probing evanescent field coupling between laser-cooled ^{87}Rb atoms and the fundamental and higher order modes of an optical nanofiber. - *Gokhroo*
Tue-055 A two-frequency ion trap confining ions with different charge-to-mass ratios - *Trypogeorgos*

Tue-056 Ion trap surface cleaning and microwave-driven gates - *Allcock*
Tue-057 Development of Microfabricated 2-D Ion Trap for Quantum Information Processing - *Kim*
Tue-058 Grating chips for quantum technologies - *Riis*
Tue-059 Double-Loop Microtrap Array for Ultracold Atoms - *Jian*
Tue-060 Sub-micron magnetic lattices for Quantum Simulation - *La Rooij*
Tue-061 Highly Efficient Free-Space Atom-Light Interface - *Fischer*
Tue-062 Hybrid trap for atoms, ions and molecules built within a Fabry-Perot cavity - *Ray*
Tue-063 Spontaneous coherence of magnons in spin-polarized atomic hydrogen gas - *Vainio*
Tue-064 Modular Quantum Systems with Photons and Phonons - *Vittorini*
Tue-065 Controlled photon emission of two ions in a cavity as enhanced quantum interface - *Casabone*

Intense Fields and Ultrafast Phenomena

Tue-066 Transverse electron momentum distribution for arbitrary polarization state of the ionizing laser pulse - *Ivanov*
Tue-067 Two-dimensional absorption spectroscopy with attosecond XUV light: Unraveling bound-state electron dynamics in strong laser fields. - *Blaettermann*
Tue-068 Low-energy enhanced multiphoton above-threshold ionization in a strong laser field of mid-infrared wavelength - *Usachenko*
Tue-069 Pressure optimization of high harmonic generation with argon gas jet - *Sayraç*
Tue-070 Effect of different transverse modes of femtosecond pulses on filament propagation - *Kaya*
Tue-071 Reduced-Density-Matrix Description for Pump-Probe Optical Phenomena in Moving Many-Electron Atomic Systems - *Jacobs*
Tue-072 Effect of nuclear mass on carrier-envelope-phase controlled electron localization in dissociating molecules - *Sang*

Quantum Information

Tue-073 Quantum Secret Sharing Using Multi-Spatial-Mode Entangled Light - *Horrom*
Tue-074 Adiabatic state transformation in the presence of classical noise. - *Xu*
Tue-075 All optical quantum storage based on spatial chirp of the control field - *Zhang*
Tue-076 Rydberg Quantum Information using a Magnetic Film Atom Chip - *Torralbo-Campo*
Tue-077 Nanophotonic and CMOS-integrated architectures for trapped ion quantum information processing - *Mehta*
Tue-078 Experimental test of state-independent quantum contextuality of an indivisible quantum system - *Huang*
Tue-079 Transfer and qubit fidelity of single atoms in a ring lattice - *Zhan*

Quantum Optics and Cavity QED

Tue-080 Scalable Source of Multipartite Continuous Variable Entangled Beams of Light - *Marino*
Tue-081 Photon-added nonlinear coherent states for a one mode field in a Kerr medium - *Récamier*
Tue-082 Advanced single photon sources with fiber-based optical microcavities - *Hunger*

Tue-083 Quantum optics with hot Rydberg atoms - *Urvoy*
Tue-084 Cross-Modulation of Two Laser Beams at the Individual Photon Level - *Beck*
Tue-085 Single Photon Transistor in Circuit Quantum Electrodynamics - *Neumeier*
Tue-086 Characterization of Non-Classical Photonics States Retrieved from a Cold Atomic Memory and Quantum Statistics of Light Transmitted through Intracavity Rydberg medium. - *Boddeda*
Tue-087 Reversing the temporal envelope of an heralded single photon using a cavity - *Srivathsan*
Tue-088 Phase-dependent double-Λ electromagnetically induced transparency - *Chen*
Tue-089 Observation of Spinor Slow Light - *Lee*
Tue-090 Three-photon electromagnetically induced absorption in a ladder-type atomic system - *Moon*
Tue-091 Line Properties of the Ladder-type Electromagnetically Induced Transparency - *Tsai*
Tue-092 Investigation of dynamical features in Λ-EIT atomic systems through noise correlation spectroscopy - *Theophilo*
Tue-093 Electromagnetically induced photonic bandgap in cold ^{87}Rb atoms - *Kim*
Tue-094 Synchronization in Superradiant Lasers - *Cox*

Rydberg Atoms

Tue-095 Imaging the Rydberg Electron Wavefunction - *Cubel Liebisch*
Tue-096 Dipolar transport in ultracold Rydberg gases - *Günter*
Tue-097 Spin squeezing and supersolids using Rydberg-dressed strontium atoms - *Sadler*
Tue-098 Ultralong Range Rydberg Molecules of Strontium - *DeSalvo*
Tue-099 Ultrafast coherent control of an ultracold Rydberg gas - *Takei*
Tue-100 Dynamical crystallization in a low-dimensional Rydberg gas - *Hild*
Tue-101 Rydberg blockade in an optical lattice - *Goldschmidt*

Spectroscopy, Atomic and Molecular Structure

Tue-102 Tune-out wavelengths for metastable helium - *Baldwin*
Tue-103 Magic polarization to eliminate Stark-induced dephasing in an optical trap - *Kim*
Tue-104 Magic Frequencies in Atom-Light Interaction for Precision Probing of the Density Matrix - *Margalit*
Tue-105 Tailoring light to enhance forbidden atomic transitions rates - *Jauregui*
Tue-106 Time-resolved measurement of velocity-changing collisions in a paraffin-coated alkali vapor cell - *Sekiguchi*
Tue-107 Atom-surface interactions using a quadrupole oscillator strength sum rule - *Babb*
Tue-108 Adsorbate Electric Fields on a Cryogenic Atom Chip - *Hufnagel*
Tue-109 Relaxation of Cs atomic polarization at surface coatings characterized by x-ray photoelectron spectroscopy - *Kushida*
Tue-110 Raman spectroscopy and NMR investigation of hydrocarbon anti-relaxation coatings upon interaction with an alkali-metal vapor - *Tretiak*
Tue-111 Nonlinear spectroscopy of atoms inside a porous sample - *Villalba*
Tue-112 Cell influence on the absolute frequency of cesium atom 6S-8S hyperfine transition - *Wu*
Tue-113 Revised and extended analysis of trebly ionized selenium: Se IV - *Noman*
Tue-114 The fourth spectrum of tin: Sn IV - *Kunari*

Tue-115 A New Simple Atom for Atomic Physics: e^+ bound to H^- in atomic state, H^{-+} - *Storry*

Atom Interferometry

Tue-116 Solitons, Interactionless BECs and Simultaneous Dual Isotopes in Atom Interferometry - *McDonald*
Tue-117 Compact atom interferometer inertial sensor with radially expanding atom ensemble - *Riedl*
Tue-118 Agile narrow linewidth single source laser system for onboard atom interferometry - *Theron*
Tue-119 A Mobile, Dual-Species Atom Interferometer for Equivalence Principle Tests in Micro-Gravity - *Barrett*
Tue-120 Matter-wave laser Interferometer Gravitation Antenna (MIGA) experiment for fundamental physics and geoscience - *Bertoldi*
Tue-121 Ytterbium Bose-Einstein condensate interferometer: current results and new construction. - *Plotkin-Swing*
Tue-122 Dynamic algebraically precise atom chip potentials - *Imhof*
Tue-123 Quantum interference experiments with macromolecules - *Eibenberger*
Tue-124 Atom interferometry of trapped BECs with tunable interactions - *Trenkwalder*

Precision Measurements and Fundamental Tests

Tue-125 Generation 2 of the ACME electron EDM search - *Baron*
Tue-126 Measuring the Xe-129 Permanent Electric Dipole Moment - *Degenkolb*
Tue-127 Cold and intense sources of large and heavy molecules for precision measurement of the electron EDM and parity violation - *Hendricks*
Tue-128 Interrogating the atomic nucleus with laser spectroscopy: francium (Fr) hyperfine anomaly and isotope shift measurements. - *Zhang*
Tue-129 Precision Measurement of Li Hyperfine & Fine Structure Intervals - *van Wijngaarden*
Tue-130 Nuclear Spin Dependent Parity Violation in Diatomic Molecules - *Altuntas*
Tue-131 Shifts due to quantum-mechanical interference from distant neighboring resonances - *Marsman*
Tue-132 Buffer gas cells and quantum cascade lasers: towards measuring parity violation in chiral molecules using vibrational spectroscopy - *Tokunaga*
Tue-133 Progress in barium tagging for the next generation ^{136}Xe double beta decay experiment - *Walton*
Tue-134 Towards an improved measurement of the n=2 triplet P fine structure of helium - *Kato*
Tue-135 Neutrino spectroscopy with atoms and molecules - *Masuda*
Tue-136 The Cold Atom Gravimeter at the µ-Gal-Level for Field Applications - *Wang*
Tue-137 Critical Nuclear Charge and Electron Charge Distribution for Two-Electron Atoms - *Drake*

Atomic Clocks

Tue-138 Progress Toward a Spin Squeezed Optical Atomic Clock Beyond the Standard Quantum Limit - *Braverman*

Tue-139 Near-Heisenberg-Limited Atomic Clocks in the Presence of Decoherence - *Borregaard*

Tue-140 Hunting for topological dark matter with atomic clocks - *Derevianko*

Tue-141 Trapping Ra^+: Optical Clock and Atomic Parity Violation - *Dijck*

Tue-142 Sorting ions in an two-species ion chain by amplitude-modulated laser beams for a new In^+ optical clock - *Ohtsubo*

Tue-143 Agile coherent control of ions in a microfabricated trap - *Thom*

Tue-144 Highly-charged ions for atomic clocks, quantum information, and search for α-variation - *Safronova*

New Experimental and Theoretical Techniques

Tue-145 High power, very narrow linewidth, micro-integrated diode laser modules designed for quantum sensors in space - *Kohfeldt*

Tue-146 Towards a fully-miniaturised magneto-optical trap system for portable ultracold quantum technology - *Aldous*

Tue-147 Locking Raman laser frequency of up to 40 GHz offset for atom interferometers - *Wang*

Tue-148 Optical phase locking of two extended-cavity diode lasers : direct modulation and serrodyne modulation - *Yim*

Tue-149 A Dynamic Magneto-Optical Trap for Atom Chips - *Rushton*

Tue-150 Holographic Laguerre-Gaussian beams for long-distance channeling of a 2D-MOT generated cold atom beam. - *Carrat*

Thursday Poster Session

Fermi Gases

Thu-001	Boltzmann-Vlasov approach and Fermi surface anisotropy in dipolar Fermi gases - *Veljić*
Thu-002	Specific heat and strong-coupling effects in the BCS-BEC crossover regime of an ultracold Fermi gas - *van Wyk*
Thu-003	Perron-Frobenius theorem on the superfluid transition of an ultracold Fermi gas - *Sakumichi*
Thu-004	Numerical Analysis of Fermion Transport Based on Nonequilibrium Thermo Field Dynamics - *Imai*
Thu-005	Triplet pair correlation in a trapped s-wave superfluid Fermi gas at T=0 - *Endo*
Thu-006	Diagrammatic Monte Carlo study of the Fermi polaron - *Vlietinck*
Thu-007	Strongly dipolar Fermi gases of erbium atoms - *Aikawa*
Thu-008	Quantum Monte Carlo simulations of muticomponent Fermi systems - *Sakaida*
Thu-009	Decoherence of many fermions in an optical lattice due to spontaneous emissions - *Sarkar*

Bose Gases

Thu-010	Faraday waves in collisionally inhomogeneous multi-component Bose-Einstein condensates - *Balaž*
Thu-011	Stochastic Coupled Growth of 2-Component Bose-Einstein Condensates - *Proukakis*
Thu-012	Creation of Topological Monopole Defects In a Quantum Field - *Tiurev*
Thu-013	Observation of Dirac monopoles in a synthetic magnetic field - *Ray*
Thu-014	Spin-nematic order and phase locking in antiferromagnetic spinor condensates - *Frapolli*
Thu-015	Quantum fluctuation of soliton in Bose-Einstein condensate beyond Bogoliubov approximation - *Takahashi*
Thu-016	Classical and quantum reflection of bright matter-wave solitons - *Marchant*
Thu-017	Bright solitons in quasi-one-dimensional dipolar condensates with spatially modulated interactions - *Abdullaev*
Thu-018	Modeling Bose-Einstein Condensates in Non-Uniformly Rotating Reference Frames - *Kandes*
Thu-019	Persistent Non-Equilibrium States In Perfectly Spherical Potentials - *Lobser*
Thu-020	Dynaimcs of Breather in linearly coupled Bose-Einstein Condensates - *Su*
Thu-021	Scissors mode and quantized vortices generated in sodium Bose-Einstein condensates by a rapid modulation of the magnetic field - *Yamazaki*
Thu-022	Position-dependent spin-orbit coupling for ultracold atoms - *Juzeliūnas*
Thu-023	Toward simulating artificial gauge fields with atom-chip based quantum simulator - *Sugawa*

Thu-024 Roton and phonon modes softening in quantum gases with spin-orbit coupling - *Ji*

Thu-025 Experimental apparatus for producing the Bose-Einstein condensate of Ytterbium(Yb) - *Mun*

Thu-026 Numerical analysis of quantum transport equation derived from nonequilibrium Thermo Field Dynamics in Markovian approximation - *Kuwahara*

Thu-027 Experimental probing of non-equilibrium Quantum Many-Body Systems - *Schweigler*

Thu-028 Creation of excitations from a uniform impurity motion in the condensate - *Suzuki*

Thu-029 Structure factor of ultra-cold bosons in two-dimensional optical lattices - *Zaleski*

Thu-030 Quantum state for zero mode of cold atomic gas system with Bose-Einstein condensate - *Nakamura*

Few Body Interactions and Collisions

Thu-031 Two-particle coalescences for the helium-like ions. - *Liverts*

Thu-032 Full control over two interacting fermions in a single double well - *Murmann*

Thu-033 Ultracold mixtures of metastable He and Rb: scattering lengths from *ab initio* calculations and thermalization measurements - *Knoop*

Thu-034 Efimov Resonances in a Mixture with Extreme Mass Imbalance - *Ulmanis*

Thu-035 The influence of confinement, dimensionality, and anisotropy on effective multibody interactions of trapped ultracold bosons. - *Johnson*

Thu-036 Towards optical Feshbach resonances with ^{40}Ca - *Pachomow*

Thu-037 Long range interactions of Sr and Yb in mixed quantum gases. - *Porsev*

Thu-038 The Degenerate Unitary Bose Gas - *Xie*

Ultracold Mixtures and Molecules

Thu-039 Dipolar gases of ground state molecules: NaK in Hannover - *Zenesini*

Thu-040 Precision measurements with ultracold Sr_2 molecules in optical lattices - *McGuyer*

Thu-041 Rf-induced association of ultracold molecules in ^{87}Rb. - *Mordovin*

Thu-042 Photoassociative production of Feshbach molecules of ytterbium by using the ultranarrow $^1S_0$-$^3P_2$ transition - *Taie*

Thu-043 Isotopic analysis of Na-K Feshbach resonances and molecules - *Simoni*

Thu-044 Ultracold molecules: far-from-equilibrium quantum magnetism - *Hazzard*

Cooling and Trapping of Atoms and Ions

Thu-045 A dual species magneto-optical trap of Cs and Yb - *Freytag*

Thu-046 Two-Stage Magneto-Optical Trapping of ^{6}Li Using D2 Line and Narrow-Line Cooling to High Phase-Space Density - *Sebastian*

Thu-047 Grey-molasses cooling of an optically trapped Fermi gas - *Edge*

Thu-048 Dual isotope magneto-optical trap with only one laser beam - *Hamzeloui*

Thu-049 Magneto-optical traps for Yb, Tm, Er, and Ho loaded from a buffer-gas beam source - *Chae*

Thu-050 Neutral Gas Sympathetic Cooling of an Ion in a Paul Trap - *Chen*

Thu-051	Quantum interactions in a hybrid atom-ion trap - *Schowalter*
Thu-052	Advancing surface-electrode ion trap capabilities: demonstrations of ball grid arrays, active in-vacuum control electronics, and integrated diffractive optics - *Amini*
Thu-053	Nano-friction between crystals of light and ions with atomic resolution and control from one- to many-body physics - *Bylinskii*
Thu-054	'Alligator' photonic crystal waveguides for single-atom trapping and strong light-matter interactions - *Yu*

Quantum Optics and Cavity QED

Thu-055	Injection of angular momentum in a polariton superfluid - *Glorieux*
Thu-056	Observation of Grand-canonical Number Statistics in a Photon Bose-Einstein condensate - *Schmitt*
Thu-057	Light-Wave Mixing and Scattering with Quantum Gases - *Deng*
Thu-058	Sympathetic cooling of a membrane oscillator in a hybrid mechanical-atomic system - *Kampschulte*
Thu-059	Optical Frequency Combs and Temporal Solitons in Optical Microresonators - *Jost*
Thu-060	Self-organized optomechanical structures - *Ackemann*
Thu-061	Feedback cooling using a near-Heisenberg-limited position measurement - *Wilson*
Thu-062	Optomechanics with ultra cold Rydberg gases - *Wüster*
Thu-063	Cavity Opto-Mechanics with Cold Atoms: Force Sensing near the Standard Quantum Limit and Coupled Oscillators - *Spethmann*
Thu-064	From membrane-in-the-middle to mirror-in-the-middle with a high-reflectivity sub-wavelength grating - *Xu*
Thu-065	A scanning cavity microscope - *Hunger*
Thu-066	Thermodynamic corrections to mechanical oscillations - *Wang*
Thu-067	A Useful Entanglement Resource; 10 dB Spin Squeezing with Cavity QND Measurements - *Cox*
Thu-068	Quantum metrology frontiers with highly squeezed quantum states of atomic ensembles - *Hosten*
Thu-069	Quantum Zeno dynamics of a Rydberg atom - *Gleyzes*
Thu-070	Generation of multiparticle entangled states using quantum Zeno dynamics - *Barontini*

Quantum Information

Thu-071	Many-particle entangled states of two-component Bose-Einstein condensates - *Schmied*
Thu-072	Atomic twin Fock states in momentum space - *Lopes*
Thu-073	Quantum networking and sensing efforts at the Army Research Laboratory - *Stack*
Thu-074	Towards the Detection of Momentum Entangled Atom Pairs - *Keller*
Thu-075	Control of Quantum Dynamics on an Atom-Chip - *Herrera*

Thu-076 High-fidelity cluster state generation of ultracold atoms in an optical lattice - *Tokunaga*

Thu-077 Coherent optical memory with 94% efficiency - *Hsiao*

Rydberg Atoms

Thu-078 Towards Single-Photon Nonlinear Optics via Pattern Formation in Spatially Bunched Atoms - *Schmittberger*

Thu-079 Optical properties of a strongly correlated array of induced dipoles - *Bettles*

Thu-080 Photonic Controlled-Phase Gate Based on Rydberg Interactions - *Khazali*

Thu-081 Single-Photon Switch and Transistor Based on Rydberg Blockade - *Duerr*

Thu-082 Strongly Interacting Photons in a Rydberg Polariton Gas: Few Photon Spectroscopy and Coulomb Bound States - *Gullans*

Quantum Simulation

Thu-083 Generating topological spin textures in spinor Bose-Einstein condensates by a stimulated Raman interaction - *Hansen*

Thu-084 Stability of a Floquet Bose-Einstein condensate in a one-dimensional optical lattice - *Choudhury*

Thu-085 Topological phases in spin-orbit coupled dipolar bosons in a one-dimensional lattice - *Ng*

Thu-086 Fractionalized Majorana fermions (parafermions) with ultracold atoms - *Maghrebi*

Thu-087 *p*-wave pair amplitude and *s*-wave superfluid phase transition in the BCS-BEC crossover regime of an ultracold Fermi gas with a spin-orbit interaction - *Yamaguchi*

Thu-088 Implementation, phase structure and real time dynamics in atomic quantum simulators of lattice Gauge-Higgs theory - *Kasamatsu*

Thu-089 Collective mode analysis of a Bose-Einstein condensate in a density-dependent gauge potential - *Edmonds*

Thu-090 Synthetic Spin-Orbit Coupling Without Light - *Anderson*

Thu-091 Self-organized Rice-Mele model in ultracold atoms - *Przysiężna*

Thu-092 Optical-lattice Floquet systems - *Eckardt*

Thu-093 Measuring geometric phases in Bloch bands: The topology of a Dirac cone - *Reitter*

Thu-094 Quantum magnetism of bosons with synthetic gauge fields in one-dimensional optical lattices: a Density Matrix Renormalization Group study - *Piraud*

Thu-095 Synthetic fields in synthetic dimensions - *Stuhl*

Thu-096 Topologically Robust Transport of Photons in a Synthetic Gauge Field - *Mittal*

Thu-097 Atomic Hong-Ou-Mandel effect in tunnel-coupled optical tweezers - *Kaufman*

Thu-098 Quantum co-walking of two interacting particles in one-dimensional lattices - *Qin*

Thu-099 Direct Observation of Strongly Correlated Bosonic Quantum Walks - *Ma*

Thu-100 In situ probing of interacting fermions in an optical lattice - *Cocchi*

Thu-101 Fermi Gas Microscope with Lithium-6 - *Parsons*

Thu-102 Quantum gas microscope of ytterbium atoms - *Miranda*

Thu-103 Experimental demonstration of more than 100 individually addressable qubits for quantum simulation and quantum computation - *Schlosser*
Thu-104 Qubit fidelity of a single atom transferred among the sites in a ring lattice - *Yu*
Thu-105 Coherent dipole-dipole coupling between two single atoms at a Förster resonance - *Ravets*
Thu-106 A 2D array of Rydberg coupled atomic qubits - *Lichtman*

Spectroscopy, Atomic and Molecular Structure

Thu-107 The $4d^8$ - $4d^7(4f+6p)$ transitions of In VI - *.*
Thu-108 Photoionizing $^{174}Yb^+$ to $^{174}Yb^{2+}$ - *Heugel*
Thu-109 Precision frequency measurement of transitions between singlet states in atomic helium - *Luo*
Thu-110 Probing near threshold double and single ionization of helium atoms - *Purohit*
Thu-111 The dynamical properties of autoionization of rare-earth Eu atom - *Dai*
Thu-112 Enantiomer-specific detection of chiral molecules via microwave spectroscopy - *Patterson*
Thu-113 Theoretical transition rates of forbidden lines in doubly-ionized iron group elements - *Fivet*
Thu-114 Second Spectrum of Selenium - *Tauheed*
Thu-115 High-precision nonadiabatic calculations of dynamic polarizabilities and hyperpolarizabilities for low-lying vibrational-rotational states of hydrogen molecular ions - *Tang*
Thu-116 Atomic hyperpolarisabilities and the non-linear optics of atomic gases - *Grunefeld*
Thu-117 Measurement of the 5D Level Polarizability in Laser Cooled Rb Atoms - *Snigirev*

Atom Interferometry

Thu-118 An analog of polarization in atom optics: a Raman waveplate to measure the Gouy phase in matter waves - *Schultz*
Thu-119 Atomic matter-wave interferometer on an external atomchip - *Kim*
Thu-120 A programmable broadband low frequency active vibration isolation system for atom interferometry - *Tang*
Thu-121 Manipulation of atomic velocities with broadband light-pulse atom interferometry - *Gregory*
Thu-122 A milliradian phase resolution Ca atom interferometer with transparent ITO electrodes - *Akentyev*
Thu-123 Large Momentum Transfer and Faster Signal Scalings in Acceleration-Sensitive Atom Interferometry - *McDonald*

Precision Measurements and Fundamental Tests

Thu-124 Progress towards in-beam hyperfine spectroscopy of antihydrogen - *Widmann*
Thu-125 ALPHA-2: an upgraded apparatus for physics with trapped antihydrogen - *Eriksson*
Thu-126 Positron storage for the production of an antihydrogen beam - *Murtagh*
Thu-127 Production of a cold antihydrogen beam with a cusp trap - *Radics*

Thu-128 Hyperfine structure and relativistic corrections to ro-vibrational energy levels of the D_2^+ ion - *Zhang*

Thu-129 μTest of the change of m_p/m_e using laser cooled and optically trapped ^{40}CaH - *Kajita*

Thu-130 Test of m_p/m_e variation via measurement of N_2^+ vibrational transition frequencies - *Kajita*

Thu-131 Test of Einstein Equivalence Principle with bosonic and fermionic quantum matter: Search for spin-gravity coupling effects - *Tarallo*

Thu-132 Species-Selective Lattice Launch for High-Precision Atom Interferometry - *Chamakhi*

Thu-133 Testing General Relativity in a terrestrial lab through laser gyroscopes - *Beverini*

Atomic Clocks

Thu-134 Magic wavelengths measurement via observation of light shift on $^{40}Ca^+$ optical frequency standard - *Gao*

Thu-135 Determination of the magic wavelength for the $^1S_0$ – $^3P_0$ transition in magnesium 24 - *Fim*

Thu-136 Improving the stability of an atomic clock - *Schioppo*

Thu-137 Reducing the Uncertainty of Blackbody Radiation Shift in a Strontium Optical Clock - *Al-masoudi*

Thu-138 Precise characterization of the blackbody radiation environment in an optical lattice clock - *Beloy*

Thu-139 The SOC2 transportable ^{171}Yb lattice clock - *Goerlitz*

Thu-140 An ultra-low frequency-noise laser based on a 48 cm long ULE cavity for a Sr lattice clock - *Häfner*

Thu-141 Dual species intercombination MOT of ^{171}Yb and ^{87}Sr: Toward a dual optical lattice clock - *Akamatsu*

Thu-142 Measurement of the clock-transition spectrum of the ultracold ytterbium atoms - *Xu**

Thu-143 Comparison between a strontium optical lattice clock with primary and secondary frequency standards - *Robyr*

New Experimental and Theoretical Techniques

Thu-144 Non-destructive imaging and feedback stabilized production of cold atomic clouds - *Gajdacz*

Thu-145 Dispersive probing as a tool for monitoring dynamical processes in ultracold gases - *Deb*

Thu-146 Compact semiconductor laser modules for precision quantum optical experiments in space - *Lewoczko-Adamczyk*

Thu-147 Subwavelength alteration of one-dimensional optical lattices using radiofrequency-induced adiabatic potentials - *Lundblad*

Thu-148 Scalable 2D array of dipole traps formed by pinhole diffraction for neutral atom quantum computing - *Gillen-Christandl*

Thu-149 Design of optical Talbot focal point array for neutral atom quantum computing - *Kim*

Thu-150 Bose-Einstein Condensation in a Periodic Magnetic Lattice - *Wang*

Beyond Atomic Physics

Thu-151 Generalized Thermodynamic Properties - *Morales*

Thu-152 Supersymmetry, shape invariance and the hypergeometric equation - *Pushpa*

Thu-153 On the Geometric Implications of Maxwell's Equations - *Smith*

INVITED SPEAKER ABSTRACTS

Quantum control of trapped ions at NIST

David Wineland

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303, USA

Research on precise control of quantum systems occurs in many laboratories, for fundamental research, new measurement techniques, and more recently for quantum information processing. I will briefly relate how the NIST ion group became involved in these topics and will describe our current experiments, but these only serve as examples of similar work being performed in many other labs around the world.

Nobel Session Invited Speaker Monday: 8:30am - 10:15am

Quantum control of trapped photons with Rydberg atoms

Serge Haroche

ENS-LKB & Collège de France, Paris, France

Cavity QED with Rydberg atoms in superconducting microwave cavities has allowed us to achieve the non-destructive observation and precise control of trapped quantum fields. I will recall the history of these experiments which bear strong similarities with those performed on trapped ions interacting with laser beams, and I will describe the research directions currently followed by the ENS-LKB Cavity QED group.

Bands with a twist and quantum sized steps

Tilman Esslinger

Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland

We use fermionic quantum gases to study the topological Haldane model in an optical lattice and the quantized conductance in an optically engineered quantum point contact for atoms. The Haldane model on the honeycomb lattice features topologically distinct phases of matter and describes a mechanism through which a quantum Hall effect can appear as an intrinsic property of a band-structure, rather than being caused by an external magnetic field. In our experiment we have realized the Haldane model in a periodically modulated honeycomb lattice and characterized its topological band-structure. Our approach allows for dynamically tuning topological properties and is even suitable for interacting fermions. In transport experiments the quantum nature of matter becomes directly evident when changes in conductance occur only in discrete steps, with a size determined solely by Planck's constant h. I will report on our observation of quantized conductance in the transport of neutral atoms. This fundamental phenomenon has so far not been observed with neutral matter. In our isolated atom device we enter a regime in which the mean free path is larger than the system size.

Quantum Gases I Invited Speaker Monday: 10:45am - 12:30pm

Efimov and beyond: New developments in few-body physics with ultracold bosons and fermions

Rudolph Grimm

Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria

Ultracold atomic ensembles with resonantly tuned interactions provide a unique test-bed for universal few-body physics. While the paradigm of the field is Efimov's scenario of three interacting bosons with its infinite ladder of three-body quantum states, a bunch of recent work has revealed a variety of few-body phenomena that go far beyond this case. In my talk, I will first stay with the original three-boson scenario and present a precise measurement of the universal scaling factor inherent to Efimov physics. The measurements have been carried out with a Feshbach-resonant gas of Cs atoms and provide a scaling factor of 21.0(1.3), very close to the ideal value of 22.7. I will then discuss another experiment with a mass-imbalanced mixture of fermions (Li-6 and K-40). On the repulsive side of a Feshbach resonance, we find that a few-body effect leads to a strong attraction between weakly bound dimers (LiK) and the heavier atoms (K). This phenomenon is absent in the commonly used spin mixtures of a single fermionic species and can fundamentally change the many-body properties of the system.

Uniform Bose gases

Zoran Hadzibabic

University of Cambridge Cavendish Lab, JJ Thomson Avenue, CB3 0HE, UK

For almost two decades harmonically trapped ultracold atomic gases have been used with great success to study fundamental many-body physics in a flexible experimental setting. Recently, we achieved the first atomic Bose-Einstein condensate in an essentially uniform potential of an optical-box trap [1]. This opened unprecedented possibilities for closer connections with other many-body systems and the textbook models that rely on the translational symmetry of the system. I will give an overview of our first experiments on this new system, which include studies of both thermodynamics and dynamics of Bose-Einstein condensation in a homogeneous gas.

References

[1] A. L. Gaunt, et al., Phys. Rev. Lett. 110, 200406 (2013).

Quantum Spin Sensors

Jörg Wrachtrup

3rd Physics Institute, Stuttgart Unversity, 70569 Stuttgart Germany

Atom and quantum optics have developed a remarkable toolbox for precision measurements. Are those techniques applicable in sensor technology and pivotal in achieving increased resolution and sensitivity in e.g. material and life science applications? The upcoming class of spin sensors in diamond or silicon carbide (SiC) seem to answer to this question affirmative. Such sensors probe a variety of parameters and operate under a wide variety of environmental conditions. In addition, they combine remarkable sensitivity with high spatial resolution. The talk will describe recent applications of diamond and SiC in detecting e.g. nuclear magnetic resonance signals. Quantum memories and error correction improve spectral resolution and sensitivity of those experiments. Limits to precision and resolution will be explored.

Coherent control of light-matter interactions in a semiconductor nanophotonic device

Edo Waks

Department of Electrical and Computer Engineering, IREAP, and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA

Semiconductor nanophotonic devices provide a pathway towards exploring cavity quantum electrodynamics in a solid-state platform. Such devices have already been shown to exhibit strong nonlinear optical interactions at energies approaching the single photon level. Methods to coherently control these interactions could open up the possibility for chip-integrated quantum optical circuits.

In this talk I will present our recent efforts to attain coherent control of light-matter interactions in a semiconductor nanophotonic device platform. I will describe our recent demonstration of a quantum gate between a single quantum dot and a photon. I will then describe how we can utilize a more complex device structure called a photonic molecule to achieve coherent control of vacuum Rabi oscillations in a strongly coupled system. Such coherent control could enable synthesis of arbitrary quantum states of light on a chip.

Artificial Atoms Invited Speaker Monday: 2:15pm - 4:00pm

Photons in synthetic gauge fields

Mohammad Hafezi

Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA

Topological features – global properties which are not discernible locally – emerge in systems from liquid crystals to magnets to fractional quantum Hall systems. Deeper understanding of the role of topology in physics has led to a new class of matter: topologically-ordered systems. The best known examples are quantum Hall effects, where insensitivity to local properties manifests itself as conductance through edge states that is insensitive to defects and disorder. In this talk, I demonstrate how similar physics can be observed for photons; specifically, how various quantum Hall Hamiltonians can be simulated in photonic systems and I report on the observation of topological photonic edge state using the silicon-on-insulator technology. Furthermore, the addition of optical nonlinearity into photonic systems provides a platform to implement fractional quantum Hall states of photons, from optical to microwave domains. More generally, I discuss how correlated states can be prepared in dissipative-driven photonic systems.

Universality in Cold Molecular Collisions

Paul S. Julienne

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As sources of cold molecules become available, the question of the character of cold molecular collisions naturally arises [1]. While cold atomic collisions have been widely studied and understood, with magnetically tunable Feshbach resonances offering a highly successful source of control, the greater complexity and number of degrees of freedom in molecular collisions make them much more difficult to treat theoretically. Consequently, it is worthwhile to examine to what extent the concept of "universality" may apply to collisions between cold molecules and atoms or other cold molecules, where "universal" is defined here to mean independent of the complicated and unknown details of short-range interactions between the colliding species. This talk gives three examples of such "universality" that will be useful in understanding cold molecular collisions and "chemistry." One example is "van der Waals universality" in the three-body recombination of three cold atoms to make a molecule. In this case a model using known parameters of two-body tunable Feshbach resonances plus the long-range van der Waals interactions among three atoms is sufficient to calculate three-body recombination rates at all scattering lengths without needing fitting parameters [2]. Another example is the universal reaction or relaxation rates of two molecules with unit probability of short-range dynamics that results in the loss of two cold molecules. Reaction rates are then universally determined by long-range threshold dynamics of the colliding molecules. The reactive collisions of ultracold KRb molecules exhibit such universality [3], which is expected to characterize a wide class of cold molecular collisions [1]. Finally, recent work has suggested that collisions of cold atoms [4] or molecules [5] may be characterized by statistical universality associated with a high density of resonance states of the collision complex of the two species.

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Studying the dynamics of a long-range interacting spin system of ultracold polar molecules

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The past decade of atomic physics has seen remarkable advances in the realization of strongly interacting systems, where interparticle interactions can dictate behavior and lead to emergent cooperative phenomena. Moreover, there has in recent years been an intense effort to realize systems dominated by long-ranged interactions, which have an inherent capacity to generate substantial long-range correlations and entanglement.

Here, we present experimental results on the realization of a strongly interacting system of ultracold ground state KRb molecules, trapped at dilute filling in an optical lattice. We are able to provide the first direct evidence for long-range dipolar interactions between ultracold polar molecules, even while working in the absence of an applied electric field. By creating a coherent superposition of two rotational states of opposite parity (pseudo spin-1/2), we couple molecules via resonant dipole-dipole exchange interactions. We study the out-of-equilibrium dynamics of our strongly interacting spin system, driven exclusively by spin interactions, through the use of coherent Ramsey spectroscopy. By tuning the strength of dipole-dipole couplings, and by controlling the molecule filling in the lattice, we have confirmed the microscopic description of dipolar interactions in our system, which realizes a long-range spin-1/2 Heisenberg XY model.

We will discuss ongoing efforts to create a denser sample of molecules, which will allow for fundamental studies of both the equilibrium properties and excitation dynamics of our strongly interacting spin system.

Generating cold ensembles of polyatomic molecules

Martin Zeppenfeld

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While the past years have seen immense progress in development of techniques to produce cold and ultracold molecules, this effort has focused almost exclusively on diatomic molecules. This is despite favorable properties of polyatomic molecules including additional internal degrees of freedom for possible applications and yet a relatively simple rovibrational energy structure and a high vapor pressure far below room temperature. In my talk, I will discuss our results including latest progress in generating cold ensembles of polyatomic molecules. This includes our centrifuge decelerator and optoelectrical Sisyphus cooling.

Roton-Maxon Excitation of Bose Condensates in a shaken optical lattice

Cheng Chin

The James Franck Institute, The Enrico Fermi Institute, and Department of Physics, The University of Chicago, Chicago, Illinois 60637, USA

Experimental evidence is presented that a Bose condensate in a resonantly shaken lattice can develop a roton-maxon excitation spectrum - hallmark of superfluid helium. The roton-maxon feature originates from the double-well dispersion of a hybridized lattice band, and can be controlled by Feshbach tuning. We determine the excitation spectrum using Bragg spectroscopy, and measure the critical velocity by dragging a speckle potential through the condensate -- both techniques are implemented with a digital micromirror device. Our results are in good agreement with an extended Bogoliubov model.

Quantum simulation using ultracold ytterbium atoms

Yoshiro Takahashi

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I will report our recent experiments on quantum simulation of condensed matter systems using quantum degenerate ytterbium (Yb) atoms. One of the unique properties of Yb atoms is the existence of a fermionic isotope of ^{173}Yb with a spin symmetry of SU(N=6) which will show novel magnetic phases. As a first step, we successfully form a Mott insulator state of ^{173}Yb fermions with SU(6) symmetry in a three-dimensional optical lattice owing to an enhanced Pomeranchuk cooling. The ultracold ^{173}Yb atoms are also successfully loaded into a recently realized optical Lieb lattice, which is important in the study of the flat-band ferromagnetism. In addition, we have recently observed magnetic Feshbach resonances between the ground state and the long-lived metastable state, which will offer interesting possibilities in the studies of possible topological superfluid, a low-dimensional gas, and an optical Feshbach resonance.

Generation and Exploration of Spin-Orbit coupled Bose Gas

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We report the experiment of quantum simulations with synthetic spin-orbit coupled Bose gas. Raman coupling technique is applied to generate the spin-orbit (SO) coupling in 1D with ultracold Bose gas of ^{87}Rb. It also leads to many new phenomena of boson superfluidity and various condensate phases. We experimentally determine the phase diagram of SO coupled Bose gas at finite temperature, including the critical temperature, the phase transition and phase boundary between density striped (ST) phase and magnetized plane wave (MG) phase, as well as the temperature that the magnetic order is established. Furthermore, Bragg spectroscopy is applied to study the excitation of SO coupled BEC. “Roton” mode and its softening is observed in the excitation spectrum, which only short range and weak atom-atom interactions is presented. The softening of phonon modes is also observed, which give us some new understanding of the superfluidity in SO coupled Bose gas. Our study shows the true power of quantum simulation.

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ACME: A Search for the Electron's Electric Dipole Moment

David DeMille, on behalf of the ACME collaboration [1]

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Time reversal (T)- and parity (P)-violating interactions that can give rise to the electron's electric dipole moment (eEDM) are predicted in many extensions to the Standard Model of particle physics, and are also required to explain the observed imbalance between matter and antimatter in the universe. The ACME experiment uses thorium monoxide (ThO) molecules to amplify the effect of the eEDM, and a cryogenic beam source to deliver high molecule flux. The structure of ThO suppresses many systematic errors. We measure a T-,P-violating energy shift $\delta E/h = 0.4 \pm 0.8_{stat} = \pm 0.5_{syst}$ mHz, consistent with zero [1]. This implies an upper limit on the eEDM of $|d_e| < 9.6 \times 10^{-29} e{\cdot}$cm x $(\mathscr{E}^0_{eff} / \mathscr{E}_{eff})$ (90% c.l.). Here $_{eff}$ is the true value of the effective electric field acting on the eEDM in ThO, and $\mathscr{E}^0_{eff}$ = 76 GV/cm is a weighted average of the two most complete calculations of this quantity [2]. This improves the previous limit[3] by an order of magnitude, and sets strong constraints on new T-,P-violating interactions at or above the TeV energy scale probed by the Large Hadron Collider. We expect a substantial increase in sensitivity in the next generation of the experiment, now under construction.

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Fundamental tests of nature and a high-precision measurement of the atomic mass of the electron

Klaus Blaum

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The presentation will provide an overview on recent fundamental applications of precision measurements with cooled and stored ions in Penning traps. One the one hand, precision Penning-trap mass measurements provide indispensable information for neutrino physics and for testing fundamental symmetries. On the other hand, in-trap measurements of the bound-electron g-factor in highly-charged hydrogen-like ions allow for better determination of fundamental constants and for constraining Quantum Electrodynamics. Furthermore, ongoing preparations for the experimental comparison of the proton and antiproton g-factors will allow us to achieve a crucial test of the Charge-Parity-Time reversal symmetry. Among others a 13-fold improvement of the atomic mass of the electron by combining a very accurate measurement of the magnetic moment of a single electron bound to a carbon nucleus with a state-of-the-art calculation in the framework of bound-state Quantum Electrodynamics will be presented.

Precision Inertial Sensing Using Atom Interferometry

Mark Kasevich

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Recent advances in atom optics and atom interferometry have enabled observation of atomic de Broglie wave interference when atomic wavepackets are separated by distances approaching 10 cm and times of nearly 3 seconds. With further refinements, these methods may lead to meter-scale superpositions. In addition to providing new tests of quantum mechanics, these methods allow inertial force sensors of unprecedented sensitivity. We will describe methods demonstrated and results obtained in a 10 m atomic fountain configuration, their implications for technological applications in geodesy and inertial navigation, and their relevance to fundamental studies in gravitational physics. We will describe supporting techniques used to cool atoms to effective temperatures below 50 pK in two dimensions and novel atom optics configurations which have achieved greater than 5 sec of quasi-inertial free fall. Finally, we will discuss the prospects of incorporating spin-squeezing methods to improve interferometer signal-to-noise.

Attosecond ionization dynamics

Ursula Keller

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Using novel attosecond measurement techniques such as attosecond energy streaking, the attoclock and RABBITT we can address very fundamental questions in quantum mechanics. For example we are looking for answers for how fast light can liberate a bound electron from atoms, molecules and surfaces. Photon ionization is normally grouped in one-photon, multi-photon and tunnel ionization. Theoretical prediction for such fundamental time delays are not conclusive.

While tunneling probabilities and escape rates, for example, are well defined and widely accepted the question of how long it takes a particle to transverse a barrier has been the subject of intense theoretical debate for decades. We found that out of four tunneling times, only the Larmor time was within experimental uncertainty, excluding the other three tunnelling time definitions (i.e. Büttiker-Landauer, Eisenbud-Wigner, and Pollack-Wigner time) as being “correct" for interpreting attoclock measurements.

Furthermore using both attosecond energy streaking and RABBITT we could measure the single-photon ionization delays between different targets such as atoms, molecules and surfaces. We use coincidence detection to determine which liberated electrons belongs to which ion. In addition, we show that the temporal structure of the ionizing single attosecond pulse (i.e. attochirp) may significantly affect the obtained time delays in attosecond streaking and we propose a procedure how to take this contribution properly into account. Our analysis reveals an atomic delay of a few tenths of attoseconds in a photon energy range between 28 and 38 eV in the emission of electrons ionized from Argon with respect to those liberated from Neon. In addition we present first RABBITT ionization delay measurements from molecules and surfaces.

The recent advances in attoscience have enabled the larger community to obtain more reliable time delays on an attosecond time scale. This talk will give an overview about these recent results.

Resolving and manipulating attosecond processes via strong-field light-matter interactions

Nirit Dudovich

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The interaction of intense light with atoms or molecules can lead to the generation of extreme ultraviolet (XUV) pulses and energetic electron pulses of attosecond (10-18) duration. The advent of attosecond technology opens up new fields of time-resolved studies in which transient electronic dynamics can be studied with a temporal resolution that was previously unattainable. I will review the main challenges and goals in the field of attosecond science. As an example, I will focus on recent experiments where the dynamics of tunnel ionization, one of the most fundamental strong-field phenomena, were studied. Specifically, we were able to measure the times when different electron trajectories exit from under the tunneling barrier created by a laser field and the atomic binding potential. In the following stage, subtle delays in ionization times from two orbitals in a molecular system were resolved. These experiments provide an additional, important step towards achieving the ability to resolve multielectron phenomena -- a long-term goal of attosecond studies.

Ultrafast Science Invited Speaker Wednesday: 8:30am - 10:15am

Laser plasma accelerators and photon sources

Cameron Geddes

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Laser-plasma accelerators (LPAs) produce GeV electron beams in centimeters, using the plasma wave driven by the radiation pressure of an intense laser. Such compact high-energy linacs are important to applications ranging from future high energy physics to brilliant femtosecond radiation sources. Operation principles and development towards the required beam quality and efficiency will be discussed. Control over laser optical mode and plasma profile extended the acceleration distance to produce efficient acceleration. This includes electrons above 200 MeV from 10 TW and up to 4.25 GeV from <400 TW. Recent experiments will be discussed where the beat between 'colliding' lasers controls injection, producing bunches with energy spreads below 1.5% FWHM and divergences of 1.5 mrad FWHM. Separate experiments recently demonstrated 0.1 mm-mrad emittance from self injected LPAs using betatron radiation, and stable beam performance. Photon sources including free electron lasers, betatron and Thomson scattering will be described.

Many-body physics with Rydberg atoms and quantum light

Thomas Pohl

Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany

By virtue of their strong interactions, Rydberg atoms have emerged as a versatile platform for exploring strong-correlation effects in few- and many-body quantum systems. For example, coherent Rydberg excitation of random ensembles, small arrays or extended lattices of ultracold atoms permits to realize artificial spin systems with large finite-range interactions. In addition, the combination of electromagnetically induced transparency with interacting Rydberg states opens up unique opportunities for quantum nonlinear optics that enabled recent breakthroughs towards generating single-photons as well as photon-photon and light-matter entanglement on a two-body level.

In this talk, I will briefly review such latest developments and present our recent progress in understanding the many-body physics of atoms and photons in these settings. For weak optical nonlinearities, incident laser fields are found to drive a crystallization of Rydberg atoms, whose dynamics will be discussed via simplified models that, moreover, permit to elucidate the transition from classical to quantum light. In the strongly nonlinear regime, on the other hand, numerical simulations suggest a rich physical behaviour with strongly correlated phases of photons, atoms or both. Recent observations and implications for potential experiments will also be discussed.

Rydberg quantum optics in dense ultracold gases

Sebastian Hofferberth

Physikalisches Institut and Center for Integrated Quantum Science and Technology IQST, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons via electromagnetically induced transparency enables manipulaion of light on the single photon level. We report the realization of a free-space single-photon transistor exploiting the interaction between Rydberg excitations with different principal quantum numbers [1]. We also present our investigation of Rydberg-groundstate atom interaction in dense systems, which leads to the formation of Rydberg molecules. We show that spectra of discrete molecular lines observed at low prinicipal quantum numbers and low density turn into density-dependent shifts of the Rydberg line at large principle quantum numbers [2] or high background density [3,4]. We discuss the implications of this effect on quantum optics experiments based on Rydberg EIT.

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Experimental investigations of resonant dipole-dipole interaction between cold atoms

Antoine Browaeys

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This talk will present our on-going effort to understand and manipulate resonant dipole-dipole interaction between cold atoms. This interaction results from the non-radiative energy exchange between two-level systems, mediated by the vacuum field between atoms. It is long-range, with scaling between $1/R^3$ to $1/R$, with R the distance between atoms.

We are working on two different systems based on laser cooled trapped atoms where this interaction plays an important role. The first one is a dense ensemble of cold atoms confined in a volume on the order of the wavelength of an optical transition. Here the dipole-dipole interaction results into the collective scattering of a near-resonant laser by the ensemble, described by a collection of eigen-modes. In particular the scattering is strongly suppressed with respect to the single atom case. The presence of this interaction leads to open question in the theory of the optical response of an ensemble of scatterers.

In our second systems, we manipulate individual atoms in arrays of optical tweezers separated by few micrometers. There we control the interaction between atoms with microwave and DC electric fields. We observe in particular the coherent energy exchange between two atoms resulting from the dipole-dipole interaction between atoms. This control of the interaction has application in quantum state engineering, quantum information and quantum simulation.

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Quantum sensing and simulation with light and matter

Jake Taylor

Joint Quantum Institute, NIST and the University of Maryland, Room 2207 Computer and Space Sciences Building, College Park, MD 20742

Advances in quantum systems in novel domains - with ensembles of atoms, spins in solids, superconducting circuits or even mechanical oscillators - lead to intriguing new possibilities for observing and controlling quantum behavior in increasingly large systems. In this talk, I consider how we can use these systems for quantum-limited measurement and transduction of forces and fields. Furthermore, I will describe techniques that can take these systems into the regime of quantum simulation, communication, and computation. Where possible, I will highlight how these developments have the potential to improve our understanding of quantum many-body systems and to test the properties and behavior of such systems in a controlled setting.

Quantum Calculation Invited Speaker Thursday: 8:30am - 10:15am

Quantum Information and Quantum Computation for Chemistry

Alán Aspuru-Guzik

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Numerically exact simulation of quantum systems on classical computers is in general, an intractable computational problem. Computational chemists have made progress in the development of approximate methods to tackle complex chemical problems. The downside of these approximate methods is that their failure for certain important cases such as long-range charge transfer states in the case of traditional density functional theory. In 1982, Richard Feynman suggested that a quantum device should be able to simulate quantum systems (in our case, molecules) exactly using quantum computers in a tractable fashion. Our group has been working in the development of quantum chemistry algorithms for quantum devices. In this talk, I will describe how quantum computers can be employed to carry out numerically exact quantum chemistry and chemical reaction dynamics calculations, as well as molecular properties. I will describe recent algorithmic developments that do not include quantum phase estimation approaches such as the adiabatic quantum chemistry strategy as well as the variational quantum eigensolver approach. Adiabatic quantum cooling as a simple strategy for preparing ground states will be surveyed. I will overview the algorithms as well as several experiments we have carried out with collaborators to demonstrate the ideas with small-scale quantum simulators.

Photonic Quantum Simulation

Andrew White

Centre for Engineered Quantum Systems and Centre for Quantum Computing & Communication Technology University of Queensland, Brisbane, Australia

In principle, quantum mechanics can exactly describe any system of quantum particles—from single electrons to unwieldy proteins—but in practice this is impossible for even moderately interesting systems as the number of equations grows exponentially with the number of particles.

A well known example is the fundamental problem faced in quantum chemistry, calculating molecular properties such as total energy of the molecule. In principle this is done by by solving the Schrödinger equation; in practice the computational resources required increase exponentially with the number of atoms involved and so approximations become necessary. Recognising this, in 1982 Richard Feynman suggested using quantum components for such calculations [1]. It wasn't until the 1990's than a quantum algorithm was proposed where the computational resources increased only polynomially in the problem size [2], and experimental implementations are even more recent, e.g. a photonic quantum computer was used in 2010 to obtain the energies—at up to 47 bits of precision—of the hydrogen molecule, H_2 [3].

Here we examine the state of play in photonic quantum simulation, highlighting the difference between wave-mechanics simulations, which can be done with single photons or classical light, and quantum-mechanics simulations, which require multiple photons. Along the way we look at phenomena and problems from biology, chemistry, computer science, and physics, including zitterbewegung, enhanced quantum transport, quantum chemistry, and topological phases. We discuss the latest advances in photon technology, notably sources [4] detectors, and nonlinear interactions, and the implications for large-scale implementations in the near to medium term, e.g. in the Boson Sampling problem [5,6].

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Ramsey-comb spectroscopy: high power and accuracy combined

Kjeld Eikema

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Frequency comb lasers have become a vital tool for precision spectroscopy, leading to highly accurate measurements from infrared to extreme ultraviolet wavelengths. Conversion to short wavelengths through harmonic generation or excitation of multi-photon transitions requires higher powers than comb oscillators typically produce. We solved this issue by amplification (to the mJ level) of just two comb pulses at different delays. At each pulse delay a Ramsey signal is recorded with the two amplified comb laser pulses. By combining these measurements, a comb of Ramsey signals is obtained that enables to recover the original frequency comb laser accuracy and resolution. In an initial experiment we demonstrated kHz-level accuracy on two-photon transitions in Rb and Cs atoms using this Ramsey-comb technique. We are now extending the method to measure the ionization energy of the H2 molecule and the He+ ion for a stringent test of QED and the proton-size puzzle.

Ultra-precise atomic timekeeping with the optical lattice clock

Andrew Ludlow

National Institute of Standards and Technology, Boulder, Colorado, USA

Optical clocks are atomic timekeepers promising new capability in the measurement of time and frequency. With applications ranging from the exploration of fundamental laws of physics to advanced synchronization and relativistic geodesy, the ability to measure time at one part in 10^{18}offers exciting prospects. One type of optical clock, the optical lattice clock, has seen rapid progress since its birth one decade ago and today several key advances are being explored worldwide. These will be broadly discussed, with focus on the ytterbium optical lattice clock developed at NIST. Our recent efforts to overcome deleterious measurement effects in the lattice clock have led to clock stability near the standard quantum limit, realizing a timing precision of 1.6 parts in 10^{18}. Large atomic ensembles trapped in the magic wavelength optical lattice have the potential to be even better, and I will discuss steps to higher performance still. Another challenging problem which has faced the optical lattice clock is characterizing and controlling large perturbative effects, such as Stark shifts of the narrowband clock transition induced from thermal blackbody radiation bathing the lattice trapped atoms. I will describe our recent efforts to create a highly-uniform and accurately-measured radiation environment surrounding the ultracold atom sample. By so doing, we constrain the room temperature blackbody Stark shift below the mHz level, an important step towards achieving clock uncertainty approaching 1×10^{-18}.

Optical clocks based on strongly forbidden electronic and nuclear transitions in trapped ions

Ekkehard Peik

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Laser-cooled and trapped ions permit the study of strongly forbidden transitions with extremely small natural linewidths and long coherence times that find applications as references in highly precise optical clocks. The frequency of the electric octupole transition $S_{1/2}$ - $F_{7/2}$ at 467 nm in $^{171}Yb^{+}$ with a natural linewidth in the nHz range is remarkably insensitive against external electric and magnetic fields [1]. The light shift induced by the higher laser intensity that is needed to drive this weak transition was regarded as problematic for a clock. We have shown that an optimized “Hyper-Ramsey” interrogation sequence can eliminate the shift [2] and reduce the associated uncertainty so that it is a minor contribution to the total systematic uncertainty, which we presently evaluate as 4E-18. An even better isolation from external perturbations can be expected for the nuclear transition in $^{229}Th^{3+}$ at about 160 nm with an expected linewidth in the mHz range. In order to excite the so far only indirectly observed transition using electronic bridge processes, we investigate the dense electronic level structure of Th^{+} [3,4] and the hyperfine structure of $^{229}Th^{+}$.

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An Aharonov-Bohm interferometer for determining Bloch band topology

Ulrich Schneider

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In addition to the familiar dispersion relation, electronic Bloch bands are characterized by topological properties that are controlled by the distribution of Berry curvature and are responsible for various intrinsic Hall effects and lead to e.g. topological insulators. Using ultracold bosonic atoms, we studied the local topological structure of individual Dirac points within a graphene-type optical honeycomb lattice. By combining Ramsey interferometry with Bloch oscillations we measured geometric Berry phases for various closed loops in quasi-momentum space. In direct analogy to the Aharonov-Bohm effect, we observed a Berry phase of Pi whenever the trajectory of the particles encloses a single Dirac point, even if the associated Berry curvature vanishes everywhere along the chosen path. By unbalancing the lattice, we moved and subsequently merged the Dirac points within the Brillouin zone and observed the resulting change in local topology. Our approach can be applied to arbitrary lattices and provides complete topological maps of the band structure. This ability forms not only an important step towards controlling 2D Dirac particles, the controlled exploitation of the geometry of Hilbert space furthermore forms the basis for geometric or holonomic quantum computing.

SU(N) fermions: multicolor physics and orbital magnetism

Leonardo Fallani

LENS & Department of Physics and Astronomy, University of Florence, Florence, Italy

I will report on recent experiments performed at LENS with ultracold ^{173}Yb Fermi gases. These two-electron atoms are characterized by a large nuclear spin and highly-symmetric interactions, which result in the possibility of performing quantum simulations of multi-component fermionic systems with intrinsic and tunable SU(N) interaction symmetry. By controlling the number of spin components N, we have studied how static and dynamic properties of strongly-correlated 1D liquids of ^{173}Yb fermions change with N, evidencing for the first time intriguing effects caused by the interplay between interactions, low-dimensionality and quantum statistics [1].

In addition to their nuclear spin, two-electron fermions offer experimental access to supplementary degrees of freedom, in particular to long-lived electronically-excited states. By coherent control of the atomic state on the ultranarrow $^1S_0$–$^3P_0$ clock transition, we have recently obtained the first demonstration of fast, coherent spin-exchange oscillations between two ^{173}Yb atoms in different electronic orbitals [2].

These experiments disclose some of the new possibilities offered by two-electron atoms for quantum simulation, opening exciting directions connected e.g. to exotic quantum magnetism and to the investigation of many-body physics of systems with extended SU(N) symmetries.

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Dipolar physics with ultracold atomic magnets

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Given their strong magnetic moment and exotic electronic configuration, rare-earth atoms disclose a plethora of intriguing phenomena in ultracold quantum physics. Here, we report on the first degenerate Fermi gas of erbium atoms, based on direct cooling of identical fermions via dipolar collisions [1]. We study the impact of the anisotropic character of the interaction following the re-thermalization dynamics of a dipolar Fermi gas driven out of equilibrium [2]. At the many-body level, we prove the long-standing prediction of a deformed Fermi surface in dipolar gas [3]. Finally, scattering experiments show a spectacularly high number of Fano-Feshbach resonances. This complexity, arising from the anisotropy of the interactions, escapes to traditional scattering models and requires novel approaches based on statistical analysis. Using the powerful toolset provided by Random-Matrix theory, we elucidate the chaotic nature of the scattering [4].

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Quantum control strategies for imaging and spectroscopy

Paola Cappellaro

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Quantum control techniques have proven effective to extend the coherence of qubit sensors, thus allowing quantum-enhanced sensitivity at the nano-scale. The key challenge is to decouple the qubit sensors from undesired sources of noise, while preserving the interaction with the system or field that one wishes to measure. In addition, tailoring the sensor dynamics can help reveal temporal and spatial information about the target.

In this talk I will show how we can use coherent control of quantum sensors to reconstruct the arbitrary profile of time-varying fields, while correcting the effects of unwanted noise sources. These control techniques can be further used to reveal information about classical and quantum noise sources. For example, they can achieve high frequency resolution, thus allowing precise spectroscopy and imaging of the spatial configuration of a spin bath.

I will illustrate applications of these strategies in experimental implementations based on the Nitrogen-Vacancy center in diamond.

Detecting the Chirality of Molecules using Buffer-gas Cooling and Phase Sensitive Three-wave Mixing

John M. Doyle

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

We devise and demonstrate a definitive, large signal, mixture compatible spectroscopic method that determines the chirality of molecules in the gas phase. Our experiments employ a novel cooling method that allows the introduction of hot polyatomic molecules into a cryogenically cooled, low density inert gas. Using this buffer gas cooling method and microwave spectroscopy we detect polar molecules, determining the exact species, including chirality. The cooling of the molecules leads to a dramatic increase in the inverse of the internal molecular ro-vibrational partition function, greatly increasing spectroscopic sensitivity.

Chirality plays a fundamental role in the activity of many biological molecules and in broad classes of chemical reactions. Previous spectroscopic methods for determining enantiomeric excess include optical circular birefringence (CB), circular dichroism (CD), and Raman optical activity (ROA). All of those chiral analysis methods yield zero signal in the electric-dipole approximation[1]. In contrast, the electric-dipole signal from sum-frequency generation (SFG) can be non-zero in a bulk chiral environment and SFG in the infrared and visible has been observed (in solution) in previous experiments[2,3]. Doubly resonant SFG in both the infrared and microwave regime has been proposed but not observed[4,5]. Here, we demonstrate enantiomer- sensitive spectroscopy by combining a resonant microwave field with either a strong adiabatically switched orthogonal non-resonant (DC) electric field[6] or a resonant microwave field[7]. Three-wave mixing provides a direct phase sensitive (180 degree opposite) enantiomeric signal. An alternative cooling method, supersonic beam expansion, can also provide high molecular internal state phase space densities. We demonstrate simultaneous strong chiral signals in a binary mixture using supersonic beams [8]. In this talk I will briefly describe buffer-gas cooling and the road to this discovery, followed by a description of the experiments, the data and conclusions.

References

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The uniform 2D Bose gas, in and out of equilibrium

Jean Dalibard

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Most experimental studies with quantum gases are performed with atoms confined in a harmonic potential. This is well suited for the investigation of some aspects of equilibrium physics, thanks to the local density approximation that relates local properties of the trapped fluid with those of a uniform system. However the non-homogenous density profile of trapped gases prevents one from addressing the part of equilibrium physics related to long-range correlations. This restriction is particularly problematic for low dimensional systems, for which a good understanding of the fluid requires the investigation of the quasi-long range order that can appear at non-zero temperature.

In this talk I will first report on our realization of a uniform quasi-two-dimensional Bose gas confined in a box-like potential [1]. I will then describe experiments addressing the emergence of coherence in the gas when it is cooled across the superfluid transition [1,2]. I will present signatures of topological defects (vortices) that are nucleated in the system in the course of cooling. I will show that the production rate of these defects is directly linked to the cooling rate, and compare our findings with predictions for the Kibble-Zurek mechanism.

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Geometric Hall Effect in a Spinor Bose-Einstein Condensate

Yong-il Shin

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When a spin-carrying particle slowly moves in a spatially varying magnetic field and its spin adiabatically follows the field direction, the particle acquires a quantum-mechanical phase known as the Berry phase. This phase originates from the geometrical properties of the parameter space of the system can generate geometric forces which act like magnetic and electric forces on the spin-carrying particle. Emergent electromagnetism of this spin origin can lead to novel spin transport phenomena and recently have been studied in many areas of physics, e.g. to understand the anomalous Hall effect in magnetic materials and for spintronics applications. In this talk, I will introduce spinor Bose-Einstein condensates of neutral atoms with Skrymion spin textures and present our experimental observation of a geometric Hall effect in the neutral atomic superfluid system. When the condensate was driven in one direction to oscillate with respect to the spin texture, we observed the development of its transverse motion perpendicular to the driving direction and the effective magnetic field direction, demonstrating the existence of an effective Lorentz force in the system. Under a resonant drive, the center of mass of the condensate showed a circular motion whose direction is determined by the chirality of the spin texture. Quantized vortices were nucleated in the circulating condensate due to the anharmonicity of the trapping potential. The geometric Hall effect in our system was characterized with the vortex nucleation rate.

Bose Gases Invited Speaker Friday: 8:30am - 10:15am

Superstripes in spin orbit coupled Bose-Einstein condensed gases

Sandro Stringari

Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy

In this talk I will present recent theoretical advances in the study of the stripe phase of BEC gases. These include both equilibrium and dynamical properties of these novel configurations characterized by the spontaneous breaking of gauge and translational invariance symmetry. Proposals to improve the visibility of fringes in currently available experimental conditions will be explicitly discussed.

Quantum Simulation of Dynamical Gauge Fields with Cold Atoms

Peter Zoller

Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria

Abelian and non-Abelian gauge theories play a central role in physics. In condensed matter physics lattice gauge theories arise in the context of quantum spin liquids, and in high energy physics quantum chromodynamics is a non-Abelian SU(3) gauge theory describing the strong interactions between quarks and gluons. In this talk we show that cold bosonic and fermionic atoms in optical lattices, and strings of cold ions provide a toolbox for quantum simulation of Abelian and non-Abelian lattice gauge theories, and we discuss various physical phenomena, which could be observed in such experiments [1-4]. Our discussion will focus in particular on the paradigmatic example of quantum spin ice in 2D, and its realization with Rydberg atoms [5]. We conclude with a general outlook on quantum simulation, touching various aspects of equilibrium and non-equilibrium dynamics, and phases and phase transitions in setups of cold atoms in optical lattices.

References

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Sympathetic cooling of molecules with laser-cooled atoms

Eric R. Hudson

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Cooling molecules through collisions with laser-cooled atoms is an attractive route to ultracold, ground state molecules [1]. The technique is simple, applicable to a wide class of molecules, and does not require molecule specific laser systems. Particularly suited to this technique are charged molecules, which can be trapped indefinitely, even at room temperature, and undergo strong, short-ranged collisions with ultracold atoms.

I will focus on recent efforts to use the combination of a magneto-optical trap (MOT) and an ion trap, dubbed the MOTion trap, to produce cold, ground state diatomic charged molecules. The low-energy internal structure of these diatomic molecules, e.g. the electric dipole moment and vibrational, rotational, and Ω-doublet levels, presents a host of opportunities for advances in quantum simulation, precision measurement, cold chemistry, and quantum information. Recent proof-of-principle experiments have demonstrated that the MOTion trap is efficient at cooling the vibrational motion of molecular ions [2].

References

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Direct photonic coupling of a semiconductor quantum dot and a trapped ion

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Coupling individual quantum systems controllably lies at the heart of building scalable quantum networks. However, interfacing fundamentally dissimilar quantum systems, such as atomic and solid state quantum emitters, poses particular challenges in establishing optimal interaction protocols with sufficiently strong coupling rates. Here, we report the first direct photonic coupling between a semiconductor quantum dot and a trapped atomic ion. We demonstrate that single photons generated by a semiconductor quantum dot controllably change the internal state of a Yb^+ ion through a fiber-optic link over 50 meters. We ameliorate the effect of the sixty-fold mismatch of the radiative linewidths with coherent photon generation in the quantum dot and a high-finesse cavity coupling the photon to the single ion. We present the transfer of information by classical correlations between the σ_z-projection of the quantum-dot spin and the internal state of the ion. This provides a promising step towards quantum state-transfer in a hybrid photonic network.

Breaking the mirror symmetry of spontaneous emission via spin-orbit interaction of light

Arno Rauschenbeutel

Vienna Center for Quantum Science and Technology, TU Wien - Atominstitut, Vienna, Austria

Light is often described as a fully transverse-polarized wave, i.e., with an electric field vector that is orthogonal to the direction of propagation. However, this is only valid in the framework of the paraxial approximation. Yet, in many physically relevant situations, like in strongly focused laser beams, plasmonic structures, nanophotonic waveguides or optical microresonators, light is transversally confined in the strongly non-paraxial regime and exhibits strong intensity gradients at the wavelength scale. According to Maxwell's equations, this leads to a significant polarization component that points in the direction of propagation of the light. In contrast to paraxial light fields, the corresponding photon spin is position-dependent - an effect referred to as spin-orbit interaction of light. Remarkably, the photon spin can even be perpendicular to the propagation direction. I will discuss experimental situations in which this extreme condition occurs and will show that the interaction of quantum emitters with such light fields leads to new and surprising effects. In particular, the intrinsic mirror symmetry of the spontaneous emission of light by atoms into silica nanophotonic waveguides or into whispering-gallery-mode microresonators is broken. This allowed us to realize a directional nanophotonic atom-waveguide interface and enabled the control and non-linear manipulation of single fiber-guided photons with a single resonator-enhanced atom. The additional control over light-matter interaction provided by spin-orbit interaction of light is thus highly interesting both from a fundamental point of view and for the implementation of next-generation communication and information processing devices.

Hybrid Quantum Systems Invited Speaker Friday: 2:00pm - 3:45pm

Two-atom quantum interference in tunnel-coupled optical tweezers

Cindy Regal

JILA - University of Colorado and NIST, and Department of Physics, University of Colorado, Boulder, Colorado 80302, USA

Motional control of neutral atoms has a rich history and increasingly interest has turned to single-atom control. I will present work in which we begin by laser cooling single bosonic atoms to near their vibrational ground state in optical tweezer traps. Our recent work has explored the interference of two of these independently-prepared atoms. We observe a massive-particle analog of the Hong-Ou-Mandel (HOM) effect when we arrange for atom tunneling to play the role of a balanced photon beamsplitter. The HOM signature is used to probe the effect of atomic indistinguishability on the two-boson dynamics for various initial conditions. I will discuss the implication of these experiments for the assembly and control of a variety of quantum systems.

Phonon counting experiments in cavity-optomechanics

Oskar Painter

Institute for Quantum Information and Matter and Thomas J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology, Pasadena CA 91125 USA

Technical advances in the fabrication of micro- and nano-structures has recently led to, among other things, the laser cooling of mechanical resonators down to their ground-state of mechanical motion [1,2]. Current experiments seek to utilize “cold” mechanical transducers for a variety of applications, ranging from precision force measurements to noise-free and efficient quantum translation of microwave and optical signals [3,4]. In this talk I will discuss our efforts at Caltech to employ phonon counting techniques to measure, prepare, and entangle the mechanical state of nanoscale optomechanical resonators.

References

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Creating entanglement in an ensemble of 40 atoms using quantum feedback and quantum Zeno dynamics in a fiber cavity

Jakob Reichel

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Multiparticle entanglement enables quantum simulations, quantum computing and quantum-enhanced metrology. Yet, there are few methods to produce and measure such entanglement while maintaining single-qubit resolution as the number of qubits is scaled up. Using atom chips and fiber-optical cavities, we have developed different strategies, one based on elementary quantum feedback and one on quantum Zeno dynamics (QZD), to create multiparticle entangled states. We measure the Husimi Q-function of such states and reconstruct the symmetric part of their density matrix. This allow us to demonstrate the creation of W states with atom numbers up to 41. We are currently working to extend quantum Zeno dynamics to other classes of entangled states. Our methods are in principle independent of atom number and may be suitable for the implementation in other physical systems such as circuit quantum electrodynamics.

Detection of entanglement of non-gaussian atomic states and upscaling of atomic squeezing to large atom numbers

Markus K. Oberthaler

Kirchhoff Institut für Physik, Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany

Spin squeezed states in atomic systems have already been generated and detected in various different physical systems employing different methods. We report on the generation of spin squeezed states building on the quantum dynamics close to an unstable fixed point of the underlying classical dynamics. This new method allows the generation of 6dB squeezed states on short time scale. Since the squeezed states can be described as slightly distorted gaussian states the observation of variances is sufficient to verify the presence of entanglement.

Our new way of squeezing generation also allows the exploration of oversqueezing states i.e. transient states towards the generation of cat states. We will report on our results preparing and characterizing these transient non-gaussian states. They reveal variances which are larger than the classical shot noise limit thus suppression of fluctuations cannot be employed as an entanglement witness. We therefore developed a novel method for detecting the presence of entanglement by extracting from the experimentally detected distribution functions a bound of the Fisher information present in the system. With that we confirm that the entanglement is still present although the states are not spin squeezed. Furthermore interferometry beyond classical limits with these states is demonstrated which can be achieved by maximum likelihood estimation of the interferometric phase.

We will also present a general approach which allows the upscaling of squeezed states to large atom numbers by employing the concept – divide and conquer. We explicitly demonstrate 5dB squeezing for more than 13000 particles. We use this resource and combined this with swapping the squeezing to magnetically sensitive states for demonstration of quantum enhanced magnetometry with high spatial resolution.

Simulating quantum many-body dynamics with trapped atomic ions

Philip Richerme

Joint Quantum Institute, University of Maryland Department of Physics and National Institute of Standards and Technology, College Park, Maryland 20742 USA

Trapped atomic ions have recently been used to study the many-body dynamics of far-from-equilibrium quantum systems. Effective magnetic spins are encoded within long-coherence-time electronic states of the ions, which are measured with nearly perfect efficiency. Tunable, long-range interactions are generated across the entire chain using state-dependent optical dipole forces and benchmarked using a coherent imaging spectroscopic technique. To study the dynamics of this effective many-body system, we induce a global quench by suddenly switching on the spin-spin couplings and allowing the system to coherently evolve. For several different interaction ranges and spin models, we determine the spatial and time-dependent quantum correlations, measure their propagation velocity, and extract the "light-cone" boundary outside of which correlations are exponentially suppressed. This system is an ideal testbed for studying a wide range of quantum many-body dynamics that are intractable to any other known approach.

Hot Topics II Invited Speaker Friday: 4:00pm - 6:05pm

Dirac Monopoles in a Synthetic Magnetic Field

David Hall

Amherst College, Amherst, Massachusetts 01002, USA

Dirac's groundbreaking 1931 theory of magnetic monopoles made it possible to consider these elementary particles theoretically within the constraints of both classical electrodynamics and quantum mechanics. Despite years of searching, no magnetic monopole has been convincingly identified. However, analogues of the magnetic monopole, existing as point sources of a synthetic magnetic field, have now been created experimentally in the context of a spinor Bose-Einstein condensate. These are the first quantum-mechanical Dirac monopoles observed in any system. The response of the condensate to the monopoles reveals their characteristic features, as first envisioned by Dirac.

Very Attractive Photons

Vladan Vuletic

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An extremely nonlinear optical medium can be generated by coherently mapping photons onto strongly interacting Rydberg atoms in a dense atomic ensemble. In this medium, slowly traveling photons exhibit strong mutual attraction, so strong that two photons can form a two-body bound state. This state can be directly observed in the correlation function of the outgoing photons. I will also report about progress towards observing a three-photon bound state, and towards generating crystals of photons.

POSTER ABSTRACTS

The *p*-orbital Bose-Einstein condensation of two-species mixture in a bipartite square optical lattice

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In recent years, the unconventional Bose-Einstein condensation (BEC) in the *p*-orbital band of an optical lattice, has been under active studies both theoretically and experimentally [1-4]. In this presentation, we investigate the *p*-orbital BEC of two-species mixture in a bipartite optical lattice by solving Gross-Pitaevskii equation numerically. We have developed a reliable imaginary-time propagation method applicable to a truncated basis where the ground state is excluded, to locate the lowest-energy states in the *p*-orbital band. We find that the *p*-orbital BEC states depend crucially on the ratio of $g_{\mathrm{AB}}/g_{\mathrm{AA}}$, where $g_{\mathrm{AB}}>0$ is the inter-species interaction and $g_{\mathrm{AA}}=g_{\mathrm{BB}}>0$ are the intra-species interactions. When $g_{\mathrm{AB}}/g_{\mathrm{AA}}<1$, each species is characterized independently by one of the two degenerate, time-reversal-symmetry-broken and staggered orbital-current orders, $p_x \pm ip_y$. Conversely, when $g_{\mathrm{AB}}/g_{\mathrm{AA}}>1$, the two species are characterized respectively by the two mutually orthogonal and time-reversal-symmetry-preserved orders, p_x+p_y and p_x-p_y, or vice versa.

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Dynamics of ultracold atoms in amplitude-modulated parabolic lattices

Tomotake Yamakoshi[1], Shun Ohgoda[1], Shinichi Watanabe[1], Alexander Itin[2]

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2. Space Research Institute, Moscow

Ultracold atoms in amplitude modulated optical lattices is a promising tool for generation of matter wavepackets for interferometry [1], and for fulfilling quantum simulations of complicated solid-state phenomena [2]. Here we extend a semiclassical theory developed by one of us (A.I.) for the Hamburg experiment with ultracold fermions [2]. We firstly consider a particle in a combined optical lattice and parabolic trap potential in 1-dimension, and predict the form of the wavepacket in an excited band of the lattice after an amplitude modulation pulse. In the bosonic system [1], it allows us to achieve more efficient population transfer. We also apply it to the system of noninteracting fermions [2] and analyze the detailed structure of the wavepacket. This allows, in particular, to predict subsequent dynamics of the system on longer times.

References

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Novel quantum phenomena of atomic quantum gas in a shaken optical lattice

Li-Chung Ha[1], Logan W. Clark[1], Karina Jiménez-García[1], Colin V. Parker[1], Cheng Chin[1, 2]

1. The James Franck Institute and Department of Physics, University of Chicago
2. Enrico Fermi Institute, University of Chicago

Ultracold atoms in optical lattices have proven to be clean, controllable systems for exploring a variety of strongly correlated many-body phenomena. We have developed the capability to hybridize targeted Bloch bands by resonantly shaking the optical lattice potential [1]. When the shaking amplitude reaches a threshold value, a Bose condensate can acquire an asymmetric dispersion relation with a minimum at a finite quasi-momentum (similar to roton dispersion in He-4). To probe the dispersion, we employ a digital micromirror device to imprint an optical excitation with controllable wavelength and energy. From time of flight and in situ images, we plan to map out the full dispersion relation and identify the minimum. Finally, we will also attempt to drag an optical barrier through the cloud and directly measure the critical velocity. Our study would demonstrate the power of shaken optical lattices to explore new classes of quantum phenomena in condensed matter materials with exotic band structure.

References

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MONDAY

MONDAY

Direct observation of chiral order in double layer superfluid

Arne Ewerbeck, Robert Büchner, Thorge Kock, Matthias Ölschläger, Andreas Hemmerich

1. Institute of Laser Physics, Hamburg

A double layer chiral superfluid is formed in the second band of a bipartite optical square lattice. In an ballistic expansion process the two layers are superimposed. The Bragg maxima thus observed exhibit interference patterns, which provide direct information on the formation of chiral order and the presence and character of low energy excitations. Furthemore we report on the progress of setting up a new bose-fermi mixture experiment.

Effective preparation of atomic condensates in excited bands of an optical lattice by standing-wave pulses

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We present a method for the effective preparation of a Bose-Einstein condensate (BEC) into the excited bands of an optical lattice via a standing-wave pulse sequence. With our method, the BEC can be prepared in either a single Bloch state in an excited band or a coherent superposition of states in different bands. Our scheme is experimentally demonstrated by preparing a BEC into the *d* band and the superposition of *s*- and *d*-band states of a one-dimensional optical lattice, within a few tens of microseconds. We also measure the decay of the BEC in the *d*-band state and carry an analytical calculation for the collisional decay of atoms in the excited-band states. Our theoretical and experimental results agree well [1]. Furthermore, the diffraction phases of different orders are studied for ultracold atomic gases scattered by a standing-wave pulse [2].

References

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Tunneling-Induced Restoration of the Degeneracy and the Time-Reversal Symmetry Breaking in Optical Lattices

Tomasz Sowinski[1, 2, 4], Mateusz Lacki[3], Omjyoti Dutta[3, 4], Joanna Pietraszewicz[1], Piotr Sierant[3], Mariusz Gajda[1, 2], Jakub Zakrzewski[3], Maciej Lewenstein[4]

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4. *ICFO - The Institute of Photonic Sciences, Barcelona, Spain*

The ground-state properties of bosons loaded into the p-band of a one dimensional optical lattice is studied. It is shown that the phase diagram of the system is substantially affected by the anharmonicity of the lattice potential. In particular, for a certain range of tunneling strength, the full many-body ground state of the system becomes degenerate. In this region, an additional symmetry of the system, namely the parity of the occupation number of the chosen orbital, is spontaneously broken. The state with nonvanishing staggered angular momentum, which breaks the time-reversal symmetry, becomes the true ground state of the system.

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Using Tilted, Modulated Lattices to Implement Novel Hamiltonians

William Cody Burton[1], Colin Kennedy[1], Woo Chang Chung[1], Georgios Siviloglou[1, 2], Wolfgang Ketterle[1]

1. *Massachusetts Institute of Technology*
2. *University of Amsterdam*

We first present our implementation of the Harper Hamiltonian in neutral atoms using the general tools of a tilted lattice with laser-assisted tunneling in one direction [1]. We have demonstrated control over the amplitude of the laser-assisted tunneling, but have not yet achieved the ground state and so have not seen the phase structure associated with Hofstadter's butterfly. Our scheme can be extended to realize spin-orbit coupling and the quantum spin Hall effect [2]. We report on further studies of a simpler system: a tilted lattice with amplitude modulation. We demonstrate restoration of coherence and a lifetime of over a thousand cycles. We explore the effect of the dimensionality of the lattice, interaction strength, modulation strength, and tilt depth on dephasing due to the dynamic instability and micromotion. We present a region of stability, which provides a starting point for the many proposals for quantum simulation using tilted lattices.

References

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MONDAY

Bosons in optical lattices: beyond the Bose-Hubbard Hamiltonian

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The standard approximation to describe a set of bosonic neutral atoms loaded in optical lattices is the discrete Bose-Hubbard (BH) Hamiltonian. In fact, the first examples of those systems were hailed as experimental realizations of that approximate model. However, we found that the set of simplifications involved in the derivation of the BH model make it unsuitable to describe many real optical lattices. We present here zero-temperature phase diagrams for the complete (non discrete) continuous Hamiltonians that model those arrangements. That allowed us to check the validity of the Bose-Hubbard approximation for quasi-one dimensional systems (''tubes'') and asymmetric ($V_x=V_y \neq V_z$) ones. In particular, we concluded that for very thin ''tubes'' and asymmetric three-dimensional lattices, the BH prescription differs significantly from our results. Our data can serve as a reference to future experiments in the field, since we explore parts of the phase diagram that are not well modeled by the BH Hamiltonian.

References

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Ultracold Atoms in a Tunable Optical Kagome Lattice

Thomas Barter[1], Claire Thomas[1], Dan Stamper-Kurn[1]

1. University of California, Berkeley

We realize the Bose-Hubbard model on a triangular lattice with a tunable basis by loading ultracold ^{87}Rb into commensurate 532 nm and 1064 nm triangular lattices. Each lattice is actively stabilized on a common path, preserving the phase relationship. We detail recent improvements to this scheme that allow dynamic in-loop control of the lattice geometry and shifting of the lattice over many periods.

This control over the lattices allows us to realize the Kagome lattice, and explore methods to populate its dispersionless third band. We investigate phase modulation of the lattice to invert the band structure, and we explore dynamic shifting of the two lattices to populate higher bands. We also explore next-nearest neighbor tunneling in an inverted triangular lattice.

Bose-Einstein condensation of ultra-cold atoms in a frustrated, triangular optical lattice

Ludwig Mathey

1. Institute for Laser Physics, University of Hamburg

We present a study of Bose-Einstein condensation of ultracold atoms in a triangular optical lattice. As demonstrated in Ref. [1], the tunneling energy between neighboring sites in an optical lattice can be controlled via lattice shaking to be negative or complex-valued. For negative, real-valued tunneling, the system condenses at one of two non-zero quasimomenta, corresponding to classical frustration. Tuning the tunneling energy to complex values corresponds to an artificial gauge field. We demonstrate that the nature of the condensation transition is modified due an additional symmetry that is broken, a chiral symmetry. Furthermore, the artificial gauge field acts as the conjugate external field to the chiral order parameter, which allows to map out magnetization curves of the chirality as a function of the article gauge field. We give analytical results on the nature of the phase transition, based on an expansion of the free energy in the interaction strength and on a renormalization group approach, and numerical ones, based on Monte Carlo simulations.

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Bose Gases Mo-011

Magnetometric Probe of an Ultra-cold Spinor Gas

James Higbie[1]

1. Bucknell University

Ultracold atoms have been shown to permit highly sensitive micron-scale magnetometric measure- ments. Here, we propose that a cold-atom magnetometer offers a new and sensitive method of probing the magnetic state of a second nearby ultracold spinor gas. We analyze the measurement back-action from such a magnetometric probe for polar-state and ferromagnetic-state probes, and compare to a Heisenberg-limited measurement.

MONDAY

Quantum dynamics of spin waves using ultracold atoms

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Ultracold-atom experiments are suitable to study out-of-equilibrium dynamics of quantum many-body systems. Here we will report the quantum dynamics of deterministically created mobile spin impurities as well as spin spirals in the bosonic atoms in optical lattices. First, we investigate the dynamics of a single-spin impurity in a one-dimensional spin chain [1]. Coherent propagation of the single spin, which generates and transfers entanglement, is observed. Second, we examine bound states of two magnons in a Heisenberg chain by tracking their dynamics. Such bound states were theoretically pointed out by H. Bethe in 1931, and our novel microscopic study of quantum magnets can directly confirm their existence [2]. Third, we study the decay of highly excited states of spin spirals and discuss their diffusive behavior.

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Quantum control of a many-body system in a spin-1 Bose-Einstein condensate

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Spin-1 condensates provide a useful platform for investigations of quantum control. By tuning the relative strength of the Zeeman and spin interaction energies, the spin dynamics behave similarly to a quantum pendulum. In the inverted pendulum case, the condensate is initialized to an unstable (hyperbolic) fixed point, and we demonstrate the dynamic stabilization by periodic manipulation the phase of the quantum states. In the case of a simple quantum pendulum, the condensate is initialized to an (elliptical) energy contour and we demonstrate the parametric excitation by modulating the relative strength of the Zeeman and spin interaction energies.

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Investigation of Kibble-Zurek quench dynamics in a spin-1 ferromagnetic BEC

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We study the temporal evolution of spin populations in small spin-1 Rb-87 condensates following a slow quench. A ferromagnetic spin-1 BEC exhibits a second-order gapless (quantum) phase transition due to a competition between the magnetic and collisional spin interaction energies. The dynamics of slow quenches through the critical point are predicted to exhibit universal power-law scaling as a function of quench speed. In spatially extended condensates, these excitations are revealed as spatial spin domains. In small condensates, the excitations are manifest in the temporal evolution of the spin populations illustrating a Kibble-Zurek type scaling [1]. We will present the results of our investigation and compare them to full quantum simulations of the system.

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Metastable Spin Texture of Spin-1 Bose-Einstein Condensates in a Ring Trap

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Various properties of superfluidity, such as persistent current, and hysteresis, were investigated by recent experiments of Bose-Einstein condensates trapped in a ring geometry[1,2,3]. Motivated by these experiments, we investigate properties of spin-1 Bose-Einstein Condensates(BECs) in a quasi-one-dimensional rotating ring by solving the Gross-Pitaevskii(GP) and the Bogoliubov equation. We find analytical solutions of metastable energy branches, which exhibit spin textures. These solutions correspond to one-dimensional version of the polar-core vortex. We also find that the number of type-I and type-II Nambu-Goldstone(NG) modes changes at a certain rotation velocity(type-I-type-II transition[4]). The physical origin of the change of the number of the NG modes will be discussed.

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MONDAY

Dipolar ultracold atoms in a double well trap

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We have investigated the physics of spin exchange processes with a chromium dipolar BEC loaded in a double well trap. We can prepare one cloud in one well in the lowest energy Zeeman state (ms=-3), and the other one in the other well in the highest energy Zeeman state (ms=+3).

We show that dipolar spin exchange processes between these two separated large ensembles of atoms are prohibited, in stark contrast with our previous results obtained in 3D optical lattices [1]. We interpret our results due to the classical behaviour of a large ensemble of spins.

When we merge the two wells, spin exchange dynamics due to contact interactions occur. Analysis of the dynamics provides the first measurement of one scattering length of ^{52}Cr, a_0. The value we find (-100 a_B) shows that the low B field ground state of the spinor ^{52}Cr BEC is polar [2,3].

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Bose Gases Mo-017

Quantum phases in an asymmetric double-well optical lattice

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We study the superfluid (SF) and Mott insulator phases of ultracold atoms trapped in a double-well optical lattice. The lattice has an asymmetric double-well geometry along the x axis and single wells along the other axes. We evaluate the tunneling and atom-atom interaction energies from exact band-structure calculations. We then show that a comparable tight binding (TB) model should include all tunneling terms between two neighboring double-wells, i.e, a total of six different hopping terms. In addition, there is tunneling $J_{\perp}$ along the other directions. We set up the appropriate Bose-Hubbard Hamiltonian, and a mean field calculation determines the SF and Mott phase boundaries as a function of lattice parameters and chemical potential μ. The boundary is largely characterized by an effective tunneling $t_{\rm eff}=t+J$ along the x axis. Moreover, for $t_{\rm eff}\ge 4J_{\perp}$, we always have a SF phase. In future, we will use the results of these simulations to construct effective lattice models where the atom-atom interaction is zero and the interactions are governed by a three-body potential. Such systems might lead to unique many-body ground states.

Experiments with BECs in a Painted Potential: Atom SQUID, Matter Wave Bessel Beams, and Matter Wave Circuits

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The Painted Potential is a time-averaged optical dipole potential which is able to create arbitrary and dynamic two dimensional potentials for Bose Einstein condensates (BECs). This poster reports three recent experiments using this technique. First, we have realized the dc atom SQUID geometry of a BEC in a toroidal trap with two Josephson junctions. We observe Josephson effects, measure the critical current of the junctions, and find dynamic behavior that is in good agreement with the simple Josephson equations for a tunnel junction with the ideal sinusoidal current-phase relation expected for the parameters of the experiment. Second, we have used free expansion of a rotating toroidal BEC to create matter wave Bessel beams, which are of interest because perfect Bessel beams (plane wave with amplitude profiles described by Bessel functions) propagate without diffraction. Third, we have realized the basic circuit elements necessary to create complex matter wave circuits. We launch BECs at arbitrary velocity along straight waveguides, propagate them around curved waveguides and stadium-shaped waveguide traps, and split them coherently at y-junctions that can also act as switches.

Bose Gases Mo-019

Observation of Solitonic Vortices in Bose-Einstein Condensates

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We observe solitonic vortices in an atomic Bose-Einstein condensate after free expansion. Clear signatures of the nature of such defects are the twisted planar density depletion around the vortex line, observed in absorption images, and the double dislocation in the interference pattern obtained through homodyne techniques. Both methods allow us to determine the sign of the quantized circulation. Experimental observations agree with numerical simulations. These solitonic vortices are likely the decay product of grey solitons spontaneously created after a rapid quench across the BEC transition in a cigar-shaped harmonic trap via the Kibble-Zurek mechanism and are shown to have a very long lifetime.

MONDAY

Ring Dark Solitons in Toroidal Bose-Einstein Condensates

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Ring dark solitons (RDSs) are examples of nonlinear quantum states that can be supported by a Bose-Einstein condensate (BEC). Unlike the well-known planar dark solitons, exact analytic expressions for RDSs are not known. We address this problem by presenting exact localised soliton-like solutions to the radial Gross-Pitaevskii equation. To date, RDSs have not been experimentally observed in cold atomic gases, either. To this end, we propose two protocols for their creation in experiments. In addition, we present results regarding the dynamics and stability of RDSs. Under certain trapping potentials, we show that the decay of RDSs into circular arrays of vortex-antivortex pairs can be reversible, but eventually the decay leads to a state with some properties of quantum turbulence.

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Bose Gases Mo-021

One dimensional atomic rings with barriers: a Luttinger liquid approach to precision measurement

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Recent experiments [1] have realized ring shaped traps for ultracold atoms which can be 'stirred' with a moving laser. Here, a similar 1D ring system is imagined and analyzed using the framework of Luttinger liquid theory. Using the duality in Luttinger theory, we simultaneously consider systems of superfluid atoms with a weak link and long-range repulsive atoms (or ions) with a weak barrier. We find that classical theory suggests high precision sensors can be constructed from these systems; we attempt to extend these results into the quantum regime.

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Finite-Temperature Effects in ring-shaped Bose-Einstein condensates

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A recent experiment performed at NIST [1], in which hysteretic behavior of a stirred, ring-shaped Bose-Einstein condensate (BEC) was demonstrated, has shown quantitative disagreement with zero-temperature mean-field theory. We have studied finite-temperature effects in this system by applying the Zaremba-Nikuni-Griffin (ZNG) theory to model the experiment. The ZNG theory describes the system as consisting of both a condensate and a non-condensate. It allows for time-dependent evolution of both parts and for them to interact and exchange particles. The evolution of the condensate is described by a dissapative generalized Gross-Pitaevskii equation while the non-condensate evolution is governed by a quantum Boltzmann equation. We show how the presence of a thermal cloud modifies the behavior of vortices produced during the stirring process compared to their behavior at zero temperature.

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Investigation of Critical correlations in an ultracold Bose gas by means of a temporal Talbot-Lau interferometery

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Phase transitions is a popular phenomena in nature, among them the transition from normal fluid to superfluid for helium is a famous one. Rubidium gas, while the temperature of it is reduced to the nano kelvin region, will alter from the normal gas to the quantum gas, the Bose-Einstein condensate, which is the phase of superfluidy. The phase transition takes at the critical point. Similar to the helium, the correlation length will grow to infinity as the critical point is approached, In this presentation we report that we develop a method, temporal Talbot-Lau (TL) interferometer, to measure this lamda transition point for rubidium gas at the temperature as low as 50 nano kelvin. This approach demonstrates the potential application of the Talbot–Lau interferometer to a wide range of critical phase transitions in ultra-cold atomic gases [1] and atomic interferometer in high sensitivity [2].

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Collective modes of a two-dimensional quantum gas

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The study of the excitation modes of a quantum gas is a way to characterize its dynamical properties. The low energy excitations of a quantum gas trapped in an harmonic potential are collective modes. They can be excited by inducing a sudden change in the trap parameters. Here, we present results of the study of two important collective modes of a two-dimensional bosonic quantum gas [1]: the monopole mode (or breathing mode), and the scissors mode. In particular, we show that the third, strongly confining dimension has a measurable effect on the breathing mode frequency, in agreement with our theoretical predictions and numerical simulations [2]. The scissors mode can be used to characterize the superfluid phase. We study its frequency and damping as a function of temperature across the transition to degeneracy.

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Measurement-based control of many-body systems

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Quantum control is an ambitious framework for steering dynamics from initial states to arbitrary desired final states. While immensely successful in low dimensions, it has been applied only to a limited extent to many-body systems such as atoms in optical lattices. Most generic quantum control schemes require either a controllable system Hamiltonian or a large set of measurement operators.

We have developed a new minimalistic control scheme based on a combination of fixed unitary evolution and repeated quantum non-demolition (QND) measurements [1].

As an initial step towards a realization we present our experimental results on the continuous, highly resolved QND probing of the quantum phase transition between a thermal cloud and a BEC. The continuous probing enables instantaneous feedback control of the system as well as very efficient single-shot detection of entire phase diagrams - a technique also applicable to the superfluid to Mott insulator transition in optical lattices [2].

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A novel experiment for coupling a Bose-Einstein condensate with two crossed cavity modes

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Over the last decade, combining cavity quantum electrodynamics and quantum gases allowed to explore the coupling of quantized light fields to coherent matter waves, leading e.g. to new optomechanical phenomena and the realization of quantum phase transitions. Triggered by the interest to study setups with more complex cavity geometries, we built a novel, highly flexible experimental system for coupling a Bose-Einstein condensate (BEC) with optical cavities, which allows to switch the cavity setups by means of an interchangeable science platform. The BEC is produced from a cloud of laser-cooled ^{87}Rb atoms which is first loaded into a hybrid trap, formed by a combined magnetic and optical potential. We use an optical setup involving focus-tunable lenses to optically transport the atomic cloud into the cavity setup, where it is cooled down to quantum degeneracy.

At first we aim to explore the coupling of a BEC with two crossed cavity modes. We report on our progress on the implementation of a science setup involving two cavities intersecting under an angle of 60°. The mirrors have been fabricated in order to spatially approach them, thus obtaining maximum single atom coupling rates of several MHz. This setup will allow us to study the coherent interaction of a BEC and the two cavity modes both in internal lambda-level transitions and in spatial self-organization processes in dynamical hexagonal lattices.

Heat Capacity of a Bose-Einstein condensate measured through Global variables

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We have developed a new technique which allows for the determination of the global heat capacity of Bose-Einstein condensates [1,2], across the phase transition. A pair of global conjugate variables is defined then we determine the system's total internal energy and its temperature derivative, the heat capacity. A rapidly changing C_V was observed in the vicinity of the critical temperature, in a ^{87}Rb BEC, very similar to the λ point in liquid ^{4}He.

The evolution of the measured C_V , near the critical temperature, suggests an interplay of the mean field interactions. The more interesting observed effects are: the T_c absolute value downshift; the C_V peak round off; and, the larger values of the normalized C_V for lower N in a relatively broad T range, below the critical temperature.

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Probing the excitation spectrum of a ring-shaped Bose-Einstein Condensate

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Bose-Einstein condensates confined in ring geometries provide us with a powerful tool to study bulk superfluidity in finite systems. Recently, the NIST experiment demonstrated the controlled introduction of quantized superfluid currents using a blue-detuned Gaussian beam as a potential barrier [1]. Here, we model an experiment where this barrier is used to selectively excite collective excitations in a ring-shaped condensate. We present full calculations of the collective excitation spectrum, and use time-dependent simulations of the Gross-Pitaevskii equation to model the proposed experimental protocol. We demonstrate that the appropriate stirring of the barrier can resonantly excite selective modes, which in turn depletes the condensate and excites atoms out of the trap, providing a clear experimental signature of the spectrum

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Dynamics of coupled mixtures in optical lattices

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Bosonic quantum-gas mixtures in optical lattices allow for a wide range of studies including disordered systems, dissipative phenomena, and out-of-equilibrium effects. We subject a bosonic rubidium gas to species-selective optical lattice potentials and drive coherently between two hyperfine ground states. We observe non-trivial coherent oscillations between the localized atoms and superfluid. Results of further experiments on the interplay between coupling strength and interactions in the mixture will be discussed.

Superfluid Atomtronic Circuits

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We have created a superfluid atom circuit using a toroidal Bose-Einstein Condensate. Just as a current in a superconducting circuit will flow forever, if a current is created in our superfluid circuit, the flow will not decay as long as the current is below a critical value. A repulsive optical barrier across one side of the torus creates a tunable weak link in the condensate circuit and can be used to control the current around the loop. By rotating the weak link, we have observed phase slips between well-defined persistent current states, which are analogous to transitions between flux states in an rf-superconducting quantum interference device (SQUID). Importantly, we have demonstrated that these transitions are hysteretic, a characteristic of many common electronic circuits like memory, digital noise filters, and, indeed, the rf-SQUID. More recently, we have realized a geometry similar to a dc-SQUID using two weak links. In this case, we can move these weak links relative to each other and observe resistive flow when the current exceeds the critical current. This observation of resistive flow is an important step to realizing the atomtronic analog of the dc-SQUID. Lastly, we have developed techniques of measuring the current flow around the ring which allows us to measure the current-phase relationship of our weak link.

Emergence of coherence in a 2D uniform Bose gas

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The emergence of coherence in a 2D Uniform Bose gas is fundamentally different from both the 3D and the 2D harmonic case. First, in this case, Bose Einstein condensation is precluded in the thermodynamics limit but it can be recovered in finite size system when the correlation length becomes of the order of the size of the system itself. Second, the 2D regime can then be reach even when the spacing of transverse ground and first excited state is not greater than the thermal energy $k_B T$. The 2D nature then rely on the so-called transverse condensation phenomenon that was previously mainly described for a 1D harmonically trapped gases [1-3].

We experimentally investigate the appearance of coherence in a Bose gas trapped by a 2D flat bottom potential and a transverse harmonic one. Here, the coherence is characterized in two ways, first by the bimodality of the density distribution in time of flight measurement, second by fringes pattern appearing when interfering two identical systems.We compute the phase diagrams of these coherence parameters versus the temperature T and the number of atoms N and enhance the importance of the transverse condensation phenomenon.

Finally, we show some dynamics features of the crossing of this superfluid transition by characterizing nucleation of single vortices by Kibble Zurek like mechanism.

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Three-body recombination of helium atoms from ultracold to thermal energies: classical trajectory vs. quantal calculations

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A general method to study classical scattering in *n*-dimensions is developed. Through classical trajectory calculations the three-body recombination rate is computed as a function of the collision energy for helium atoms, as an example. The energies treated range from the ultracold up to the thermal regime. The classical results for zero total angular momentum are compared with the quantum calculations for the $J^{\Pi} = 0^{+}$ symmetry, yielding a good agreement for E > 1 K. The classical threshold law is derived and numerically confirmed for the three-body recombination rate. Finally, a relationship is found between the quantum and classical three-body elastic cross section at high collision energies that resembles the well-known shadow scattering in two-body collisions.

Field dependent studies of inelastic scattering properties in an ultracold mixture of lithium and metastable ytterbium

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The ultracold mixture of excited state alkaline-earth-like and ground state alkali atoms is a novel system in which to study two-body and few-body physics. Unlike the ground state of ytterbium, the long lived metastable $^3P_2$ state is predicted to support broad magnetic Feshbach resonances with the ground state of lithium, offering a promising route towards the production of ultracold heteronuclear ground state dimers with both magnetic and electric dipole moments. We report on measurements of the field dependence of inelastic scattering properties in this mixture over a wide range of magnetic fields. We also present progress towards a three dimensional optical lattice for the Li-Yb mixture. A tunable optical lattice provides useful tools to control and study collisions in our system, can enhance molecule production efficiency, and can serve as a platform for quantum simulation and information science. Additional potential studies include the use of Yb as an impurity probe of strongly-interacting Li fermions.

Measurements of Na - Na^+ total collision rate

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The realization of a hybrid trap, which is an ion trap overlapped with a neutral species trap, has greatly increased experimental and theoretical interest in cold ion-neutral collisional studies. The hybrid trap used by our group consists of a sodium (Na) magneto optical trap (MOT) concentric with a Linear Paul Trap (LPT) containing sodium ions. We present preliminary measurements of the total collision rate (both charge exchange and elastic) between optically dark Na^+ and Na and compare it with theoretical (quantal *ab-initio*) calculations of the total collision rate constant. Furthermore, we investigate the rate constant's dependence on the neutral polarizability by varying the Na MOT's average excited state population, which profoundly changes the effective polarizability. In doing so, we will also present a (two-level) model-independent study of the MOT's excited state fraction.

Dynamics of gas phase Ne*-ND_3 Penning ionization at low temperatures

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We study Penning ionization of ammonia molecules with metastable neon atoms in the range of collision energies from 0.1 to 250 K in a merged beam experiment. The reaction leads to the formation of ND_3^+ and ND_2^+, the two reaction channels differing by the ND_3 orbital from which ionization occurs. We observe a constant branching ratio for these channels over the entire energy range studied here, which spans three orders of magnitude. We also measure the total ionization rate constant. At low energies the experimental results are well reproduced by multichannel quantum defect theory calculations that rely on the long-range interaction potential. At higher energies the importance of short-range potential details is increased, which changes the collision energy dependence of the observed rates.

Few Body Interactions and Collisions Mo-036

Few-body interactions in an ultacold Bose-Fermi mixture

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Ultracold mixture composed of different atomic spieces has become attractive today, which can expand our research range due to its more adjustable parameters. While at the same time, more experimental challenges should be solved. In this poster, we will introduce our experimental progress on the way to approach the ultracold degenerate Bose-Fermi mixture (rubidium87, pottasium40 and lithium6). Based on this experimental setup, we propose to study the two-body and three-body interactions in the ultracold mixture. As a preparation for the experiment, we will also introduce some theoretical predictions about few-body interaction in the ultracold quantum gas. For example, the width of the Feshbach resonance has a big effect on the binding energy of a molecule [1]; compared to a wide resonance, the interaction shows a surprising exotic behavior in a narrow resonance [2].

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Collisional Properties of Ultracold Radium Isotopes

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Ultracold atoms are in use for different experimental goals such as optical frequency standards, quantum degenerate gases, atom interferometry, fundamental symmetry studies and many other applications. In particular, ultracold radioactive isotopes have been in use for beta-decay studies, atomic parity violation and for searches of permanent Electric Dipole Moment (pEDM) studies. Group II alkaline earth radioactive element radium (Ra) has been proposed to be good candidate for pEDM experiment [1, 2] and also as an optical frequency standard [3]. Recently, optical dipole trapping of ultracold ^{226}Ra has been demonstrated [4]. In this context, we have calculated the elastic collisional properties and s-wave scattering lengths of the long lived bosonic and fermionic isotopes of Ra based on the available potentials and dispersion coefficients. We report preliminary results of our calculations.

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Very low power two-photon absorption in cold ^{87}Rb atoms using an optical nanofiber

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Here, we demonstrate the use of cold atoms and an optical nanofiber (ONF) to probe 2-photon absorption at a few nanowatts of powers. Apart from its spectroscopic importance, this study will be useful for all optical switching [1] and quantum logic gates at low powers. An ONF, having a subwavelength diameter, is characterized by a strong evanescent field around the waist region even when very low powers propagate through the fiber. When an ONF is integrated with a cold atom setup, this evanescent field is used to couple the cold atoms with the guided light in the ONF.

In our experiment, the ONF is fabricated by the heat-and-pull technique using hydrogen: oxygen flame [2]. Laser-cooled ^{87}Rb atoms are excited from $5S_{1/2} \rightarrow 5D_{5/2}$ via a 2-photon excitation process using $5P_{3/2}$ as an intermediate level. Using a few nanowatts of 780 nm ($5S_{1/2} \rightarrow 5P_{3/2}$) and 776 nm light ($5P_{3/2} \rightarrow 5D_{5/2}$) through the ONF, the atoms are excited to the $5D_{5/2}$ state and thereby spontaneously emit 5.2 μm ($5D_{5/2} \rightarrow 6P_{3/2}$) and 420 nm ($6P_{3/2} \rightarrow 5S_{1/2}$) photons which is coupled to the ONF itself. We detect the 420 nm fluorescence photons via the ONF and study the effects like ac Stark effect and power broadening in this process for such a system.

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A nanostructured tapered optical fiber for cold atom trapping

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Optical micro and nanofibres (MNFs) are invaluable tools for the study and manipulation of cold atoms [1]. Of particular interest is the trapping of around the MNF, for which a number of techniques have been proposed and demonstrated [2-4]. To-date, only the two-color trap [2-4] has been experimentally realized. In this configuration the forces due to the off-resonance fields of a far-detuned red and blue laser are used to create a potential to trap the atoms around the fiber. Here, we propose

a novel scheme for a tapered optical fiber-based atom trap, whereby a nanoscale slot aligned along the fiber axis is produced at its waist using focused ion beam (FIB) techniques. This change in the fiber geometry results in high evanescent field intensities both within the slot and at the external surfaces of the fiber, allowing multiple atom trapping sites to be realized through two-color trapping [5].

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MONDAY

Laser cooling with three-level cascade transitions: calculations for group I and II atoms and prospects for tests with calcium

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Motivated by finding alternative cooling techniques for alkaline-Earth atoms, we analyze two-color laser cooling with three-level transitions. For cascade transitions in which the upper level has longer lifetime than the intermediate one, and for cooling in “EIT regime”, using "strong" and "weak" lasers, we theoretically find that temperatures below the Doppler limits associated with each one of the individual transitions are expected [1]. Here we present estimations of temperatures as function of detunings and laser intensities for alkaline-Earth (Mg, Ca, Sr, Yb, Zn, Cd) and metal-alkaline atoms (Rb, Cs, Na), which can help guiding further experiments and stimulate additional theoretical work. We study the influence of coherences (affected by phase fluctuations between the lasers) on the final temperatures, and suggest a simpler method to estimate temperature limits in terms of dressed states decay rates. We will also present our progress towards experimental tests in a calcium MOT.

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Atomic Interactions with a Bichromatic Field: Stimulated Emission and Laser Cooling

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We report numerical results for interactions of a two level atom with the bichromatic field with the atom modelled to undergo stimulated emission only. Changes in the entropy, temperature and the atomic states present evidences laser cooling of atom in our system. The changes in the entropy of the field supports the argument for fields to be efficient reservoirs for the entropy lost by the atom. Efficiency of such cooling scheme is suggestive ideally to be Carnot efficiency limited.

Dynamics of Polychromatic Optical Forces for Deceleration of Atoms and Molecules

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MONDAY

To gain insight into the dynamics and limitations of coherent optical forces, we have performed numerical studies of the bichromatic force in a two-level system [1]. We discovered an improved explanation for the robustness of the force against imbalanced beam intensities. These studies also led us to develop a four-color polychromatic (4CF) variation, offering an increased velocity range and a decreased excited-state fraction. Experimental studies of the 4CF in helium are planned.

We have also numerically modeled a three-level system with a weakly coupled dark state. The bichromatic force remains effective, although it depends strongly on the power of a repumping laser. This is encouraging for applications to molecular systems, which we are exploring experimentally by utilizing the near-cycling B ↔ X transition in CaF. We are initially performing beam-deflection studies on a supersonic molecular beam, with longitudinal slowing to follow. Support for this work provided by NSF.

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Laser Cooling without Spontaneous Emission

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It is usually presumed that spontaneous emission is necessary to remove both the energy and entropy lost by an atomic vapor during laser cooling. While this is true for monochromatic light in both Doppler and Sisyphus molasses and also in a MOT, we have shown that a multifrequency optical field itself can do both [1]. Previous bichromatic force (BF) experiments have demonstrated strong forces over a large, finite velocity range resulting in atomic beam collimation and slowing [2,3]. Our BF experiment uses the 2^3S-3^3P transition in helium at λ=389 nm, and its short duration (180 ns) precludes multiple spontaneous emission events (3^3P lifetime is 106 ns). The resulting atomic velocity distributions are shifted by very many atomic recoils, verifying that the force derives from multiple, rapid, stimulated processes. Removing the need for spontaneous emission allows laser cooling without the usual requirement for cycling transitions.

Supported by ONR

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Localized Interactions between Laser-cooled Atoms and Optical Near-field

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Precise manipulation of laser-cooled atoms near surfaces is a powerful technique for the accurate detection of atoms-surface interactions [1, 2]. We have experimentally studied higher-order interactions between laser-cooled atoms and an optical near-field. We have prepared laser-cooled ^{85}Rb atoms in crossed far-off resonance traps and loaded them into an optical near-field region near a glass surface. We report on interactions between atoms and glass surfaces using precise controlled optical dipole force traps. Additionally, we have calculated numerically higher-order interactions of atoms and an optical near-field.

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Surface Science with Trapped Ions

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We present efforts to characterize electric field noise at the surface of an ion trap [1]. A novel setup, combining the ion trap with surface analysis tools, allows for studies of the surface composition and cleaning of the trap combined with precision measurements of surface noise using a single ion as the electric field noise sensor. Reducing noise levels by identifying and targeting the cause will allow for advancement in the use of ion traps for scalable quantum computing, as well as other noise sensitive applications.

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Towards a MOT of CaF

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We report on our progress toward laser cooling and magneto-optical trapping (MOT) of CaF molecules. In this experiment, we use a two-stage buffer-gas cooled beam source to produce a cold and slow beam of CaF with an average forward velocity of 60 m/s [1]. We plan to load a MOT from this buffer-gas source. Similar to the steps taken for laser cooling of YO [2] and SrF [3], we will use "white-light" to slow the molecular beam below the MOT capture velocity. With the aim of depopulating magnetic dark states in the MOT, we are oscillating the trapping magnetic fields and simultaneously switching the MOT laser polarizations at a frequency of ~ 6 MHz (comparable to the natural lifetime of the CaF excited state).

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MONDAY

Magnetic Slowing, Optical Loading and Magnetic Trapping of CaF and K

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We demonstrate a general method for trapping magnetic molecules using few photon scattering in combination with magnetic slowing [1]. Starting from a two-stage cryogenic buffer-gas beam source, calcium monofluoride (CaF) molecules with an initial velocity of 30 m/s are slowed as they enter a 800 mK deep superconducting magnetic trap. Irreversible trap loading is achieved using optical pumping, where two scattered photons remove molecular energy and lead to trapping. We observe trapped CaF molecules in the $X^2\Sigma^+(v=0, N=1)$ state with lifetimes exceeding 500 ms, which is limited by background collisions. Potassium (K) was also trapped using the same approach with trap lifetimes beyond 9 s. Our future plans are to co-trap calcium monohydride (CaH) molecules with K atoms for studying K-CaH sympathetic cooling and the trapping of polyatomic molecules.

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Laser cooling and slowing of CaF molecules

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Producing ultra-cold and dense samples of polar molecules is a technical challenge and has been investigated with several techniques over the last decade [1]. Some of the future applications are related to quantum information, ultra-high resolution spectroscopy, tests of fundamental symmetries and ultra-cold chemistry. Laser cooling is a direct technique and can be applied to a wide range of molecules with suitable vibrational structure [2,3].

We have experimentally demonstrated longitudinal laser cooling and slowing of CaF molecules in a pulsed, seeded supersonic beam machine [4]. We have pursued a laser frequency chirp cooling experiment, where the chirp frequency rate is set in order to keep the laser in resonance during the cooling process.

Further, we present our progress towards a magneto-optical trap of CaF molecules. We start from a slow buffer gas source and plan to apply Sisyphus cooling and slowing to increase the number of trapped molecules substantially.

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MONDAY

MM-Wave Spectroscopy and Determination of the Radiative Branching Ratios of ^{11}Bh for Laser Cooling Experiments

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We aim to slow a supersonic, molecular beam of ^{11}BH using a Zeeman slower and subsequently cool the molecules to sub-millikelvin temperatures in a magneto-optical trap [1]. Most molecules are not suitable for direct laser cooling because the presence of rotational and vibrational degrees of freedom means there is no closed-cycle transition which is necessary to scatter a large number of photons. As was pointed out by DiRosa [2] there exists a class of molecules for which the excitation of vibrational modes is suppressed due to highly diagonal Franck-Condon factors. Furthermore, Stuhl et al. [3] showed that angular momentum selection rules can be used to suppress leakage to undesired rotational states. Here we present a measurement of the radiative branching ratios of the $A^1\Pi$ to $X^1\Sigma^+$ transition in ^{11}BH - a necessary step towards subsequent laser cooling experiments. We also perform high-resolution mm-wave spectroscopy of the J = 0 to J = 1 rotational transition in the $X^1\Sigma^+(v = 0)$ state near 708 GHz. From this measurement we derive new, accurate hyperfine constants. The measured hyperfine splittings and branching ratios suggest that it is possible to laser cool ^{11}BH molecules close to the recoil temperature of 4 μK using three laser frequencies only.

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Magneto-Optical Trapping of a Diatomic Molecule

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The magneto-optical trap (MOT) is the workhorse technique for atomic physics in the ultracold regime, serving as the starting point in applications from optical clocks to quantum-degenerate gases. Although MOTs have been used with a wide array of atomic species, realization of a molecular MOT was long considered infeasible. Here we present the first magneto-optical trap for a molecule, strontium monofluoride (SrF). Our MOT produces the coldest trapped sample of directly-cooled molecules to date, with temperature T ~2.5 mK. The SrF MOT is loaded from a cryogenic buffer-gas beam slowed by laser radiation pressure. Images of laser-induced fluorescence allow us to characterize the trap's properties. Although magneto-optical trapping of diatomic molecules is in its infancy, our results indicate that access to the ultracold regime may be possible for several molecular species, with potential applications from quantum simulation to tests of fundamental symmetries to ultracold chemistry.

Towards ultracold LiK ground-state molecules

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Ultracold heteronuclear molecules have seen increasing interest in the scientific community over the last few years [1]. Due to their large electric dipole moment of 3.6 Debye LiK ground-state molecules are particularly suited to investigate the physics of strongly-interacting dipolar quantum gases.

In our experiment [2] we create quantum degenerate mixtures of $8x10^4$ Li and $9x10^4$ K atoms. These are subsequently combined into weakly-bound molecules via Feshbach association yielding samples of around $3x10^4$ ultracold Feshbach molecules close to quantum degeneracy. A subsequent ground-state-transfer scheme using coherent stimulated Raman adiabatic passage (STIRAP) is currently being investigated. Here we present details of our setup and our transfer scheme. Further we give an update on the current experimental status.

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Dual Component ^{87}Rb and ^{41}K Bose-Einstein condensates in configurable optical potentials

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Multi-component Bose-Einstein condensates (BECs), whether composed of spin mixtures or different atomic species, present features not seen in single component gases. In particular, interactions between the components allow for more diverse superfluid behaviour. These interactions are tuneable via Feschbach resonances, enabling a host of rich behaviour to be studied [1].

We present our ongoing development of a two-component BEC, consisting of ^{87}Rb and sympathetically cooled ^{41}K, loaded into configurable optical potentials. By utilising a digital micromirror device (DMD) and high-resolution imaging system, a wide range of precise 2D potentials can be created. We propose to first use this system to study the coarsening dynamics of the miscible-immiscible superfluid transition in a flattened optical trap. Utilising high-resolution imaging of the condensates, a study of classical percolation on a DMD-produced optical lattice will be subsequently undertaken.

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Mixtures of Bose-Fermi superfluids

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We report on the observation of a mixture of Bose and Fermi superfluids with dilute gases of Lithium isotopes [1]. We probe the collective dynamics of this system by exciting center-of-mass oscillations that exhibit extremely low damping below a certain critical velocity. Using high precision spectroscopy of these low-lying modes we observe coherent energy exchange and measure the coupling between the two superfluids. Our observation can be captured theoretically using a sum-rule approach that we interpret in terms of two coupled oscillators.

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Designing an ultracold Yb-Li mixture with controllable interactions

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Over the last two decades ultracold atoms proved valuable to investigate basic properties of many-body physics with an unprecedented degree of control and purity. In recent years interest shifted to also include systems with impurities, a step towards the simulation of the more complex processes in real materials. We here present recent experimental progress on a quantum degenerate atomic mixture of Ytterbium (Yb) and Lithium (Li) [1] to be used for quantum simulation. Our current efforts are to establish a fine tuned control over the interspecies interaction via suitable Feshbach Resonances, a standard tool in alkali atoms experiments. We present a gravity compensated far-off resonant optical trap (FORT) to ensure good spacial overlap of the large mass-imbalance mixture. To establish controllable interspecies interactions, we strive to study the properties of predicted Feshbach resonances [2] between Yb in the excited $^3P_2$ state and Li in the $^2S_{1/2}$ ground state.

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High-Resolution Spectroscopy of Trilobite-Like States of $^{85}Rb_2$

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We present new, high-resolution spectra of low-n trilobite-like states in $^{85}Rb_2$. Trilobite states are novel long-range molecular states consisting of a ground-state atom embedded in the Rydberg wavefunction of a second atom. We utilize a bound-bound excitation to populate these states from photoassociated ultracold molecules in high-ν levels of the lowest triplet state. The excitation is stimulated by a frequency-doubled pulse-amplified CW laser for narrow linewidth, under 200 MHz. Upon excitation, the trilobite-like states rapidly autoionize and are mass-selectively detected by an ion detector. This technique gives a two orders-of-magnitude improvement over the previous excitation method, which was done by a broader linewidth conventional pulsed laser as reported in Ref. [1]. This work is supported by the NSF and AFOSR.

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The creation of ultracold RbCs molecules in the rovibrational ground state

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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment. The anisotropic, long range dipole-dipole interactions between such molecules offer many potential applications [1], including novel schemes for quantum simulation. Here we demonstrate the creation of ultracold RbCs molecules in the rovibrational ground state. The molecules are created from a high phase space density mixture of ^{87}Rb and ^{133}Cs [2] in a two-step process. First weakly bound RbCs molecules are created using magnetoassociation on an interspecies Feshbach resonance [3]. The molecules are then optically transferred into the rovibrational ground state of the singlet potential by stimulated Raman adiabatic passage (STIRAP) following the route outlined in [4]. We report our progress towards measuring the electric dipole moment of the molecules and subsequently realising a dipolar quantum gas.

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Thermalization and progress to degeneracy in a mixture of rubidium-87 and ytterbium

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Rubidium-87 has been the workhorse for degenerate gas experiments for over a decade. The large number of ytterbium isotopes and range of interactions [1],[2] available make it a promising element for a mixture with rubidium. Here we present studies of thermalization in an ultracold mixture of rubidium-87 and ytterbium in a two-color optical dipole trap [3] consisting of a 1064 nm and 532 nm beam. We characterize the properties of our trap and will describe a possible avenue for creating a degenerate mixture of these two species using a new “rubidium-blind” cross-dipole trap at 423 nm.

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MONDAY

Electron Dynamics and Terahertz Emission in Two-Color Photoionization

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Two-color laser photoionization has been widely used as a versatile tool for broadband terahertz (THz) generation [1-3]. The physics of THz generation is also compelling, raising fundamental questions about the interaction of strong electromagnetic fields with atoms and molecules in the nonperturbative regime. Microscopically, THz generation arises from the evolution of laser-driven electron wavepackets in a strong electric field and their transition from atomic to plasma states [2-3]. To verify such a microscopic detail, we apply a dichroic interferometry method to measure the relative phase at the focus. Simultaneously, we observe electric currents arising in the vicinity of the focus where THz radiation originates. Our results show that both THz fields and electric currents peak at a relative phase of π/2, consistent with the semiclassical plasma current model. This indicates that electron-ion scattering does not significantly affect THz radiation in the tunnel ionization regime.

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Electron-Rescattering from Ar and Xe induced by Intense Laser Filed: Above Threshold Ionization and Rydberg Excitation

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Electron-rescattering with ionic core plays a key role in atom-strong-field physics, which may lead to high-order above threshold ionization (HATI, elastic rescatteing), non-sequential double ionization (NSDI, inelastic rescatteing), high-order harmonic generation (HHG, radiative recombination), or even Rydberg excitation. Here, we performed experimental studies on several rescattering-related processes of Ar and Xe atoms. We observed fine ATI structures in the 2-D electron momentum, which are dependent on both laser intensity and wavelength obviously. The results indicate that channel close or resonance effect could be significant in ATI process. By measuring the yield of neutral Rydbergs as a function of laser intensity, we observed the “knee” structure in Rydberg excitation, similar as in NSDI but less dependent on the laser ellipticity, which indicates a “soft-rescattering” in Rydberg excitation. The study could provide further understanding for the electron-rescattering of atoms in strong laser fields.

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MONDAY

Benchmark H_2 few-cycle photoionisation measurements and laser intensity calibration with percent-level accuracy

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Photoionisation of atoms and molecules from intense few-cycle laser pulses is the source of many strong-field phenomena that have been used to image molecular dynamics [1], probe electron localization [2] and measure the laser carrier-envelope phase [3]. Correct experimental observation and interpretation of such highly non-linear effects thus requires both highly accurate data and knowledge of the laser peak intensity. We present benchmark photoionisation measurements for molecular hydrogen (H_2) that is certified by excellent theory-experiment agreement for atomic hydrogen (H). Our results in H_2 provide an order-of-magnitude improvement in reference data for simulations of complex strong-field phenomena, and serves as a stringent test for molecular theories of strong-field ionisation. Building upon previous work [4], we incorporate our H_2 data into an easily accessible technique for calibrating the laser peak intensity to an accuracy of 3%. This technique can be readily applied to intensity calibrate almost any few-cycle strong-field experiment.

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Ionisation of metastable states of neon using few-cycle light fields

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We present results for experiments involving the ionisation of metastable neon (Ne*) using ultra-short (sub-6fs) laser pulses. The study of interactions between ultrafast light and matter is topical due to the broad range of effects that can be observed [1-3]. We utilise a DC discharge type source to generate Ne* atoms which interact with the laser pulses in a Cold Target Recoil Imaging Spectroscopy device, which records time of flight and maps the momentum of Ne ions created in the interaction. We will present ion yields for laser pulses with intensities ranging from 10^{13}-10^{15}W/cm^2 and compare this data to current theories.

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Characterisation of intense few-cycle laser pulses from photo-ionisation of atomic hydrogen

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The photo-electron spectra produced by the interaction of atomic hydrogen with an intense few-cycle laser pulse can provide a useful means of obtaining accurate information about the incident laser pulse. In particular, comparison of simulated and experimental results allows for measurements of peak laser intensity – a parameter which is difficult to measure directly, but which is crucial for evaluating experimental results in strong field physics. These comparisons require a large number of computationally demanding simulations that are capable of reproducing photo-electron spectra to arbitrary accuracy. The simulations must be able to adequately account for pulse-to-pulse variation in the laser field and varying intensity across the profile of the laser beam. We demonstrate how a single atom photo-electron spectrum is sensitive to variation in the laser field by comparing simulated spectra for different carrier-envelope phases and intensities. We show that these results give good agreement with experimental data.

Strong-field ionization of helium by elliptically polarized light in attoclock configuration

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We perform time-dependent calculations of strong-field ionization of He by elliptically polarized light in configuration of recent attoclock measurements [1]. By solving a 3D time-dependent Schrödinger equation, we obtain the angular offset Θ of the maximum in the photoelectron momentum distribution in the polarization plane relative to the position predicted by the strong field approximation. This offset is used in attoclock measurements to extract the tunneling time. Our calculations [2] clearly support the set of experimental angular offset values obtained with the use of non-adiabatic calibration of the *in situ* field intensity, and disagree with an alternative set calibrated adiabatically. These findings are in contrast with the conclusions of Ref. [1],that found a qualitative agreement of semiclassical calculations with the adiabatic set of experimental data. This controversy may complicate interpretation of the recent atto-clock measurements [3-4].

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Improving conversion efficiency of high harmonic generation with gas mixtures

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We report an improvement of the conversion efficiency of the fundamental IR light into XUV high harmonic photons by using mixtures of two gases (H_2 and Ne) with significantly different ionization potentials (IP). The initial high harmonic generation (HHG) takes place in the component with low IP, inducing excited states and facilitating ionization and HHG in the component with high IP [1]. We observed up to a 2.5 fold enhancement of HHG compared to pure H_2 and up to $3\text{x}10^3$ enhancement compared to pure Ne at moderate laser intensities at the gas jet ~$1.5\text{x}10^{14}$ W/cm^2 . Thus, mixing of gases with low and high ionization potentials opens up new possibilities for the efficiency enhancement of the HHG process.

This work was supported by the Robert A. Welch Foundation Grant No. A1546 and the Qatar Foundation under the grant NPRP 5 - 994 - 1 – 172.

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Signatures of field-induced intramolecular quantum interference in high-order harmonic generation by laser-irradiated homonuclear diatomic(s)

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The strong-field phenomenon of high-order harmonic generation (HHG) in laser-irradiated homonuclear diatomic species (H_2^+, H_2) is studied theoretically under conditions corresponding to intermediate values of the so-called *Keldysh parameter* ($\gamma \leq 1$). The problem is addressed within the *length-gauge* formulation of molecular *strong-field approximation* (SFA) [1] complemented with the *density-functional-theory* (DFT) applied for numerical composition of initial (laser-free) molecular state using the routines of GAUSSIAN-03 code [2]. Our DFT-SFA calculation results well reproduce and suggest a pronounced interference-related minimum arising in high-frequency region of respective molecular HHG spectra that evidently demonstrate the clear signatures of the field-induced *intramolecular* interference [3] of strong-field ionization amplitudes corresponding to photoelectron emission from different atomic centers. In particular, the location of the minimum proved to be very sensitive to the laser wavelength λ and the angle Θ of molecular axis orientation with respect to the laser field polarization as well as to internuclear separation R_0.

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MONDAY

Quantum Optics and Cavity QED Mo-066

Coherent population trapping (CPT) coupled by magnetic dipole interactions

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We report our study on CPT driven by magnetic dipole interactions. We consider a Λ system consisting of a pair of Zeeman sublevels in one hyperfine level and another sublevel in the other hyperfine level coupled by a pair of radio-frequency fields. We use lithium atoms in an optical trap for our experimental study. The system allows independent control of the main parameters characterizing CPT. Moreover, by turning off the applied fields, the system is frozen so that its quantum state can be measured precisely. We studied the line shapes and dynamics of the CPT system, and measured the phase relation of the dark superposition state to find excellent agreement with theory. The possible application of the scheme as a method to cool optically trapped atoms below the recoil limit in a manner analogous to velocity-selective coherent population trapping is to be discussed.

Quantum Optics and Cavity QED Mo-067

High Conversion Efficiency in the Resonant Four-Wave Mixing Process

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We systematically studied the energy loss and conversion efficiency in four-wave mixing (FWM) processes. The FWM can be used to convert probe light into signal light with the presence of the coupling and pump fields experimentally; In order to determine the condition, we design two specializing FWM systems and find the relationship between system response time and coupling rising time. Based on this study, we propose a scheme that in the steady state the input probe can be nearly 100% converted to output signal with negligible energy loss. The proposed scheme is very useful for the sum frequency generation and can significantly advance the technology in nonlinear optics.

Dynamics of strongly interacting photons in waveguides: a generalized input-output formalism

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We present a generalized input-output formalism to describe the propagation of strongly interacting photons through an atomic ensemble. Standard approaches typically involve approximations to eliminate the atomic degrees of freedom, to subsequently arrive at a nonlinear field equation describing the optical modes. On the contrary, we show that, by effectively integrating out the photonic field, a spin model containing only discrete atomic degrees of freedom can be obtained. Then by explicitly solving for the atomic dynamics, the optical fields are reconstructed exactly, including S-matrix and any correlation function. Our approach to provide a complete description of the system dynamics represents a powerful tool to explore a wide range of new phenomena in nonlinear quantum optics. We discuss the formalism in several experimental situations.

Coherent population trapping in a two field cavity-QED system: Semiclassical Theory

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We calculated the steady state transmission and reflection spectra of coherent population trapping (CPT) in a two field cavity-QED system consisting of few to many three-level atoms coupled with two longitudinal modes of an optical cavity. In this scheme, both the probe beam and the coupling beam have comparable intensities and are coupled into the same cavity, driving corresponding intra-cavity field. Results are presented with different coupling beam detuning under different atom number and light intensities. Meanwhile we discussed the conditions required to realize two field intra-cavity CPT. We also find that small cavity detuning has little influence to the presence of CPT, which renders the system feasible in experimental realization with current technology.

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Coherent coupling of hybrid alkali vapor through spin-exchange collisions

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Spin-exchange collisions are a major decoherence process in warm alkali vapor, as they induce random transitions between the hyperfine levels. However, at very low magnetic fields, the evolution of a spin-polarized ensemble effectively becomes spin-exchange relaxation-free (SERF) [1]. Here we study experimentally and theoretically a hybrid system of two alkali species, in which one specie inherits the magnetic properties of the other. We demonstrate that spin-exchange collisions induce a transfer of coherence between potassium and rubidium at low magnetic fields. We show that the potassium atoms inherit the gyromagnetic ratio and the life time (T1) of the rubidium atoms. As a result, the elimination of spin-exchange relaxation for the potassium atoms survives up to a much higher magnetic field threshold, corresponding to the rubidium's threshold. We explain these phenomena analytically by the hybridization of the two species via the spin-exchange interaction.

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Observation of Paired Superradiance

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A single photon (E1) emission rate is greatly enhanced by using a material coherence. This phenomenon is known as "Superradiance". The enhancement of the emission rate is proportional to N^2, where N is a number density of atomic ensemble. A two-photon emission rate from metastable state of atoms/molecules may also be greatly enhanced by use of such "macroscopic coherence". We proposed this macro-coherent enhanced two-photon emission process as "paired superradiance" [1]. Similar proposal of effective parametric down-conversion was proposed by Harris [2]. However, to our knowledge, there is no experimental demonstration of paired superradiance so far.

In this poster, we report the observation of paired superradiance. We prepared a large coherence between ground and vibrational excited state of para hydrogen molecules by adiabatic Raman process; and observed two-photon emission from excited state. About 10^{19} enhancement of emission rate is obtained. Updated results and detailed analysis will be presented.

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Cavity QED in the Recoil Resolved Regime

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We are experimentally exploring the light matter interaction of a Bose-Einstein condensate with a high finesse optical standing wave cavity with a Purcell factor far above unity. The unique feature of our cavity is its extremely small linewidth comparable to the single photon recoil frequency. As a consequence, cavity assisted scattering can only occur in a narrow resonance window such that only very few selected motional states are coupled. We discuss recent experiments showing sub-recoil cavity cooling [1], extreme non-linear collective behavior, like optomechanical hysteresis and bistability [2], and superradiance - or self-organization instabilities related to the Hepp-Lieb-Dicke phase transition.

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Nonequilibrium phase transitions in periodically-driven cavity QED systems

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Ensemble of atoms confined in an optical cavity displays several collective phenomena. In equilibrium, the system exhibits the Dicke transition associated with the symmetry breaking. Under the time-periodic driving such as laser irradiation, it is known that the system shows the optical bistability and undergoes the discontinuous transition without the symmetry breaking.

Here we report our theoretical discovery on the new kind of phase transitions with symmetry breaking in the ultra-strong coupling and driving regime [1]. We argue that these transitions are understood by the concept of coherent destruction of tunneling, which is a simple quantum interference effect under the time-dependent external field.

We will also discuss about the effect of finite system size by performing the $1/N$ expansion.

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Strong atom-light interactions in 1D photonic crystals

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Nano- and microscale optical systems have shown great progress towards realizing efficient and scalable quantum interfaces through enhanced atom-field coupling in both resonators and waveguides [1]. Beyond these conventional topologies, new opportunities emerge from the integration of cold atoms with nanoscale photonic crystal devices. In photonic crystal waveguides (PCW), light-matter interaction can be engineered for both trapping and strong atom-photon interactions [2], enabling exploration of novel quantum transport, quantum many-body phenomena, and Casimir-Polder forces [2-4]. We have developed an integrated optical circuit with a PCW capable of both localizing and interfacing atoms with guided photons. From reflection spectra measured with average atom number of 1.1 (0.4), we infer the fraction of single-atom radiative decay into the PCW to be $\Gamma_{1D}/\Gamma' = 0.32$ (0.08), where Γ_{1D} (Γ') is the atomic spontaneous emission rate into the guided (all other) mode (s) [5]. We discuss progress towards trapping atoms within the PCW, which should enable a regime where $\Gamma_{1D}/\Gamma' \sim 10$.

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Crossover from Lasing to Photon Bose-Einstein condensation by Photon Gas Thermalization

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Thermal equilibrium is the condition most frequently found in cold gases and solid-state physics. In general however, driving and loss can force a system away from equilibrium. A prominent example for the emergence of an ordered state in nonequilibrium physics is the laser, where one engineers photon loss inside a cavity to achieve a large population of the desired optical modes. Interestingly, such an ordered photon state is also achieved with a thermal equilibrium phase transition, by Bose-Einstein condensation. We report the observation of a crossover between a lasing state and a photon condensate in a dye microcavity by in-situ monitoring the photon dynamics. When thermalization to the dye temperature by absorption and re-emission of photons is faster than their loss, photons accumulate at low energy states near the cavity cutoff and form a Bose-Einstein condensate. In contrast, when photons leave the cavity before they thermalize, the system remains in e.g. a mode-locked laser state.

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Fiber cavity-based photon-ion interfaces

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Strong light-matter interaction is a key ingredient for a number of linked quantum system applications, such as entanglement distribution, quantum simulation, and distributed quantum computing. Our approach to this research area combines fiber-based cavities with ion traps [1], aiming to capitalize on both the benefits of high-finesse cavities and the established quantum control of trapped atomic ions. For this we trap Yb-ions in specialized Paul-type ion traps that address the challenges of tightly placed dielectric materials close to the ion, while keeping scalability of the system as a major design goal in mind. The poster will present our recent progress in using these systems as intrinsically fiber-coupled efficient single photon sources. We show polarization-spin state correlation and polarization dependent absorption demonstrating the feasibility of using our system as quantum network node.

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Building a hybrid quantum system of neutral atoms coupled to a superconducting circuit

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One avenue for creating hybrid quantum systems is the coupling of a neutral atomic ensemble to superconducting circuits via a magnetic dipole transition. Here we present progress towards trapping cold rubidium atoms within 10 micrometers of a superconducting circuit using a cryogenically-compatible atom trap and a tunable, light-insensitive, high-Q superconducting resonator. Evanescent fields around an optical nanofiber with 99.95% transmission form an atom trap suitable for a 10 mK dilution refrigerator. We systematically study how low levels of optical light scattered from a tapered fiber positioned near the superconducting resonator affect its linewidth and frequency.

Work supported by NSF, the Atomtronics MURI, and the PFC at JQI.

Atom induced cavities and tunable long-range interactions between atoms trapped near photonic crystals

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The use of cold atoms to simulate strongly interacting quantum systems is rapidly progressing. However, achieving tunable, coherent, long-range interactions between atoms is challenging, leaving a large class of models inaccessible to quantum simulation. We propose a solution exploiting the powerful new platform of cold atoms trapped near nano-photonic systems. We show that atoms trapped near photonic crystals act as dielectric elements that seed localized cavity modes around each atom. In a dynamic form of 'all-atomic' cavity QED, the length of these cavity modes can be tuned, and atoms separated by the order of the effective cavity length can interact coherently with each other. Considering realistic conditions such as fabrication disorder and photon losses, coherent long-range potentials or spin interactions can be dominant in the system over length scales up to hundreds of optical wavelengths. These systems may be used to study long-range interactions in many-body atomic systems as well as to realize effective long-range interactions between photons for non-local, non-linear optics.

2-D spectrum of an optical microcavity coupled to a few atoms

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Past studies [1, 2] have demonstrated a fibre-coupled optical microcavity for high-cooperativity cavity quantum electrodynamics in the fast the cavity regime, where $\kappa > g > \gamma$ (κ is cavity decay rate, g is atom-cavity coupling, γ is atom decay rate) and g2 > κ*γ. To complete the understanding of such systems, we have measured the 2-D spectrum that covers both atom-laser detuning and cavity-laser detuning, observed both in reflection from the cavity and in fluorescence from the atom excited through the side of the cavity. Although the coupled atom-cavity system is not in the strong coupling regime, we observe a strong dispersive splitting in the 2-D reflection spectrum and not in the fluorescence spectrum.

The experiment comprises a ^{87}Rb Magneto-optical trap (MOT) and a microcavity, which is formed between a micro-spherical-mirror array chip and a plane mirror-coated fibre tip. The ^{87}Rb atoms are trapped, cooled and pushed into the microcavity, which is locked to a stable single frequency laser, whose frequency is simultaneously monitored by a wavemeter with 100 MHz precision. As the atoms enter, they are pumped either through the fibre or transversely through the side of the cavity. The 2-D spectra are measured by scanning both pump laser and cavity resonance frequency. The measured spectra are compared with a theoretical model, which allows us to understand why the reflection spectrum exhibits anticrossing, while the fluorescence spectrum does not.

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Graphene plasmons quality factors

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Plasmons in graphene hold great potential for applications since they enable strong confinement of electromagnetic energy at subwavelength scales [1]. This confinement results in strong light-matter interaction at the single photon level, like the high decay rates and vacuum Rabi splittings of quantum emitters in the proximity of the graphene sheet [2]. However all of these exciting effects depend on the quality factors of plasmons. Since they live in a complicated solid state environment, there are numerous excitations that can reduce the quality factors. In my poster I will present our work on the various scattering mechanisms and plasmon damping. Particularly I will focus on the interaction of plasmon with optical phonons, since this process gives an intrinsic limit on the plasmon quality factor at infra-red frequencies [1]. Moreover I will discuss a screening effect on the optical scattering rates for charge impurity scattering and surface polar phonon scattering [3].

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Single-photon second-order nonlinear processes in graphene

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Intense efforts have been made in recent years to realize nonlinear optical interactions at the single-photon level. Much of this work has focused on achieving strong third-order nonlinearities, such as by using single atoms or other quantum emitters, while the possibility of achieving strong second-order nonlinearities remains unexplored. Here, we describe a novel technique to realize such nonlinearities using graphene, exploiting the strong per-photon fields associated with tightly confined graphene plasmons in combination with spatially non-local nonlinear optical interactions. Under realistic conditions, we show that the interactions are strong enough to observe the generation of non-classical light and allow near-deterministic down-conversion of a single plasmon into an entangled plasmon pair.

Room temperature coherent population trapping with nuclear spins in diamond

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Nuclear spins are attractive candidates for solid-state quantum information storage and processing owing to their extremely long coherence time [1]. However, since this appealing property results from a high level of isolation from the magnetic environment, it remains a challenging task to polarize, manipulate and readout individual nuclear spins [2].

In this work, we show room temperature coherent population trapping with nuclear spins in diamond using single nitrogen-vacancy defect. We investigate sequential building of the dark state and we use this effect to demonstrate a polarization process of nuclear spins. This mechanism, which operates in the microwave domain, could find applications in solid-state quantum information and in micro-wave photon storage.

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Coherent spin control of a nanocavity-enhanced qubit in diamond

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A central aim of quantum information processing is the efficient entanglement of multiple stationary quantum memories via photons [1-3]. Among solid-state systems, the nitrogen-vacancy (NV) centre in diamond has emerged as an excellent optically addressable memory with second-scale electron spin coherence times [4,5]. Recently, quantum entanglement and teleportation have been shown between two NV-memories [6–8], but scaling to larger networks requires more efficient spin-photon interfaces such as optical resonators [9]. Here, we demonstrate such NV-nanocavity systems with optical quality factors approaching 10,000 and elec- tron spin coherence times exceeding 200 μs using a silicon hard-mask fabrication process. The on-chip integration of our system with microwave circuits for coherent spin control provides a compact architecture for quantum repeaters [10], spin-based microprocessors [11], and quantum networks [12].

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Size-dependence of radiation power thermally emitted from a microparticle

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MONDAY

Although Planck's law of blackbody radiation well describes spectral profiles of thermal radiation from macroscopic objects, it remains an open question if Planck's formula applies to particles of size comparable to optical wavelengths. Our laser-trapping technique spacially and thermally isolates a high-temperature particle in the Mie regime, and enables emission spectroscopy of the single particle [1]. Thermal radiation spectrum from a dielectric microsphere exhibits sharp resonances with whispering gallery modes of the spherical resonator. Measurements of the mode spacing provide precise data of the particle size and size-dependence of the emission spectra. Total radiation power emitted from a macroscopic object linearly depends on its surface area. In contrast, our analysis of the microparticles reveals cubic dependence of the emission power on the particle size, showing a micron-sized dielectric particle is a volume emitter where not only its surface but atoms inside contribute to the thermal radiation.

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Experimental Realization of Environment Assisted Speed Up of the Quantum State Evolution in the Open Quantum System

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Manipulation of the quantum speed of the state evolution is important in quantum information and quantum engineering. We have experimentally measured the quantum speed of the state evolution in the open quantum system (optical cavity QED system) under weak driving. We consider the system the mode of the electromagnetic field with a preferential coupling to a tunable environment: the atoms. By controlling the environment, i.e. changing the number of atoms coupled to the optical cavity mode, we can experimentally realize the environment assisted speed up of the quantum state evolution in the optical cavity. And our result demonstrates that the quantum speed of the state re-population in the optical cavity increases, as the interaction between the optical cavity mode and the environment (the number of atoms) increases. Work is supported by NSF.

Modal decomposition and control of higher-order modes in silica nanofibers

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Atoms confined in optical nanofiber evanescent-field traps experience strong coupling to photons propagating through the fiber. This strong coupling is ideal for quantum technologies and sensors. Strong atom-photon interactions have been demonstrated in fibers with submicron diameters, small enough to admit only the HE_{11} mode. Higher-order vector modes open another set of trapping geometries in fibers with diameters above the HE_{11} cutoff value. We have previously achieved 97% transmission of the first excited mode family, which contains the TE_{01}, TM_{01}, and HE_{21} modes, but due to their near degeneracy, excitation of a pure mode within this family in the nanofiber waist is challenging. In this work, we discuss techniques to measure mode purity through modal decomposition of the output field and analysis of Rayleigh scattering in the waist. This work was funded by ONR, the ARO Atomtronics MURI, DARPA, and the NSF through the PFC at JQI.

QUANTUM INFORMATION

Entanglement Generation in a Multi-Qubit System Coupled to Heat Bath

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The entanglement generation in a multi-qubit system interacting with heat bath and an external local magnetic field is investigated in the framework of the master equation. The time-evolution for the most general density matrix of the multi-qubit system is obtained and solved. It is shown that the two-qubit system ends up in an entangled stationary state independent on the initial separable state.

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Quantum storage based on the control field angular scanning

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Continuous change of the propagation direction of a classical control field in the process of its off-resonant Raman interaction with a weak signal field in a three-level atomic medium is suggested for quantum storage of a single-photon wave packet. It is shown that due to the phase matching condition such an angular control allows one to reversibly map the single-photon wave packet to the Raman spatial coherence grating. Thus, quantum storage and retrieval can be realized without using inhomogeneous broadening of the atomic transitions or manipulating the amplitude of the control field. Under some conditions the proposed scheme proves to be mathematically analogous to the quantum storage scheme based on controlled reversible inhomogeneous broadening of the atomic states [1].

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Time-Continuous Bell Measurements

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We combine the concept of Bell measurements, in which two systems are projected into a maximally entangled state, with the concept of continuous measurements, which concerns the evolution of a continuously monitored quantum system. For such time-continuous Bell measurements we derive the corresponding stochastic Schrödinger equations, as well as the unconditional feedback master equations [1]. Our results apply to a wide range of physical systems, and are easily adapted to describe an arbitrary number of systems and measurements. Time-continuous Bell measurements therefore provide a versatile tool for the control of complex quantum systems and networks. As examples we show that (i) two two-level systems can be deterministically entangled via homodyne detection, tolerating photon loss up to 50%, and (ii) a quantum state of light can be continuously teleported to a mechanical oscillator, which works under the same conditions as are required for optomechanical ground-state cooling.

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A Monte Carlo wavefunction method for semiclassical simulations of spin-position entanglement

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Many simulations of atoms are semiclassical: they simulate the internal state of atoms quantum mechanically, but positions and momenta classically. Laser cooling, for example is simulated in this way. However a conflict arises when the force on an atom depends on its internal state. Actual atoms in a superposition of spin states in a magnetic field gradient, for example would move in multiple directions, resulting in spin-position entanglement, which can't be modelled semiclassically.

I describe a Monte Carlo wavefunction method that resolves this conflict by considering the resulting entanglement to be a quantum measurement, and using decoherence to include it as a probabilistic jumping between different spin states of the atom as it follows only one classical trajectory through space.

Quantum Information Mo-091

Individual Addressing of Trapped Ions with MEMS-based Beam Steering

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Scalability is one of the major challenges of trapped ion based quantum computation, mainly limited by the ability to manipulate an increasing number of qubits. For individual addressing of qubits, microelectromechanical systems (MEMS) technology allows one to design movable micromirrors to focus laser beams on individual ions and steer the focal point in two dimensions [1]. This system provides low optical loss across a broad wavelength range and can scale to multiple beams.

Using a microfabricated surface trap from Sandia National Laboratories we trap chains of $^{171}Yb^{+}$ ions. Using MEMS mirrors, we perform single qubit gates on individual $^{171}Yb^{+}$ ions in a chain with Raman transitions driven by stabilized frequency combs [2]. Using this setup, we sequentially perform single qubit gates on multiple qubits and characterize gate performance using quantum state tomography. Our system features negligible crosstalk to neighboring ions, and switching speed comparable to typical single-qubit gate times.

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MONDAY

Quasiparticle engineering and entanglement propagation in a quantum many-body system

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The key to explaining and controlling a range of quantum phenomena is to study how information propagates around many-body systems. Quantum dynamics can be described by particle-like carriers of information that emerge in the collective behaviour of the underlying system, so called quasiparticles. Here, we experimentally study quasiparticle dynamics observed in a quantum many-body system of up to 20 trapped atomic ions with a tunable interaction range. Making use of a tightly focused laser beam to address individual ions and single-ion resolved imaging, we investigate and characterize the propagation of entanglement distributed by specifically engineered quasiparticles in different experimental regimes [1]. We further perform quantum state tomography of subsets of the full chain in order to investigate the possibility of an efficient representation of the full quantum state using matrix product states and -operators [2,3].

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Femtosecond Ramsey interferometry for atomic qubit state measurement

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Experimental demonstration of ultrafast optical implementation of all three angular rotations (x-, y-, and z-rotations) of single qubits composed electronic states of cold rubidium atoms is presented. The spatial confinement of cold rubidium (Rb) atoms in a magneto-optical trap has enabled uniform nonlinear interaction of ultrafast lasers with the atomic ensemble, or high-fidelity Rabi oscillations. Aside from the usual Bloch sphere rotation about x-axis to say, the other two angular rotations are constructed, respectively, by carrier-envelope phase control and far-off resonant strong-dispersive interaction. All the interactions are induced by shaped ultrafast laser pulses, permitting operations on a sub-picosecond time scale or at terahertz speeds. For the phase evolution measurement of the Bloch vector, we used laser-pulse shaping technique to facilitate femtosecond Ramsey interferometry.

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Quantum Simulation of Unphysical operation with a Trapped Ion

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We report on the experimental quantum simulation of unphysical symmetry operations such as complex conjugation, charge conjugation and time reversal with a trapped ion [1]. In particular, we focus on anti-unitary operations in the context of Majorana Equation. Generally, quantum operation is unitary and it is considered to be impossible to implement an anti-unitary operation in quantum system. We experimentally study the interesting various phenomena in Majorana equation with a single 171^Yb^{+} ion in an enlarged Hilbert space based on the proposal in Ref [1]. Quantum simulation may eventually provide a solution to a certain complex problem that is intractable with classical computation. In our study, we explore the other aspect of quantum simulation, where it brings purely theoretical or imaginary concepts to the table top experiment.

This work was supported in part by the National Basic Research Program of China Grant 2011CBA00300, 2011CBA00301, the National Natural Science Foundation of China Grant 61033001, 61061130540. KK acknowledge the support from the recruitment program of global youth experts.

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Propagation of information in long-range interacting quantum lattice system.

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Propagation of information in short-range interacting systems is restricted to within a linear "light cone", as proven by the well-known Lieb-Robinson bound, thus ensuring a well defined notion of locality. Whether long-ranged interactions can lead to a different shape of this light cone, and the breakdown of the associated notion of locality, is an important but largely unexplored question. We will present our theoretical progress towards a complete understanding of locality in long-range interacting systems, and especially how, as the interaction range shrinks, locality is recovered [1].

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Single phonon addition to thermal mechanical motion of trapped ion

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We propose schemes for generation of nonclassical motional states of a single trapped ion and present our progress towards realization of ion trapping apparatus for their experimental tests.

We analyze dynamics of red and blue-detuned spin-oscillator couplings and conditional operations of phonon subtraction and addition to the thermal state of motion. We provide estimations of observability of negative Wigner distribution in realistic experimental conditions. By driving initially excited two-level system coupled to a harmonic oscillator on a blue motional sideband and realizing projective measurement on the electronic ground state, a single excitation can be added to the state of the oscillator. Motional state becomes highly nonclassical even for initially thermal distribution and for imperfect projective measurements, which is demonstrated by large negative values of the Wigner function.

MONDAY

Quantum Computing with Ba and Yb Ion Chain

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Building a quantum computer requires individual addressing and coherently controlling qubits. Benefiting from long lived internal states and motional states, trapped ions are very good candidates for quantum computing and quantum information tasks. The ion chain with different species, reducing the crosstalk between ions, may improve the fidelity of quantum operations. Using high intensity, ultrafast laser pulse to manipulate the quantum states, the speed of quantum computing can be significantly increased. In our experiments, we trap mixed Ba/Yb ion chains in linear ion traps (macroscopic and chip-scale microfabricated), to realize basic quantum operations.

Quantum Simulation Mo-098

Ultrafast entanglement of trapped ions

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We have demonstrated ultrafast spin-motion entanglement of a single atomic ion using a short train of intense laser pulses. This pulse train gives the ion a spin-dependent kick where each spin state receives a discrete momentum kick in opposite directions. Using a series of these spin-dependent kicks we can realize a two qubit gate. In contrast to gates using spectroscopically resolved motional sidebands, these gates may be performed faster than the trap oscillation period, making them potentially less sensitive to noise. Additionally this gate is temperature insensitive and does not require the ions to be cooled to the Lamb-Dicke limit. We show that multiple kicks can be strung together to create a ``Schrodinger cat'' like state, where the large separation between the two parts of the wavepacket allow us to accumulate the phase shift necessary for a gate in a shorter amount of time. We will present a realistic pulse scheme for a two ion gate, and our progress towards its realization.

Population transfer collisions involving nD Rydberg atoms in a CO_2 optical dipole trap

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There has been an increasing interest in cold Rydberg atoms over the last several years. The primary reason for this attention is that interactions between Rydberg atoms are strong and lead to many interesting and useful phenomena, which require high atomic density samples. In this work, we have loaded Rb atoms into a CO_2 optical dipole trap. After the loading, we turn off the dipole trap and excite the Rydberg state using a combination of two cw laser beams at 780 nm and 480 nm respectively. Finally, the Rydberg atoms are detected using pulsed field ionization technique. By analyzing the electrons signal, we can study the population transfer from the nD state to the (n+2)P as a function of the atomic density for $37 \leq n \leq 45$. As the atomic density increases, the excitation of the nD state saturates, suggesting the occurrence of dipole blockade. Nevertheless, the (n+2)P is quadratically proportional to the nD population. We have also investigated the role of a dc electrical field in such process. This work was supported by Fapesp and INCT-IQ.

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Aggregation of Rydberg excitations in a dense thermal vapor cell

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Interacting Rydberg atoms in dense gases are of growing interest, due to new physics enabled by the Rydberg blockade effect. Among others, strongly interacting many-body systems with Rydberg atoms were recently studied in cold atomic gases [1][2]. Here we consider a very dense gas of thermal atoms at room temperature excited off-resonantly to a Rydberg state. At a certain distance of an already excited atom the excitation of another atom is facilitated, since the interaction compensates the laser detuning [3]. This allows for the creation of Rydberg aggregates growing exponentially from their boundaries.

We present our experimental results on the creation of such Rydberg aggregates in a vapor cell. We are able to monitor the growth dynamics of the aggregates in time and extract scaling laws for the characteristic timescale. Our findings are consistent with a model based on an effective Master equation.

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Design and simulation of a cold Rydberg atom production and detection system.

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The design of an experimental system to produce and detect cold Rydberg atoms is presented. We plan to use a three-photon excitation scheme to produce nf states of atomic rubidium. The geometrical constraints imposed by the CAD design are then used in simulating programs for the parameters of the magnetic quadrupole trapping field and the shape of the intersection between the magneto-optical and the three laser beams responsible for the excitation. Simulations are also used to design the electric field applied to parallel plates that will be used for field ionization. The study of ion trajectories for the time of flight detection of the Rydberg atoms is also presented.

3-body resonant interaction in cold Cs Rydberg atoms

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Cold Rydberg atoms are a promising tool for studying few-body and many-body interaction because of their strong and long-range dipole-dipole interactions. One example is Förster resonance, a 2-body energy exchange resonance [1] analogous to FRET in biology [2].We have observed 3-body Stark-tuned resonances in a cold Cs Rydberg gas for different principle quantum number n, described by the following equation:

$3xnp_{3/2}\ m_J=1/2(m_J=3/2)\leftrightarrow(n+1)s+ns+np_{3/2}\ m_J=3/2(m_J=1/2)$.

We excite the Rydberg state via a three-photon excitation starting from a Cs MOT, tuning the resonance with an external electric field [3]. This new FRET process could be used to design a 3-Qbit quantum gate or to provide an effective Quantum Non Demolition measure of entanglement between 2 atoms, measuring the 3rd. It could improve imaging techniques in biology that already use 2-body FRET [2] and new solar cell technology which already tries to mimic light-harvesting that is ruled by FRET.

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MONDAY

Quantum simulations of biochemical processes with Rydberg atoms

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Excitation transport through resonant dipole-dipole interactions is a fundamental feature that is shared by arrays of ultra-cold Rydberg atoms and biological light-harvesting complexes. This can be exploited twofold:

Firstly, we show that quantum simulations of light-harvesting processes are possible with an aggregate of Rydberg atoms embedded in- and monitored by a background cold gas [1]. Determining the location of excitation energy in the system decoheres quantum excitation transport. We thus can engineer an open quantum system with tuneable environment coupling and disorder.

Secondly, novel quantum coherent energy transport schemes can be devised in the simple atomic system, that might then be generalisable to the more complex light-harvesting devices. The inclusion of atomic motion naturally provides adiabatic excitation and entanglement transport. Different geometries allow the creation of artificial conical intersections and transport switches [2]. We then consider whether the processes uncovered may hold relevance for real biological systems [3].

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Molecular alignment measured with photoelectron ionization yields

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We studied the rotational wavepacket evolution of linear molecules aligned by a femtosecond laser pump pulse with detection of electron photoionization yields produced by a variably delayed probe pulse. The same experimental setup was used as was previously employed for above-threshold ionization (ATI) measurements [1]. The temporal evolution of the photoelectron yields as a function of the probe pulse delay was measured for linearly or circularly polarized pump pulses, and revivals of the rotational wavepacket were observed in O_2 , CO, and C_2H_2 gases. It is shown that this new method based on detection of photoelectrons is versatile and sensitive and opens new possibilities in studies of a field-free molecular alignment in addition to common approach that uses ion yields for the detection.

This work was supported by the by the Robert A. Welch Foundation grant No. A1546 and the Qatar Foundation under the grant NPRP 5-994-1–172.

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Investigating (*R*)-3-methylcyclopentanone Conformers using Temperature Dependent Raman Spectroscopy

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Recorded temperature dependent Raman spectra of neat (*R*)-3-methylcyclopentanone (*R*3MCP) over the Raman active C-H stretch region (2850 – 3000 cm^{-1}) are being employed to determine conformer energy difference ($\Delta H° = 4.83 \pm 0.45$ kJ/mol) between *R*3MCP equatorialand axial isomers [1]. Upon comparison with spectra obtained at room temperature, crystalline *R*3MCP Raman spectra recorded at liquid nitrogen temperature (~77 °K) are being utilized to assist identifying Raman vibrational modes rising due to *R*3MCP equatorial and axial conformers [2]. Correspondingly, DFT calculations (correlation function type B3LYP using a moderate 6-31G* and large aug-cc-pVDZ basis sets) are also manipulated to obtain highly resolved Raman spectra for the optimized geometries of equatorial and axial conformers which are also used to help identify vibrational modes rising due to each conformer [3]. Reported calculated spectra of the individual *R*3MCP conformers are shown to have good agreement with corresponding experimental Raman spectra.

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Time-sliced 3D momentum imaging of photofragmentation H_2^+

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The photofragmentation of H_2^+ was investigated with 800nm, 50fs laser pulses by employing a time-sliced 3D imaging technique that enables the measurement of all three momentum components P_X, P_Y, P_Z , which are linearly related with the pixel position and the slicing time, simultaneously for each individual product particle arriving at the detector. This allows us to measure the three-dimensional fragment momentum vector distribution without having to rely on mathematical reconstruction methods, which also require the investigated system to be cylindrically symmetric. We experimentally reconstruct the laser-induced photofragmentation of H_2^+. In most experiments, neutral molecules are used as a target, but in this work, using molecular ions, already prepared by an electric discharge, provides well-defined starting conditions and allows experiments at lower intensities.

This work was supported by the Robert A. Welch Foundation Grant No. A1546 and the Qatar Foundation under the grant NPRP 5-994-1-172.

A new method to measure photoexcitation cross-sections with a Gaussian laser beam questions the photodetachment cross-section of H^-

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A new method based on the expected behavior of the signal in the saturated regime, is described to measure photoexcitation cross-sections when a Gaussian light beam is used. The method is implemented on a negative ion beam, with a single-mode pulsed Nd:YAG laser (1064 nm), to provide the first laser measurement of the photodetachment cross-section of H^-. This cross-section is of primary importance both as the photodetachment cross-section of the most elementary negative ion and as a key parameter for the production of fast neutral H and D atoms, for plasma heating by photodetachment from accelerated ions. The obtained value 4.5(6) x 10^{-21} m^2 is greater than the one known from ancient measurements and most ab initio calculations.

Weakly bound $^{87}Rb_2(5s_{1/2}+ 5p_{1/2})1_g$ molecule: Hyperfine interaction and improved LeRoy-Bernstein analysis including nonlinear terms

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Data on $(5s_{1/2} + 5p_{1/2})$ $1_g{}^{87}Rb_2$ state under the D_1 limit, provided by a photoassociation experiment on cold atoms, have been analyzed by an improved LeRoy-Bernstein (LRB) approach including non-linear terms and provides a c_6 value of the asymptotic potential. To do that, using a model for hyperfine structure shifts, we have first subtracted the hyperfine effects observed by splitted lines and deduced the vibrational energies of each level. Then, we have compared three LRB type models to fit the data. We conclude that the next improved LRB ones is well appropriate and allows us to deduce an experimental value of c_6 (c_6=(15.14±0.05)×10^4 a.u.) [1].

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Observation of the $X^1\Sigma^+$ and $C^1\Sigma^+$ States of NaD Molecules

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Using pulsed optical-optical double resonance fluorescence depletion spectroscopy, the $X^1\Sigma^+$ and $C^1\Sigma^+$ states of gaseous sodium deuteride molecules have been observed and characterized. The vibrational quantum numbers of the ground $X^1\Sigma^+$ state are found from 11 to 19 by the technique of stimulated emission pumping. By comparing the theoretical calculations and utilizing the isotope-shift effect, the absolute vibrational numbering is primarily determined and the observed vibrational quantum numbers are from 10 to 57. However, the calculated potential curve of the $C^1\Sigma^+$ state shows a double-well, the rovibrational levels within the energy regime of the adiabatic double wells display irregularly in energy positions.

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Resonance transition in atoms passing through a magnetic grating

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We study atomic spin resonance in a rubidium beam obliquely incident on a magnetic transmission grating. The atoms experience a periodic perturbation from the grating as they pass through it. The magnetic resonance transition occurs when a perturbation frequency matches the transition frequency. The magnetic grating is made by vapor-depositing magnetic material, Co-CoO, on a polyimide film, which has multiple 150- μm-wide slits separated from each other by 150 μm. This magnetic grating is relatively easy to be miniaturized, and may lead to a new type of “optics” for velocity-selective manipulation of atoms through the transition between magnetic sublevels. We have found a strong dependence of resonance spectra on whether the magnetization direction of the film is parallel or perpendicular to the surface.

Lifetime of a Spin State in an Isolated Rydberg Ion

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Forbidden transitions in metastable atomic states are useful in frequency standards and measurements of fundamental constants. Some potential applications for cosmology, atomic clocks, and quantum information are being explored in highly-ionized atoms [1]. An experimental technique has been developed recently at NIST to study forbidden transitions in multiply ionized atoms at low energy. Ions extracted from an ion source are selectively captured in a palm-sized Penning trap, isolating the charge state of interest at ~100 times lower energy within 1 ms. The radiative lifetime is measured by photon counting of spontaneous emissions from the stored ions. For the case of decay via spin-flip (M1) transition in Kr^{17+}, a relativistic Rydberg atom, various theoretical predictions are in agreement with the result of this technique at the 1% level [2]. Its transition probability has a remarkable lack of sensitivity to configuration mixing that is useful for tests of higher-order QED.

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Non-Resonant Correlation Spectroscopy in Cold Atoms: Extracting the Correlation Information of Light Sidebands

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In some of our previous work [1, 2], we have explored the noise correlation spectroscopy for laser fields under electromagnetically induced transparency condition in cold atomic ensembles. In all those studies, one of the lasers is always kept in atomic resonance and other is scanned around the resonance. We extend the analysis to the non-resonant cases of the fixed beam, coupling Zeeman transitions in $5S_{1/2}(F=1)$-$5P_{3/2}(F`=1)$ of Rb^{87}. Besides the asymmetric correlation spectra, where one can switch from correlation to anti-correlation or vice-versa just by changing the laser frequency, we could get the correlation information of sidebands of the lasers. The role of analysis frequency for extracting the sidebands is highlighted as well. We observe that in the resonant case, correlation is dominated by the carriers and contribution from sidebands is suppressed. Our experimental findings are supported by a theoretical model based on conversion of phase noise to amplitude noise [3].

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Driving Rydberg-Rydberg transitions with an amplitude-modulated optical lattice

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We demonstrate a novel spectroscopic method that couples Rydberg states using an amplitude-modulated optical lattice. The method is fundamentally different from typical microwave spectroscopy: it engages the A^2-term rather than the Ap-term of the atom-field interaction Hamiltonian[1]. The method allows us to drive microwave transitions between Rydberg states with optical spatial resolution, and it is not subject to the usual electric-dipole selection rules (i.e., higher-order transitions are driven in first-order time-dependent perturbation). In the experiment, cold rubidium Rydberg atoms are excited and confined in an optical lattice of wavelength 1064nm using the ponderomotive force[2]. The $58S_{1/2}$-$59S_{1/2}$ transition is driven in first-order by modulating the intensity of the optical lattice using a tunable electro-optic fiber modulator. Maximum population transfer occurs at a lattice modulation frequency of 38.76861(1) GHz, in agreement with calculations. We display experimental results of this new lattice modulation spectroscopy.

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Towards multi-photon Raman scattering with higher excited levels of rubidium atoms in a warm ensemble

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Raman scattering in warm atomic vapors is a serious candidate for a robust light-matter interface. One possible scheme would consist of the generation of quantum information via Stokes scattering, its storage in the ground state atomic coherence and subsequent retrieval via anti-Stokes scattering.

However, intrinsic properties of atoms also lead to generation of light by many incoherent processes that cannot be spectrally separated. Our proposal is to include more levels of rubidium atom in the process, and use the diamond configuration [2,3] instead of the well-known Λ configuration. Such a system will enable us to generate quantum light at the wavelength significantly different than any Raman pump wavelength, thus greatly reducing the problem of spectral separation.

On the poster we will present theoretical results concerning four-photon Raman scattering in the diamond configuration, as well as our experiment on four-wave mixing with the abovementioned, previously undescribed, diamond configuration.

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Probe-intensity dependence of velocity-selective polarization spectroscopy at the rubidium D_2 manifold

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This work shows the effect of a strong, circularly polarized coupling beam on a probe beam locked to a hyperfine transition of the rubidium D_2 manifold [1]. We present experimental spectra for co- and counter-propagating beams and a rate equation calculation that does not neglect the probe beam intensity. Absorption and polarization spectra for both configurations are well reproduced by the calculation. The effect of the probe beam intensity is studied in detail in the counter-propagating configuration. Saturation and power broadening effects are observed, with different saturation intensities for each atomic line. Our analysis allows us to estimate the effective probe beam saturation intensity. In both configurations, the polarization spectra produces dispersion features ideal for locking the frequency of the coupling beam to well identified resonant frequencies. The dispersion profile slopes increase with the intensity of the probe beam, which can then control the gain of the locking device.

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Methods for Characterizing the Dispersion of Passive Optical Cavities using a Femtosecond Optical Frequency Comb

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Passive optical cavities are frequently used with optical frequency combs in order to perform broadband trace gas detection. However, group delay dispersion (GDD) from the cavity mirror coatings reduces the optical bandwidth that can be simultaneously coupled into the cavity. As the cavity finesse increases to improve the sensitivity of absorption measurements, this bandwidth reduction becomes more severe. For a finesse of 15000, GDD of 1fs^2 halves the useful bandwidth transmitted through the cavity.

Characterization of the cavity dispersion is performed by scanning the relative frequencies of the comb and cavity modes whilst recording the time delay between different parts of the optical spectrum resonating with the cavity. This is achieved by dithering the cavity length[1], or the frequency offset of the comb using an acousto-optic modulator. We compare these two approaches, as well as examining the use of Optical Vernier Spectroscopy[2] to measure dispersion with higher spectral resolution.

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Coherent interactions between matter and radiation in neutral hydrogen clouds in the interstellar medium

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We investigate the possibility of coherent interactions between matter and radiation in neutral hydrogen (HI) clouds in the interstellar medium (ISM), with the goal of determining their impact on the measurement of the abundance of atomic hydrogen. Hydrogen is the most abundant species in the Universe, and the precise measurement of its density has a significant impact on our understanding of the universe. It is usually assumed that the interaction between matter and radiation is fully non-coherent in the ISM, and hydrogen abundances are calculated with this assumption. We reexamine this assumption by adapting Dicke's coherence formalism [1] to different sets of initial conditions in HI clouds in the interstellar medium and determining the intensity equation in different ensembles of atoms. We compare this intensity relation with the one calculated by the non-coherent radiation model, and discuss the order of potential corrections in the abundance measurements. In the study of coherent interactions, we have derived the Maxwell-Bloch equations for an ensemble of N hydrogen atoms interacting with the 21 cm magnetic dipole transition in the electronic ground state of the hydrogen atom. This set of equations is then solved numerically and the possibility of limited superradiance and coherence is investigated.

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Sensitivity improvements to the YbF electron electric dipole moment experiment

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We present a series of improvements to the preparation and detection of YbF molecules in our supersonic molecular interferometer [1]. Combined with existing improvements these will allow a ninety-fold reduction in the statistical uncertainty of our measurement of the electron's electric dipole moment (EDM), enabling us to search for an EDM below the recent upper limit of $8.9*10^{-29}$ e.cm [2]. Using laser, microwave and rf fields, we propose to pump more YbF molecules into the ground state, where they can participate in the experiment. In the detection region we plan to use techniques developed for molecular laser cooling to dramatically increase the number of scattered photons, and to use improved collection optics. Some of these techniques will also be used in the YbF fountain [3]. With this more sensitive interferometer, we will be able to continue the search for physics beyond the Standard Model.

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Improved Limit on the Electric Dipole Moment of the Electron

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The ACME collaboration has measured the electron's electric dipole moment d_e with unprecedented precision. We find d_e = (-2.1+-3.7$_{stat}$ +-2.5$_{syst}$)*10^-29 e cm [1, 2], which corresponds to an upper limit of d_e < 8.7*10^-29 e cm with 90 percent confidence. This result represents an order of magnitude improvement upon the previous best limit [3]. We describe our method of measuring d_e using a buffer gas cooled beam of thorium monoxide (ThO) and our approach to finding and quantifying systematic effects. We also discuss some of the implications of this result for fundamental physics beyond the Standard Model.

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Measuring the Electron Electric Dipole Moment with Trapped Molecular Ions

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Molecular ions in a radiofrequency trap are well-suited to measurements of the electron electric dipole moment (eEDM) due to their long coherence times. Our experiment focuses on the metastable $^3\Delta_1$ state of HfF^+, confined in a Paul trap with superimposed rotating electric and magnetic bias fields. We have measured the lifetime of this state to be 2.1(1) s, providing the ultimate limit to our possible coherence time. We have demonstrated the ability to state-selectively transfer population to the desired $^3\Delta_1$ J=1 state and to efficiently measure the population in single spin states using photodissociation. With these techniques, we performed eEDM-sensitive Ramsey spectroscopy in a rotating bias field with up to 400 ms coherence time and two counts per shot. We identify two decoherence mechanisms, bias field spatial inhomogeneity and ion-ion interactions.

Mercury Monohalides as Candidate Molecules for Electron Electric Dipole Moment Searches

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The possible existence of the electron electric dipole moment (eEDM) can lead to important insights into new physics beyond the Standard Model, and the matter-antimatter asymmetry of the Universe. Certain polar molecules are considered to be the best candidates for eEDM experiments, because of their large internal electric fields. The determination of the eEDM requires a combination of experimental measurements, and calculation of the molecule's internal electric field. Using relativistic many-body theory, we have established that the internal electric fields in the ground states of mercury monohalides are substantially larger than those in ThO (the molecule that leads to the current best limit on the eEDM) and YbF. In addition to their large internal electric fields, these molecules also have properties that are advantageous for experiments. This suggests that mercury monohalides are promising candidates for eEDM search experiments.

Precision Experiments with Multiply-ionized Atoms in Compact Ion Traps

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Highly charged ions have recently been isolated at low energy in compact Penning traps [1], facilitating a variety of spectroscopic studies of interest in atomic physics and metrology—such as the possibility of new atomic frequency standards [2]. One application is the study of charge-exchange (electron capture) processes using fully-stripped ions isolated at low energy. Another application involves the production and formation of low-Z, one-electron ions in high angular momentum states that are favorable for measuring fundamental constants [3]. We report on the development of a miniature electron beam ion trap (EBIT) with an attached rubidium beam oven to allow charge exchange between laser-excited Rydberg rubidium atoms and isolated bare nuclei to form one-electron ions in Rydberg states. Optical comb-based spectroscopy of such ions could provide an independent determination of the Rydberg constant [3] to help resolve the discrepancy in the proton charge radius measurements [4].

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Precision spectroscopy of atomic hydrogen for a new determination of the Rydberg constant and the proton charge radius

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The ‘proton size puzzle’ , i.e. the seven standard deviations discrepancy of the values for the proton r.m.s. charge radius extracted from hydrogen spectroscopy and elastic electron-proton scattering on the one hand and muonic hydrogen on the other hand, exists for more than three years now [1]. Still, no convincing solution to the discrepancy could be found so far. Here, we report on a new precision spectroscopy experiment, aiming to shed light on the regular hydrogen part of the puzzle: our measurement of the 2S – 4P transition frequency is the first experiment of its kind being performed on a cryogenic beam of hydrogen atoms in the 2S state [2]. We will show how this helps to efficiently suppresses leading order systematic effects of previous measurements and discuss our recent progress towards an improved determination of the Rydberg constant and the proton charge radius from high resolution spectroscopy of electronic hydrogen.

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Progress on a separated-oscillatory-field microwave measurement of the n=2 Lamb shift of atomic hydrogen

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Recent measurements of the n=2 energy separations in muonic hydrogen lead to a determination of the proton charge radius which differs from that obtained from spectroscopy in ordinary hydrogen by 7 standard deviations. We are in the process of measuring the n=2 Lamb shift of hydrogen to shed light on this discrepancy. The measurement is performed using metastable hydrogen atoms obtained from charge exchange between 50-keV protons and a neutral gas. Separated oscillatory fields are used to narrow the 100-MHz natural linewidth of the 2S-2P transition. A high signal-to-noise ratio is obtained by quenching the metastable atoms in an electric field and observing the resulting Lyman-α photons in a large-solid-angle photoionization detector.

We acknowledge funding from NSERC, CFI, CRC, ORF, and NIST.

Unshielded Radio-Frequency Magnetometer

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Tunable radio-frequency atomic magnetometers show promising potential as a means of detecting low-field magnetic resonance signals, for instance in substance detection by nuclear quadrupole resonance; however, previous results were obtained from magnetometers within mu-metal and radio-frequency shielding, impractical for field applications. We demonstrate a sensitivity of 0.6 fT/Hz$^{1/2}$ and a Q of 630 at 0.42 MHz without mu-metal shielding using magnetic coils and automatic shimming to compensate for earth's field. By using spatially separated magnetometers (two voxels within the same cell) as a gradiometer, sensitive to local sources, we observe interference rejection with a ratio of 1-2 orders of magnitude in a partially unshielded configuration. We are currently limited by slight mismatching of the resonance frequencies and T_2's between the two voxels, but will address how to handle this with more precise calibration and post-processing. The goal is to extend these results to a completely unshielded setting.

Experimental Test of Quantum Jarzynski Equality with a Trapped Ion

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We report on the experimental test of the quantum Jarzynski equality. The Jarzynski equality connects work done on the system to the free energy difference of the corresponding equilibrium states even through a non-equilibrium process [1]. While many experimental tests of Jarzynski equality have been performed in classical regime, the verification of the quantum version has not yet been fully demonstrated due to experimental challenges [2]. We perform the experimental test with a trapped Yb171+. We first prepare the initial thermal states of motion and we apply the laser induced force to the ion. This forces rise to the fixed maximum in different speeds ranging from quasi-static to far-from equilibrium. By projecting the initial phonon thermal state to phonon Fock state and measuring the transition probability to the different finial phonon energy states, we get the dissipated work distribution. For all these protocols, our experiment results show the Quantum equality is valid.

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Free Spin Precession as a Tool for Testing Fundamental Physics

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In the free precession of nuclear magnetic moments, any non-magnetic spin interaction will add a shift to the corresponding Zeeman splitting. In spin clocks, employing simultaneously two nuclear species, the Zeeman interaction is eliminated. This makes spin clocks a powerful tool in the search of symmetry breaking phenomena in physics. Examples of such searches include the axion particle, electric dipole moment of electron or atoms, and the Lorentz invariance violation. The sensitivity of these spin-clock based precision measurements ultimately relies on how accurate the precession frequency of the signal can be determined. There exists a statistical lower-bound in such a frequency estimation regardless of the measuring and estimating procedures adopted. We show here the evaluations of such minimum variances in case of a finite spin coherence time and compare it with our experimental data obtained by SQUID detectors.

NEW EXPERIMENTAL AND THEORETICAL TECHNIQUES

New Experimental and Theoretical Techniques Mo-128

High-Performance Parallel Solver for 3D Time-Dependent Schrodinger Equation for Large-Scale Nanosystems

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A parallelized three-dimensional time-dependent Schrodinger equation (TDSE) solver for one electron systems is presented in this paper. The TDSE solver is based on finite-difference method in Cartesian coordinates and uses simple explicit leap-frog numerical scheme. This simplicity provides very efficient parallelization and high performance of calculations using graphical processing units (GPUs). E.g. calculation of 106 time-steps on the 1000x1000x1000 numerical grid takes only 16 hours on 16 Tesla M2090. The TDSE solver demonstrates scalability (parallel efficiency) close to 100% with some limitations on the problem size. The comparison with other TDSE solvers shows that GPU based TDSE solver is 3 times faster for the problems of the same size and the same cost of computational resources, this benefit can be increased up to 10 times using problem-specific non-Cartesian coordinates. The TDSE solver was applied to the calculation of the resonant charge transfer during H^+ - H^0 collision.

New Experimental and Theoretical Techniques Mo-129

Time of Flight Mass Spectrometer for Molecular Ion Trapping

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A time of flight mass spectrometer is implemented for a linear quadrupole trap which allows for measurement of trapped-ion reaction rates with background gasses, introduced buffer gasses, and co-trapped species. Measurements of the decay rate of SrF^+through various modes demonstrate the viability of the technique.

Coherent Stern–Gerlach momentum splitting on an atom chip

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In the Stern–Gerlach effect, a magnetic field gradient splits particles into spatially separated paths according to their spin projection. The idea of exploiting this effect for creating coherent momentum superpositions for matter-wave interferometry appeared shortly after its discovery, almost a century ago, but was judged to be far beyond practical reach. Here we demonstrate a viable version of this idea [1]. Our scheme uses pulsed magnetic field gradients, generated by currents in an atom chip wire, and radio-frequency Rabi transitions between Zeeman sublevels. We transform an atomic Bose–Einstein condensate into a superposition of spatially separated propagating wavepackets and observe spatial interference fringes with a measurable phase repeatability. The method is versatile in its range of momentum transfer and the different available splitting geometries. These features make our method a good candidate for supporting a variety of future applications and fundamental studies.

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Phase space tomography using an atom chip with random and engineered fragmentation potentials

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We demonstrate tomographic reconstruction of the phase space distribution of atoms oscillating in a harmonic trap with weak potential corrugation caused by nano-scale imperfections in an atom chip wire [1]. Deformations of these distributions – explained in terms of angular velocity dispersion of iso-energetic phase space trajectories – are highly sensitive to anharmonic components of the potential. This method may be important for characterizing future devices based on trapping and guiding atoms.

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Injection locking of a high power ultraviolet laser diode for laser cooling of ytterbium atoms

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We have developed a high-power light source at 399nm for laser cooling of ytterbium atoms with an ultraviolet laser diode by using injection-locking. So far, the output power of a laser diode system was limited to 80mW[1] for this wavelength. We implemented an injection-locking system of a high power laser diode (NICHIA NDV4B16) and obtained 220mW of output power.

The output wavelength of the slave laser diode was originally centered at 402nm and was shifted to 399nm by decreasing the chip temperature to -16 degrees. In order to avoid condensation, the box was purged with nitrogen gas. 5mW of master laser source was prepared by using a frequency-doubled CW Ti:S laser. This light source can be used for Zeeman slowing, magneto-optical trapping[2], and transverse two-dimensional cooling of ytterbium atoms[3]. In the poster, we will present the systematic method for aligning the injection-locking using a Fabry-Perot interferometer.

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A deterministic laser-cooled source of single Si ions for solid state qubits

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An all solid state, scalable quantum computer architecture proposed by Kane[1] utilizes P dopants in Si as qubits. The major difficulty is the placement of a single qubit with nanometer precision. Laser cooling and trapping a single atom, followed by resonant photo-ionization at threshold, provides a deterministic source of a single ion which may be deposited at low energy to meet the stringent spatial demands.[2] There is no cw laser for direct manipulation of P. However, ^{31}Si beta decays to ^{31}P, and has a cooling wavelength at 221.74 nm which is achievable with a frequency quadrupled Ti:Sapphire laser.[3] In our laboratory the cooling and repump lasers, Si atomic beam with a novel Zeeman slower[4], Te_2 and I_2 frequency references and optics to detect fluorescence from single atoms for a magneto-optic trap have been developed and investigated. Progress of this research will be reported.

Work supported by the W.M. Keck Foundation.

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New Experimental and Theoretical Techniques Mo-134

Room-Temperature Microwave Saturation Spectroscopy of Nitrogen-Vacancy Ensembles in Diamond

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The nitrogen-vacancy (NV) color center in diamond has generated much recent interest for use in quantum information and sensing. The NV ground-state microwave transitions suffer from inhomogeneous broadening, which limits the achievable sensitivity and coherence time, especially in high-density NV ensembles. To better understand and remove the sources of broadening, we performed saturation spectroscopy of the NV microwave transitions. We show that the inhomogeneous broadening comes primarily from differences in magnetic field from nearby spins, and we demonstrate that saturation spectroscopy is useful for magnetic-field-insensitive NV thermometry.

MONDAY

Diamond Magnetometry of Superconducting Thin Films

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In recent years diamond magnetometers based on the nitrogen-vacancy (NV) center have been of considerable interest for applications at the nanoscale. An interesting application which is well suited for NV centers is the study of nanoscale magnetic phenomena in superconducting materials. We employ NV centers to interrogate magnetic properties of a thin-layer yttrium barium copper oxide (YBCO) superconductor [1]. Using fluorescence-microscopy methods and samples integrated with an NV sensor on a microchip, we measure the phase transition temperature and the penetration field of vortices, and observe pinning of the vortices in the layer. These measurements are done with a 10 nm thick NV layer, so that high spatial resolution may be enabled in the future. Based on these results, we anticipate that this magnetometer could be useful for imaging the structure and dynamics of vortices with the hope of contributing new experimental insight to the open question of high Tc superconductors.

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A single frequency tunable laser near 1000 nm for spectroscopic applications

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We have built a tunable single frequency laser using the master oscillator power amplifier (MOPA) configuration. The laser has an output power over 1 W in the spectral range from 990 nm to 1030 nm. For further applications, the laser will be used to study the optogalvanic spectroscopy of the atomic neon and Doppler-free two-photon spectroscopy of the He $2^1S_0 \rightarrow 3^1D_2$ transition as well as used to excite atomic potassium from the ground state 4S through the 5P state to the highly lying Rydberg state nS (n > 20) for studying the ultracold potassium Rydberg atoms.

ATOMIC CLOCKS

Hyperfine structure in $^{229g}Th^{3+}$ as a probe of the $^{229g}Th \rightarrow ^{229m}Th$ nuclear excitation energy

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We describe a potential means to extract the $^{229g}Th \rightarrow ^{229m}Th$ nuclear excitation energy from precision microwave spectroscopy of the $5F_{5/2,7/2}$ hyperfine manifolds in the ion $^{229g}Th^{3+}$. The hyperfine interaction mixes this ground fine structure doublet with states of the nuclear isomer, introducing small but observable shifts to the hyperfine sub-levels. We anticipate that accurate atomic structure calculations may be combined with measurements of the hyperfine intervals to quantify the effects of this mixing. Further knowledge of the magnetic dipole decay rate of the isomer, as recently reported, allows an indirect determination of the nuclear excitation energy.

A search for ultra-low energy nuclear isomer state of Thorium-229 -- New method using synchrotron radiation X-ray source--

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Thorium-229 has been known for its extreme low energy isomer state. The recent indirect measurement of the energy level (~7.8 eV) implied that it could be excited with laser light and many experimental techniques related to atomic- and molecular-physics could be adapted. Since the nucleus is shielded by core electrons and relatively insulated from the influence of its external field, it attracts a lot of interest from many fields, e.g. atomic clock, fundamental physics, and etc. However, no direct evidence of excitation/de-excitation signal of thorium-229 isomer state was achieved so far.

Aiming to adopt this system as a target system for neutrino mass spectroscopy, we proposed to search for the isomer state directly using intense X-ray source. In this conference, we will describe the new search method and report recent result of the pilot experiment using naturally abundant thorium-232 at spring-8, synchrotron radiation facility.

Towards a measurement of the nuclear isomer transition in Thorium-229

Simon Stellmer[1, 2], Georg Winkler[1], Matthias Schreitl[1], Georgy Kazakov[1], Enikoe Seres[1], Joszef Seres[1], Thorsten Schumm[1, 2]

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The ^{229}Th nucleus is unique as it possesses an extremely low-lying isomer state. Its energy is expected to be about 7.8 eV [1], corresponding to a transition into the nuclear ground state of 160 nm. This transition has been proposed for a nuclear clock, which would be largely immune against perturbations of the environment [2]. The transition frequency might be highly sensitive to drifts in fundamental constants. A direct evidence of this transition, however, is still pending.

We follow two approaches to confirm the existence of the isomer state and determine its energy. The first approach employs a magnetic micro-calorimeter with supreme resolution. We record the spectrum of gamma photons originating from the decay of excited nuclear states, aiming to resolve the ground state doublet structure.

In a second approach, we directly excite the isomer transition using VUV light around 160nm. The ^{229}Th atoms are embedded into a VUV-transparent CaF_2 host crystal, and we measure its fluorescence as the laser is scanned across the resonance.

We report on the current status of these experiments.

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Search for optical excitation of the low-energy nuclear isomer of Th-229

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Direct optical excitation of the nuclear transition between the ground state and the 7.8 eV isomer in Th-229 is the missing link towards a study of this system as a precise nuclear clock. We plan to use two-photon laser excitation via electronic bridge processes in Th^+ [1]. In resonant two-step laser excitation of trapped Th^+ ions, we observe 43 previously unknown electronic energy levels within the energy range from 7.3 to 8.3 eV [2,3]. The high density of states promises a strongly enhanced nuclear excitation rate. Using laser ablation loading of the ion trap and photodissociation of molecular ions that are formed in reactions of Th^+ with impurities in the buffer gas, we now efficiently load and stably store ions of the radioactive Th-229 isotope. We have measured the hyperfine structure of the 402 nm resonance line and have started a search for the nuclear resonance over the presently wide wavelength uncertainty range.

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^{229}Th and ^{232}Th Optical Spectroscopy System for Nuclear Frequency Standard

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The results are presented on comparison of different techniques of producing thorium ions: from solid $Th(NO_3)_4$ and ThO_2 compounds by laser ablation, from nitrate solution of ^{229}Th and ^{232}Th by inductively coupled plasma mass-spectrometry, and also from metallic thorium by electron-beam evaporation.

The electron-beam evaporation technique provides a basis for the high-resolution optical spectroscopy system developed at MEPhI, Moscow. This system allows performing the following tasks:

to form a mass selective beam of singly and triply charged $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions with mass resolution better than 1 amu;

to capture and hold multiply charged $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions coming from the mass selective ion source with energy between 1 to 500 eV, in RF quadrupole linear ion trap;

to cool trapped $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions in buffer gas atmosphere to room temperature;

to proceed to high-precision research on optical and nuclear isomeric emission and absorption spectra of ^{229}Th isotope.

Improving atomic clocks using coherence preserving measurements

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Atomic clocks have reached stabilities at the 10^{-18} level thanks to a tremendous progress in the development of ultra-stable optical local oscillators (LOs). Nevertheless, the decoherence source represented by noise of the local oscillator still limits the clock stability. We want to remove this limitation using coherence preserving measurements of the atom-LO phase, to achieve longer effective interrogation times. We implemented a non-destructive frequency modulation detection for the measurement of the number difference on the ^{87}Rb clock transition. With this probe we could observe the real time evolution of a collective spin and correct it using feedback [1].

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Development of an ultra-stable universal synthesiser for state-of-the-art frequency metrology

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Technical details and evaluation results will be presented from a new femtosecond comb system being developed at NPL to act as a 'universal synthesiser' for high accuracy frequency metrology. This concept allows multiple frequency standards to benefit from the stability of a single 'master oscillator', currently a Nd:YAG laser stabilised to a 30 cm-long ULE cavity with fused silica mirrors and projected thermal noise of $1x10^{-16}$. A multi-branch fibre comb simultaneously transfers the stability of the master oscillator to the microwave domain and to several optical frequencies. The microwave signal will be used for interrogation of the NPL Cs fountains, promising quantum projection noise limited performance. The optical frequencies, designed for 10^{-16} level stability at 1 s, correspond to clock transitions in the Yb^{+}, Sr^{+} and Sr optical frequency standards at NPL. A 1.5 µm branch also allows remote comparison of these standards with those in other laboratories over telecom fibres.

Towards Optical Clocks and Coherent Frequency Transfer in Sweden

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Within SPs commitment as a National Metrology Institute (NMI), a program towards optical clocks and coherent frequency transfer are being initialized. With the aid from Swedish Post and Telecom Authority (PTS), we have recently been able to equip a new laboratory with an optical frequency comb and an ultra-stable laser from Menlo Systems.

With this equipment as a foundation, SP are now working towards an optical lattice clock based on strontium atoms. The system will be built with the aim of being robust and easy to upgrade. The hope is that the system will be a future Swedish frequency reference and a source for frequency transfer over optical fiber. Even without a fully operational clock, the ultra-stable laser will allow for testing frequency transfer methods way below the 10^{-13} level.

The poster will present the research program in more detail, the current status, and our future plans within the field.

TACC - Trapped Atom Clock on a Chip

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Trapped atoms have grown in importance for atomic clocks and atom interferometers. Besides optical lattice clocks, devices for in-the-field application benefit from the reduced volume combined with high sensitivity. Here, chip-scale devices are particularly appealing. Operating a clock with ^{87}Rb trapped on a microchip [1], we evaluate the performance of such systems under metrology conditions. At ultra-low temperatures, we have observed spin self-rephasing and 58s coherence time [2]. Spectroscopy has revealed the underlying energy gap between pair-wise singlet and triplet states due to s-wave interaction [3].

Here we present the clock stability of 6 10^{-13} at 1s and 6 10^{-15} at 30 000s. The absolute clock frequency shows an evolution with Ramsey time, which we model using the spin self-rephasing mechanism. We identify a range of parameters presenting particular advantages to the clock operation. Our findings apply to any trapped atom sensor and may impact quantum information processing.

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Compact Frequency Standard with Cold Atoms: Transportable System

Stella Torres Müller[1], Rodrigo Duarte Pechoneri[1], Jair de Martin Júnior[1], Caio Bueno[2], Andres David Rodriguez Salas[2], Vanderlei Salvador Bagnato[2], Daniel Varela Magalhães[1]

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The theoretical and experimental knowledge acquired with other standards are now employed in the development of a mobile atomic frequency standard based on cold sample of cesium atoms.

The basic principles shown previously allow us to build a new model of atomic clock with the cold cloud expanding inside a cylindrical microwave cavity. The operation of this experiment is different from conventional cold atoms fountains, since all the steps are sequentially performed in the same place. In addition to this main characteristic, this new model is suitably compact to allow several applications, where all the essential parts are being coupled in a single metal block. All these parts (cavity, lasers, microwave chain, vacuum chamber and control system) require mechanical and electrical stability, and an efficient vacuum. The metal block addition to provide mechanical stability to the system will also obtain the thermal stability necessary for the microwave cavity and lasers.

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Decoherence time of Ramsey fringes observed in a cesium atomic fountain clock

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The Ramsey fringes of the cesium atomic fountain clock NMIJ-F2 were analyzed rigorously as a function of the interefence time from 0.1 s to 0.7 s, which was adjusted by changing the velocity of the launched atoms. The obtained fringes were fitted by the function of the theoretical Ramsey fringes with a velocity spread. The analytical results showed that the temperature spread of the vertical direction was 1.7 μK, which corresponds to the value obtained from the measurement of time-of-flight. The visibilities of fringes as a function of the interaction times were well fitted by a function of $V(t)=V(0)\exp[-g(t)t]$, where $g(t)$ is the decay rate that is proportional to an atom density. The corrected decoherence time was obtained to be t_d =56 s. Such a long time will indicate that the quantization scale of gravity is longer than $3200L_P$ m where L_P is Plank length.

Half metallic antiferromagnetic ordering of cold fermions induced by resonant tunneling

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An optical superlattice enables us to simulate the Hubbard model with staggered lattice potential by widely varying the onsite interaction U and the level difference Δ. When U=Δ, the resonant tunneling drastically changes the dynamical properties of atoms providing us with an opportunity to study novel quantum magnetism. The recent experiment utilizes this tunneling mechanism to reveal the magnetic phases of the Ising model [1].

We investigate the phase diagram of the staggered Hubbard model of two component fermions using the dynamical mean-field theory. We find that the resonant tunneling induces the novel half-metallic antiferromagnetic phase, where one spin component is metallic and the other is insulating. At finite temperatures, we find the emergence of this phase at half-filling without spin imbalance. On the other hand, at T=0, this phase only appears in the region away from half-filling.

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New Quantum Simulation with Multi-component Fermi Gases

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I will report on the latest results in the Ytterbium lab at LENS where we achieved quantum degeneracy of fermionic ^{173}Yb. The specific features of this atomic element provide a powerful test bench for large-spin models ranging from quantum simulation of spinful one-dimensional (1D) systems to the realization of spin-orbit coupling in multicomponent ultracold fermions. The realization of 1D, strongly-correlated liquids of ultracold fermions interacting repulsively [1] with a tunable number N of spin components is reported. We observe that static and dynamic properties of the system deviate from those of ideal fermions and, for $N>2$, from those of a spin-1/2 Luttinger liquid. In the large-N limit, the system exhibits properties of a bosonic spinless liquid. I will also show some preliminary results and perspectives on the physics of a spin-orbit coupled multicomponent Fermi gas accessible by opportunely engineering Raman couplings between the nuclear spin components of ^{173}Yb.

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TUESDAY

Ultracold Dysprosium gases: towards a topological superfluid

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We present a new experimental setup on ultracold Dysprosium gases. The current status of the project is the realization of a magnet-optical trap using a narrow-line optical transition. Dysprosium atoms present an electronic structure suitable for obtaining synthetic spin-orbit coupling with very low heating rate compared to alkali atoms. The modification of the Fermi surface due to this artificial coupling can lead to an effective spin-polarized Fermi gas with p-wave interactions, whose superfluid phase will present topologically non-trivial features. In particular, the edge excitations associated with the superfluid phase - that can be described as Majorana's fermonic quasiparticles - are expected to be strongly localized at the boundaries of the system and to have an energy lying in the middle of the superfluid gap.

Breakdown of Landau's Fermi liquid theory in a Strongly Interacting Fermi Gas

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We present a novel measurement of the single particle spectral function for a homogeneous Fermi gas above the critical temperature throughout the BCS-BEC crossover. We observe that the dispersion can be fitted extremely well by a function composed of two parts: the spectral function of bound pairs and that of a Landau Fermi liquid (FL). We find that already at unitarity, the FL theory is largely unsuited to describe the data, which exhibits a predominantly pair-like dispersion. For diminishing attractive interactions, the spectral function converges to that expected by a FL, from which we get the effective mass of the fermionic quasiparticle. Our data reconciles different past experimental observations by showing how the many-body behavior of fermions in the BCS-BEC crossover changes from a FL to a molecular bose gas over a rather small region.

Diffusion of spin in a unitary Fermi gas

Scott Smale[1], Chris Luciuk[1], Scott Beattie[1], William Cairncross[1], Alma Bardon[1], Stefan Trotzky[1,2], Joseph Thywissen[1, 2]

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Understanding the non-equilibrium dynamics of strongly interacting particles is one of the current challenges in physics. We have investigated spin transport for a degenerate Fermi gas of 40K atoms in the unitary regime. As our initially spin polarized gas relaxes we find that to properly characterize the magnetization dynamics one must consider the Leggett-Rice spin rotation effect in addition to spin diffusion. Using a Feshbach resonance to access the unitary regime we probe our entire cloud using NMR-like spin echo sequences. We have quantified both the spin diffusion and the Leggett-Rice effect and their dependence on temperature and interaction strength.

Exploring the phase diagram of a strongly interacting 2D Fermi gas

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We present our experiments on ultracold fermions trapped in a two-dimensional potential and report on the observation of a quasi-condensate of fermion pairs. For this measurement we prepare a quantum degenerate gas of ^{6}Li atoms in the two lowest hyperfine sublevels confined in a single layer of a standing wave optical dipole trap. A magnetic Feshbach resonance allows us to tune the interaction strength in the system from the weakly to the strongly interacting regime. By using a matter wave focussing technique we obtain the radial momentum distribution of our sample and observe a bimodal distribution of a thermal cloud and a low-momentum condensate. Self-interference of the condensate indicates quasi long range phase coherence as theoretically predicted for a BKT-like phase. By measuring the condensed fraction as a function of temperature and interaction strength we map out the phase diagram of a strongly interacting two-dimensional Fermi gas.

Experimental studies of an interacting 2D Fermi Gas

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Ultracold Fermi gases allow unique insight into the behaviour of particles at the quantum level. Manipulation of parameters associated with interaction and confinement can also lead to the creation of exotic phases of matter. Specifically, 2D Fermi gases will open the way to studies of the crossover from a Bardeen-Cooper-Schrieffer to Berezinskii-Kosterlitz-Thouless superfluidity as the strength of attractive interactions are tuned via a Feshbach resonance. By application of a cylindrically focussed blue-detuned TEM01 mode laser we confine Fermi gases of lithium-6 atoms to 2D by making the vibrational states of the harmonic potential in the transverse direction energetically inaccessible compared to the radial. Here we present data showing the transition from 2D to quasi-2D in a Fermi gas with tunable interactions as well as our progress towards a precise determination of the thermodynamic equation of state.

Fermi Gases Tu-008

Production of a degenerate fermi gas of chromium

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I will present recent results we have obtained for the cooling of the fermionic chromium isotope ^{53}Cr. As for the bosonic isotope, our strategy has been to load directly in a far detuned dipole trap atoms in metastable states produced in a MOT [1]. As the fermionic MOT is disturbing the bosonic MOT [2], we first load the dipole trap with fermions, and then with bosons, before starting sympathetic cooling. We have optimized the dipole trap geometry to obtain 10^6 bosons with 3.10^4 fermions before evaporation in a crossed dipole trap.

Analysis of populations show an almost suppression of fermionic atoms losses way before the end of the evaporation ramp. Preliminary measurements indicate a large boson-fermion scattering length compatible with a bosonic assisted hydrodynamic regime for the fermions.

We obtain 10^{353}Cr atoms at a temperature of 250 nK, while the Fermi Energy is estimated at 330 nK.

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Bose Gases Tu-009

ZNG – Theory for Dipolar Quantum Gases

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We study harmonically trapped three-dimensional ultracold Bose and Fermi gases in the presence of the short-range isotropic contact and the long-range anisotropic dipole-dipole interaction (DDI). The Hartree-Fock mean-field dynamics of such quantum systems can be described within the framework of the Zaremba-Nikuni-Griffin (ZNG) theory. Usually, the underlying Boltzmann-Vlasov (BV) equation is solved by the relaxation-time approximation for the collision integral, where the relaxation time is treated as a phenomenological parameter. We develop a formalism to determine the relaxation time microscopically for ultracold quantum gases at finite temperature, which allows us to include collision effects self-consistently in the BV formalism.

TUESDAY

Bose Gases Tu-010

Dynamics of spinor condensates in a microwave dressing field

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We experimentally study dynamics in a sodium antiferromagnetic spinor condensate as a result of spin-dependent interactions c and microwave dressing field interactions characterized by the net quadratic Zeeman effect q_{net}. In contrast to magnetic fields, microwave dressing fields enable us to access both negative and positive values of q_{net}. We find an experimental signature to determine the sign of q_{net}, and observe harmonic spin population oscillations at every q_{net} except near each separatrix in phase space where spin oscillation period diverges. Our data in the negative q_{net} region exactly resembles what is predicted to occur in a ferromagnetic spinor condensate in the positive q_{net} region. This observation agrees with an important prediction derived from the mean-field theory: spin dynamics in spin-1 condensates substantially depends on the sign of q_{net}/c. This work may be the first to use only one atomic species to reveal mean-field spin dynamics, especially the remarkably different relationship between each separatrix and the magnetization, of spin-1 antiferromagnetic and ferromagnetic spinor condensates.

Non-Equilibrium Dynamics of Component Separation in a Binary Bose Gas

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Binary mixtures of atomic Bose gases provide a platform for studying rich phenomena at the interface of atomic physics, nonlinear waves and nonequilibrium dynamics, driven by the nonlinear interactions between the two species. Commonly, a single-species Bose gas is first formed and then a proportion of the atoms are coherently transferred to a second hyperfine state. This transfer, instantaneous with respect to the external gas dynamics, places the system in a nonequilibrium state. Using a classical field description, we model the formation and subsequent thermalization of this nonequilibrium state, mapping the dependence on the nonlinear interactions and the proportion of transferred atoms. In general we find that component separation leads to a reduction of condensate fraction and an associated heating of the system which, in certain regimes, can be considerable. Furthermore, we discuss the formation of topological defects - domains and vortex excitations - during these dynamics.

Bose Gases Tu-012

Nonlinear interferometric scaling from spin-mixing density oscillations

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We show that spin-dependent atom-atom interaction strengths for spin-1 atoms in an optical lattice can be measured with super-Heisenberg scaling as a function of the number of atoms per lattice site. In our proposal, a superfluid ground state in a shallow lattice is suddenly quenched by increasing lattice depth, creating a nonequilibrium state where atom-atom spin-exchange collisions drive oscillations of the different spin component populations. We show that in-situ measurements of the spin-population dynamics can yield the interaction strengths with super-Heisenberg scaling. We further explore how the scaling behavior depends on the initial ground state. Since spin-mixing density oscillations have already been observed with spin-1 atoms in a harmonic trap, demonstrating this scaling behavior should be within experimental reach.

Kinetic Model of a Finite Temperature Multi-Component Condensate

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We construct a finite temperature theory describing the out of equilibrium dynamics of two interacting Bose-Einstein condensates. This is accomplished by treating the non-condensed degrees of freedom with kinetic (Boltzmann) equations coupled to dissipative Schrödinger equations that describe the dynamics of the two condensates [1], [2]. It is shown that in comparison to a single component condensate, the additional density-density interaction between the condensates and thermal clouds facilitate a number of new transport processes, including the intra and inter-component collisional transfer of non-condensate and condensate atoms [3]. The importance of these new terms is quantified with realistic experimental parameters, by numerically calculating the collision rates for both intra and inter-component collisions.

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Bose Gases Tu-014

Mapping the phase diagram of spinor condensates via adiabatic quantum phase transitions

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We experimentally study two quantum phase transitions in a sodium spinor condensate immersed in a microwave dressing field. We also demonstrate that many previously unexplored regions in the phase diagram of spinor condensates can be investigated by adiabatically tuning the microwave field across one of the two quantum phase transitions. This method overcomes two major experimental challenges associated with some widely used methods, and is applicable to other atomic species. Agreements between our data and the mean-field theory for spinor Bose gases are also discussed.

Fast thermalization and Helmholtz oscillations of an ultracold Bose gas

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We analyze theoretically the transport properties of a weakly-interacting ultracold Bose gas enclosed in two reservoirs connected by a constriction. We assume that the transport of the superfluid part is hydrodynamic, and we describe the ballistic transport of the normal part using the Landauer-Buttiker formalism. Modeling the coupled evolution of the phase, atom number, and temperature mismatches between the reservoirs, we predict that Helmholtz (plasma) oscillations, induced by an initial imbalance in atom numbers, can be observed at non-zero temperatures below Tc. We show that, because of its strong compressibility, the ultracold Bose gas is characterized by a fast thermalization compared to the damping time for plasma oscillations, accompanied by a fast transfer of the normal component through the constriction. This fast thermalization also affects the gas above Tc, where we present an explicit comparison to the ideal fermionic case.

BEC dynamics with solitons and vortices

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Bose-Einstein Condensates (BEC) are excellent macroscopic systems to observe the quantum behavior of matter. Since its experimental production [1], there are important aspects related to this system that have been intensively explored, like the collective modes of the BEC in harmonic trap [2], its tunneling through a potential barrier [3] and the excited states of this system (including vortices and solitons) [4,5]. In this work, we investigate the singular aspects that coming from the tunneling of a composite system: a trapped BEC containing an excitation. We studied the energy exchange between the two subsystems and the movement frequency changes to explain the new aspects presented by our system.

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Production of Two Species Superfluid to Study Quantum Turbulence and Vortices.

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In this work we are dealing with a mixture of Na/K Bose-Einstein Condensates. With the mixture of these two superfluids, we are going to investigate effects of transferring quantum excitations, vortices formation and quantum turbulence, as well. Effects of modulation of the scattering length and excitation will be object of investigation in the BEC of K verifying the consequences on the second specie (Na). Our experimental system is a composition of two independently atomic sources attached to a main chamber. We produce magneto-optical traps of Na and K atoms from 2D MOTs, which utilize a novel Zeeman slower configuration [1]. The whole system size is of the order of the previous standard Zeeman slower we had only for Na atoms. A next step is transferring the atoms to a crossed dipole trap and performing the experiments.

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TUESDAY

Coherent matter wave propagation with BECs in toroidal guiding potentials for atom interferometry and ATOMTROMICS based quantum simulators

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We are establishing a novel platform for the application of BEC-based coherent matter waves in toroidal guiding geometries for ATOMTRONICS devices (such as atomic SQUIDS), atom interferometry, and quantum simulation. Our architecture is based on a novel type of toroidal dipole-force potential generated by conical refraction providing a pair of concentric annular intensity distributions. Depending on detuning, these serve as a concentric pair of red-detuned potential minima or as a single blue-detuned potential minimum. By changing the parameters of the refractive crystal and the impinging laser beam, ring diameter and well dimensions can be varied with high flexibility. We load BECs into a ring with 340 micron diameter and accelerate or split the wave function by Bragg diffraction. We rotate the wave function with 2 or 4 photon momenta or create two partial waves with +2 and -2 photon momenta. Before and after rotation we perform interferometric coherence measurements.

Towards producing atomic circulations in a toroidal trap in a Rb87 Bose-Einstein condensate

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We have designed a setup to experimentally study atomic circulations of ultracold atoms in a ring-shaped trapping potential. To make Bose-Einstein condensates (BEC) of Rb87 atoms, we first capture zeeman-slowed atoms in a MOT, perform polarization gradient cooling, and then load the atoms into a quadrupole magnetic trap. After 3.5s of rf-evaporation, these pre-cooled atoms are transferred into a hybrid potential, a crossed optical dipole trap with a weak magnetic confinement. We perform evaporative cooling for 9s in the dipole trap, and a condensate with 3e5 atoms is produced. Our next step is to load the atoms into a toroidal dipole trap and use two Raman beams with orbital angular momentum to create synthetic magnetic flux, thus generating atomic circulations.

Bose Gases Tu-020

A continuous atom laser extracted from sodium condensates using two-photon Raman transition

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Using the two-photon stimulated Raman transition, a partial of sodium condensates in the un-trapped state was extracted continuously during 8 ms from the main Bose-Einstein condensates trapped in the cloverleaf trap. The two-photon Raman beams with a Rabi frequency of $2\pi\times800$ Hz and the frequency difference between two Raman beams of $2\pi\times890$ kHz were applied to the Bose-Einstein condensates with a number of 10^7 atoms. The intersection angle between two Raman laser beams was 80 degrees at the condensates. The condensates in the un-trapped state transited by the two-photon Raman beam were extracted with a recoil velocity from the main condensates in the trapped state. The beam divergence angle of the atom laser was 3.0 ± 1.5 mm/s. The coherence properties of the atom laser were discussed.

Observation of a reduced damping rate of collective oscillations of a quasi-1D Bose-Einstein condensate

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We investigate the damping of the collective centre-of-mass motion of a quasi-one-dimensional Bose-Einstein condensate at finite temperature, magnetically trapped on an atom chip. We find that the observed damping rate is more than three times slower than that predicted by the Landau damping theory for a three-dimensional uniform gas [1]. We present a simple model in which a discrete level spectrum is imposed on the system by defining a finite transverse width. We show that this simple model matches the experimental measurements well when this width is of the order of the width of the condensate. Furthermore, our theory predicts that changing the transverse width of the system can vary the damping rate over a broad range.

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TUESDAY

Bose Gases Tu-022

Spin dynamics in a two dimensional quantum gas

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We have investigated spin dynamics in a 2D quantum gas. Through spin-changing collisions, two clouds with opposite spin orientations are spontaneously created in a Bose-Einstein condensate. After ballistic expansion, both clouds acquire ring-shaped density distributions with superimposed angular density modulations. The density distributions depend on the applied magnetic field and are well explained by a simple Bogoliubov model. We show that the two clouds are anti-correlated in momentum space. The observed momentum correlations pave the way towards the creation of an atom source with non-local Einstein-Podolsky-Rosen entanglement.

Vortex Pair Annihilation in Two-Dimensional Superfluid Turbulence

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We investigate thermal relaxation of two-dimensional superfluid turbulence in a highly oblate Bose-Einstein condensate. We identify annihilation of vortex-antivortex pairs by directly observing coalesced vortex cores with a crescent shape and their disappearing as being filled with atoms. The vortex number of the condensate exhibits nonexponential decay behavior due to the vortex pair annihilation process. We measure the two-body decay rate of the vortex number for various sample conditions and find that the local decay rate is proportional to T^2/μ, where T is the temperature and μ is the chemical potential.

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Bethe ansatz approach to prethermalization in a coherently split 1D Bose gas

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We discuss the prethermalization dynamics of a coherently split one-dimensional Bose gas by using the Bethe ansatz method. Prethermalization is a relaxation process to a quasi-stationary state before reaching the true equilibrium state. The concept of prethermalization is important for understanding the fundamental aspects of quantum statistical mechanics such as “equilibration” and “relaxation” in isolated quantum many-body systems. Prethermalization and its connection to integrability in one-dimensional quantum systems have been intensively studied experimentally and theoretically. For instance, M. Gring et al. [1] recently observed the evolution of a rapidly and coherently split 1D Bose gas for large numbers of particles and compare the evolution of the system to the prediction of the Tomonaga-Luttinger liquid (TLL) theory.

Here we argue that the splitting of the 1D Bose gas is formulated by a kind of quantum quench, and precisely analyze the prethermalization process over a long-time scale beyond the TLL prediction.

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Enhanced scattering in a Bose-Einstein condensate and a measurement of the heat capacity.

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We study the refractive index of an ultra-cold bosonic gas in the dilute regime. Our atomic clouds are analyzed for temperature and particle number using nearly non-destructive phase-contrast imaging with light detuned from resonance by several tens of linewidths. After each pulse of probe light a small fraction of the atoms is lost, while the cloud is simultaneously slightly heated, allowing us to study the scattering rate as a function of temperature using only a single sample. We observe that the scattering rate increases below the critical temperature for Bose-Einstein condensation by more than a factor of 3 compared to the classical value. Our results are in fair agreement with the predictions by Morice et al. which take two-body correlation and resonant Van-der-Waals forces into account [1]. Currently we are expanding our method to perform calorimetry and directly measure the heat capacity of the BEC.

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Atom chip based ultracold potassium for testing microwave and RF potentials

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We present progress on an experiment to manipulate and trap ultracold atoms with microwave and RF (μ/RF) AC Zeeman potentials produced with an atom chip. These μ/RF potentials are well suited for atom interferometry and spin-dependent trapping for 1D many-body physics studies due to their ability to operate in conjunction with magnetic Feshbach resonances to tune interactions. Calculations show that μ/RF potentials will significantly suppress the inherent atom chip roughness associated with DC magnetic potentials. We have assembled a dual species, dual chamber apparatus that produces ultracold ^{39}K samples and ^{87}Rb Bose-Einstein condensates on an rf-capable atom chip, with access to other isotopes. On-chip ^{39}K will be sympathetically cooled through the microwave evaporation of rubidium, and transferred to a co-located dipole trap for a series of spatial manipulation experiments to study the capabilities and performance of μ/RF potentials.

Experimental Investigation Of Quantum Turbulence in a Trapped Superfluid

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Continuing our recent work on the demonstration of emergence of a turbulent regime in a sample of trapped super fluid Rb atoms we present new features associated with it. The main aspects of vortices formation, proliferation are described in terms of amplitude and time of excitation. Using free expansion we obtain the momentum distribution n(k). The analysis is performed to identify the inertial range of momentum and associated with the appearance of the power law dependence . Details of the experiment are presented. The verification of a direct cascade of energy during the time evolution for a turbulent cloud is described. Evolution of the turbulent state to granulation and codnensate destruction are discussed. Finally, arguments are presented concerning the importance of the phenomenon of quantum turbulence in trapped atoms and the new window of opportunities in this new modality of experiments. Support from FAPESP, CNPq and CAPES . We thanks the productive collaboration with *A. Fetter, V. Yukalov ,R. Hulet , A. N. Novikov and M. Tsubota*

TUESDAY

Thermodynamics With Global Variables For a Trapped Bose Gas

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Using the concept of Global Variable we have characterized the Bose condensation for a trapped Bose gas. First, a pair of global conjugate variables is defined then we determine the system's total internal energy and its temperature derivative, the heat capacity. In a ^{87}Rb BEC, a rapidly changing C_V was observed, in the vicinity of the critical temperature, T_c, in close similarity to the lambda point in liquid ^{4}He. In a second set of measurements we have determined the isothermal compressibility, showing that k_T obeys the Curie law. Recovering ideas initially proposed by Niels Bohr, we measured an uncertainty type relation between the global *pressure* and *volume* of a Bose-Einstein Condensate of ^{87}Rb atoms trapped in a hybrid trap determining the relation of the minimal possible values for pressure and volume parameters showing that at T=0 they cannot be simultaneously zero . In a future perspective we are planning the use of global variable thermodynamics to characterize variations present in a turbulent cloud of trapped BEC. Figures showing(in the sequence):Phase diagram, Heat capacity, isothermal compressibility and relations of pressure volume at minimum number at T=0. Work supported by FAPESP, CNPq and CAPES.

Bose-Einstein Condensation of ^{86}Sr

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We report on the successful Bose-Einstein condensation of ^{86}Sr and the measurement of the ^{86}Sr three-body decay rate in a thermal gas. The cooling cycle includes two MOT stages and evaporative cooling in an optical dipole trap. Due to the large scattering length (a = $823a_0$) of ^{86}Sr, evaporation must be performed at low density and proceed quickly in order to avoid loss due to three-body recombination. We are able to reliably generate pure condensates of about 20,000 atoms. Future work will include the investigation of optical Feshbach resonances as well as optical lattice experiments.

QUANTUM SIMULATION

Non-equilibrium wave-packet dynamics in 1D optical lattices

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We study the non-equilibrium dynamics of localized density excitations in systems of ultracold atoms in Bose-Hubbard lattices. In particular, we investigate transport and interferometry properties via wave-packet propagation in one-dimensional and Y-junction geometries. By means of time-dependent Density Matrix Renormalization Group methods, we study the quantum many-body dynamics on the lattice and correlations between excitations in the strongly interacting, superfluid regime. Direct comparison to the solution of the time-dependent, discrete nonlinear Schrodinger equation reveals characteristic features of the dynamics of these excitations that cannot be captured by such a simplified mean-field description, which typically describes wave excitations in the weakly interacting, superfluid regime.

A Dissipative Quantum Many-Body System with Long-Range Interactions

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A Bose-Einstein condensate whose motional degrees of freedom are coupled to a high-finesse optical cavity via a transverse pump beam constitutes a dissipative many-body system with long-range interactions. The cavity-mediated long-range interactions drive the atomic cloud from a superfluid to a supersolid phase. As the transverse pump field constantly probes the atomic density via cavity-enhanced Bragg scattering, it maps the density fluctuations to the intracavity field which we monitor in real-time. Using heterodyne detection, we spectroscopically resolve the cavity output field which contains the dynamic structure factor of the atomic gas. We extract the critical exponents of diverging density fluctuations on both sides of the phase transition. They deviate from the closed-system values and show the dissipative character of the system due to the leaking cavity field. In addition, we investigate the competition between cavity-mediated long-range interactions and short-range contact interactions by loading into deep two-dimensional optical lattices.

Quantum Simulation Tu-032

Dissipative Transport in a Many Body Quantum System

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Understanding the effect of intrinsic dissipation on the transport mechanism of a many body quantum system is one of the essential task as it plays an important role in many areas ranging from mesoscopic conduction to molecular electronics. We experimentally realize such a quantum transport system and investigate the influence of dissipation on the transport of particles. We prepare our system by loading Bose condensed ^{87}Rb in a 1D optical lattice with high atom occupancy per lattice site. Subsequently we remove all the atoms from a central lattice site. While the atoms from neighboring sites tunnel into the empty site, we observe a clear signature of on site dissipation on the tunneling transport mechanism.

Ballistic Atom Pumps

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Researchers have long been interested in electron transport through mesojunctions containing time-dependent potential barriers, a process often called ``quantum pumping.'' A useful model of such a system is a ballistic atom pump: two reservoirs of neutral ultracold atoms connected by a channel containing oscillating repulsive potential-energy barriers. This system can create net particle transport in either direction, and, even if there is no net particle transport, energy can be pumped out of or into each reservoir. We also show a ``particle rectifier'' which under specified conditions permits net particle pumping in only one direction. Classically, this system is a nice model of chaotic transport, and the quantum description cannot be fully understood without analyzing the underlying classical dynamics. We use classical trajectories, along with phase information, to construct a semiclassical approximation to the quantum description. This approach explains the locations and relative heights of Floquet peaks seen in quantum theory.

The effects of phase noise on the delta-kicked rotor

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We report on the effects of phase noise in the atom-optics implementation of the delta-kicked rotor. A paradigm for experiments on quantum chaos, this system has demonstrated dynamic localisation and ballistic energy growth as a function of the number of kicks for different kick periods [1], and the influence of amplitude and frequency noise on the kicks has been studied [2].

In the experiment we report on here, we start with an all-optical BEC of ^{87}Rb atoms, and subject it to a kick sequence at the anti-resonance, where subsequent kicks destructively interfere. We modulate the phase of the kicks, with an adjustable frequency and amplitude. We observe resonances, conversion from localisation to ballistic growth and sub-diffusion in this system.

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Dynamics of atoms in bilayer optical lattices, and adiabatic state preparation

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We study ultracold quantum gases trapped in optical lattices consisting of two layers (which can each either be one-dimensional or two-dimensional). We propose schemes for adiabatic state preparation of low-entropy states of bosons and fermions given tunable inter-layer couplings. In this context it is possible, to use one layer as an entropy reservoir, which removes entropy from the other layer, before decoupled from it. For the case of two coupled one-dimensional layers, we calculate the time-dependent dynamics exactly using the time-dependent density matrix renormalization group technique and identify parameter regimes such entropy transfer occurs, and the emergence of characteristic many-body correlations in the low-entropy layer can be observed. This process is especially effective when the desired state in the low-entropy layer is gapped, and these states can be used as a starting point also for other adiabatic preparation protocols, including the realisation of metastable excited states.

Observation of a disordered bosonic insulator from weak to strong interactions

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Understanding the behavior of disordered, interacting systems is one of the challenges of quantum physics. We employ ultracold atoms with controllable disorder and interaction to study the paradigmatic problem of disordered bosons in the full disorder-interaction plane. Combining measurements of coherence, transport and excitation spectra, we get evidence of an insulating regime extending from weak to strong interactions and surrounding a superfluid-like regime, in general agreement with the theory [1]. For strong interaction, we reveal the presence of a strongly-correlated Bose glass coexisting with a Mott insulator. For weak interaction, we also study the momentum-dependend transport, finding a sharp crossover from a weakly dissipative regime to a strongly unstable one at a disorder-dependent critical momentum. The vanishing of this critical momentum can be used to locate the fluid-insulator transition driven by disorder [2].

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Particle-hole entanglement of ultracold atoms in an optical lattice

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We study the ground state of two-component bosonic atoms in a one-dimensional optical lattice. By applying an external field to the atoms at one end of the lattice, the atoms are transported and becomes localized at that site. The holes are then created in the remaining sites. The particle-hole superpositions are produced in this process. We investigate the entanglement entropy between the atoms in the two different parts of a lattice. A large degree of particle-hole entanglement is generated in the ground state. The particle-hole quantum correlations can be probed by the two-site parity correlation functions. The transport properties of the low-lying excited states are also discussed.

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Quantized Scattering from an Oscillating Barrier for Atomic Quantum Pumps

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We present progress on an experiment to study 1D quantum mechanical scattering by an amplitude-modulated barrier. Numerical simulations confirm the oscillating barrier imparts or subtracts kinetic energy from the scattered atoms in discrete amounts of $\hbar\omega$, where ω is the modulation frequency. We present an atom chip-based experimental system to study the scattering dynamics by directing Bose-Einstein condensates (BEC) of ^{87}Rb at a tightly focused, 532nm laser beam that serves as an oscillating barrier, located in the center of the trap. We present methods for measuring the scattering spectrum and the use of dark-ground imaging for high sensitivity detection. This experiment represents a first step toward implementing a quantum pump for ultracold atoms based on two such barriers modulated out of phase with one another.

A Dynamic, Ultra-Slow Optical-Matter Wave Analog of Event Horizon

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We investigate theoretically the effects of a dynamically increasing medium index on optical-wave propagation in a rubidium condensate. A long pulsed pump laser coupling a D2 line transition produces a rapidly-growing internally-generated field. This results in a significant optical self-focusing effect and creates a dynamically growing medium index anomaly that propagates ultra-slowly with the internally-generated field. When a fast probe pulse injected after a delay catches up with the dynamically increasing index anomaly, it is forced to slow down and is prohibited from crossing the anomaly, thereby realizing an ultra-slow optical-matter wave analogue of a *dynamic* white-hole event horizon

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Breaking of time-reversal symmetry during coherent transport in disordered media

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Coherent transport in disordered media has been a thriving topic for many decades. Started with the seminal paper by Anderson in 1958, introducing the possiblity of strong localization of waves, the interest is still alive nowadays as open questions remain. In the last years our group was able to observe Anderson Localisation (in 1D and 3D) and Coherent Backscattering (CBS) with ultracold atoms, allowing to study these phenomena in a precise way. In particular CBS, a very first manifestation of coherence in disordered media, relies on the time-reversability of the wave propagation. Here we show our latest experimental results where we deliberately break this symmetry in a precise way, enabling us to observe the destruction, and a short revival of the coherent signal when time reversal symmetry is briefly reestablished.

Superexchange Mediated Dynamics of Anti-Feromagnetic Order in an 2D Optical Lattice

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We study experimentally the non-equilibrium dynamics of a 2D antiferromagnetic (AF) initial state in an optical lattice with one atom per site. We observe the decay of the staggered magnetization after a quench from a deep lattice to a shallow lattice, above the Mott insulator transition. In addition to final lattice depth, we vary a checkerboard like, state-independent energy offset. Over a range of lattice depths and staggered tilts we observe two decay time scales, a fast one of the order direct tunneling and a slower one of the order of a tilt-modified superexchange. Number dependence of the AF order decay is indicative of many body effects. In the presence of sufficiently staggered tilt, the fast tunneling is suppressed and our system is expected to be described by the Heisenberg Hamiltonian for unit filling. Our experiment is an ideal platform for studying many-body dynamics of states far from equilibrium.

Optimally Shaped Gates for Trapped Ion Chains

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Scalable entanglement in trapped ion system is complicated by the multiple collective modes of motion [1]. We perform high fidelity and programmable multipartite entanglement by coupling all transverse modes of motion using optimal laser pulse shaping in a chain of five Yb+ qubits [2]. A focused mode-locked laser beam optically addresses subsets of qubits to perform entangling XX gates on any pairs of adjacent qubits. Pulse shaping by modulating the amplitude and phase of the laser can drive high fidelity gates for certain pulse solutions that are relatively insensitive to detuning errors and fluctuations. Using the pulse shaping, the individual addressing, and ion shuttling, we create tripartite entangled GHZ states in programmable approach. The optimally engineered pulse shapes coupling to multiple modes scale well for large qubit registers by keeping gate times short.

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Quench dynamics in ion chains with variable-range interactions

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We study theoretically the non-equilibrium dynamics of one-dimensional chains of ions confined in linear traps. By coupling spin states of ions with collective phonon modes it is possible to tailor interactions along the chain so that their decay in space can be tuned in a wide range. Starting from a selection of initial states, we explore the dynamics of the system after the interactions are suddenly turned on, in particular focussing on the growth of bipartite entanglement in the chain and behavior of reduced density matrices. These can be obtained in experiments for small sub-chains via quantum state tomography. Following on from previous studies in which it was observed that the qualitative behaviour of the system differs for long and short range interactions, we investigate how the entanglement growth depends on the initial states and on the details of the Hamiltonian parameters.

Quantum Simulation and Many-Body Physics with 2D Ion Crystals in a Penning Trap

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Quantum simulations promise to reveal new materials and phenomena for experimental study, but few systems have demonstrated the capability to control ensembles in which quantum effects cannot be directly computed. We report on new experiments characterizing a system of hundreds $^{9}Be^{+}$ ions that form 2D crystals in a Penning trap and can be used as a platform for incalculable quantum simulations. The $^{9}Be^{+}$ valence electron spins can be coupled using an effective Ising interaction with a tunable strength and range, coupling tens to hundreds of spins. We characterize the new experimental apparatus using the ion crystal stability, the spin-spin coupling strength, and the coherence time of the ensemble. Furthermore, we report on efforts to bench-mark quantum effects of the spin-spin coupling using a spin-squeezing witness, laying the foundation for future experiments including observation of entanglement dynamics under the quantum Ising Hamiltonian, high efficiency molecular spectroscopy, and studies of quantum thermalization.

TUESDAY

Tunable spin-spin interactions and entanglement of ions in separate wells

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Quantum simulation [1,2] may provide an understanding of the many quantum systems which cannot be modeled using classical computers. Despite impressive progress [3-5], a major challenge is the implementation of scalable devices. In this regard, individual ions trapped in separate tunable potential wells are promising [6-8]. Here we implement the basic features of this approach and demonstrate deterministic tuning of the Coulomb interaction between two ions, independently controlling their local wells. The scheme is suitable for emulating a range of spin-spin interactions, but to characterize the performance of our setup we select one that entangles the internal states of the two ions with 0.82(1) fidelity. Extension of this building-block to a 2D-network, which ion-trap micro-fabrication processes enable [9], may provide a new quantum simulator architecture with broad flexibility in designing and scaling the arrangement of ions and their mutual interactions. To perform useful quantum simulations an array of tens of ions might be sufficient [4,10,11].

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Experimental Developments towards studying Quantum Dynamics in Trapped Ions

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In this work, we present experimental developments towards studying the quantum dynamics in trapped ions. Our focus will be on the traditional linear trap design modified such that it allows us to dynamically evolve the the trap Hamiltonian by electric fields only. Commencing with a brief introduction to the theoretical framework for the possible observation of geometric phases as well as non-Abelian to Abelian transitions, we will show the experimental development towards realizing it.

Implementing scaleable remote ion-photon entanglement

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Recent work in quantum information processing with trapped ions has demonstrated many of the elements required for realizing a quantum computer with hundreds of qubits distributed across multiple connected ion traps. Efficient collection and fiber coupling of fluorescence light from trapped ions is critical for fast qubit state detection and for generating the remote entanglement of ions necessary for such a quantum computer. We are currently working with barium ions and are investigating two possible approaches to collecting 493 nm fluorescence; custom large area external aspheric optics and trapping ions at the focus of a custom parabolic mirror.

Preparation of High NOON State of Phonon in a Trapped-ion System

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Highly entangled NOON states have a wide range of potential applications in quantum communication, quantum information processing and quantum precision measurement. Here we realize the NOON state with two motional modes of a single ion in a standard Paul trap. We develop a composite-pulse scheme of stimulated Raman transitions to prepare arbitrary size of NOON state in the trapped-ion system and verify its fidelity by observing the parity oscillation of the state depending on the measurement basis.

A microwave trap for sympathetic cooling of polar molecules

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In the Centre for Cold Matter, we have been developing techniques to cool molecules into the microkelvin regime. One such method is sympathetic cooling, using ultracold atoms as a refrigerant to cool molecules. Previous work has suggested that atoms and molecules can be trapped in the antinode of a Fabry-Perot microwave cavity [1][2].

The most efficient way to couple microwave power into this cavity is from a rectangular waveguide, via a small coupling hole in one mirror. We have developed an analytical model that helps us understand this coupling mechanism, and gives us a good idea of how the size of the coupling hole affects both the coupling of the cavity and the cavity's finesse. We carried out finite-difference time-domain simulations and performed experiments on a prototype cavity to verify this model.

We have now designed and built this trap for operation under ultra-high vacuum, with the ability to cool the cavity mirrors to 77 K and couple in up to 2 kW of microwave power. This will allow us to trap molecules with a moderate dipole moment at temperatures of hundreds of millikelvin, as well as atoms at a few millikelvin.

We will present our work thus far in creating the microwave trap - the results of our model, our understanding of the mode in the cavity and how best to create the deep trap we will need to sympathetically cool molecules. We will also present our first results demonstrating trapping of lithium atoms in the microwave trap

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Towards a Three Dimensional Magneto-Optical Trap for Diatomic Molecules

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We present progress towards a three-dimensional magneto-optical trap (MOT) for diatomic molecules. A dual-stage cryogenic buffer gas beam source produces a cold, slow beam of YO molecules with a mean forward velocity of 70 m/s. White light slowing will be used to decelerate a portion of the YO beam to within the MOT capture velocity, about 10 m/s. The AC magnetic field for the MOT is generated with in-vacuum magnetic coils with a resonant frequency of 5 MHz. The modulation of both the magnetic field and optical polarization of the MOT beams provides for rapid remixing of the Zeeman states in YO, which is essential to maintain the MOT trapping force given by the electronic radiative process.

A cryogenic buffer-gas BaH beam for molecular laser cooling and ultracold fragmentation

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We report on the current status of a new experiment on cooling and trapping barium monohydride (BaH) diatomic molecules. This molecule is a good candidate for laser cooling, and is attractive for future studies of ultracold fragmentation due to the large mass ratio of its constituent atoms. We describe the plans for the cryogenic beam apparatus and the initial spectroscopy of thermal BaH molecules produced by laser ablation. We also discuss different strategies to perform laser cooling of BaH.

Photoassociation spectroscopy of RbYb in a conservative trap

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The creation of ultracold heteronuclear molecules with anisotropic electric dipole interaction is one of the prominent goals in ultracold atom physics. While the widely used bialkalis possess no magnetic moment in the electronic ground state, RbYb is paramagnetic and thus has an additional degree of freedom.

Here we report on our most recent step towards the creation of ultracold RbYb ground state molecules namely photoassociation of RbYb in a conservative trap. In a newly designed trap consisting of a magnetic trap for Rb and an optical trap near the intercombination line for Yb we perform one-photon spectrosocopy on weakly-bound vibrational levels of excited Rb*Yb molecules. This combines our previous studies on photoassociation spectroscopy of RbYb in a magnetooptical trap [1,2] and simultaneous conservative trapping of the two species [3].

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Continuous formation of rovibronic ground state RbCs molecules via photoassociation

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We recently demonstrated the direct formation of vibronic ground state RbCs molecules via short-range photoassociation (PA) [1]. We identified the PA resonances as vibrational levels in the $(2)^3\Pi_{0+}$ potential by comparing the resonance locations with spectroscopic data. We also obtained satisfactory agreement between experimental molecule production rates and Franck-Condon factor calculations, and devised a simple method for analyzing rotational line strengths in PA spectra. In this poster, we will report on recent progress in populating the rovibrational ground state X(v=0, J=0) formed following PA, which was confirmed by depletion spectroscopy with a narrow-band CW diode laser. This is an important step to verify the feasibility of our future prospects to accumulate a large sample of ground-state RbCs molecules by continuous PA, and to purify this sample by collisional “scrubbing” of rovibrational excited states.

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Probing evanescent field coupling between laser-cooled ^{87}Rb atoms and the fundamental and higher order modes of an optical nanofiber.

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Optical nanofibers (ONFs), with subwavelength diameters, have a strong evanescent field around them. When an ONF is combined with a cold atom setup, the surrounding cold atoms interact with the different modes present in the fiber via evanescent field coupling. To date, most experimental studies have focused on ONFs that support only the fundamental mode. ONFs supporting higher order modes have advantages since they have a larger diameter - thereby being more robust - and the evanescent field extends further from the fiber surface - leading to light coupling with more atoms.

Motivated by the work of Masaloav and Minogin [1] we studied the fluorescence emission from, and absorption coupling of, cold atoms to an ONF supporting the fundamental (HE_{11}) and the first group of higher modes (TE_{01}, TM_{01}, HE_{21}). We observed that fluorescent light from the atoms coupling in to the nanofiber through the waist has ~ 6 times higher pumping rate for the higher-order fiber modes compared to the fundamental mode. We also demonstrated that there is more absorption of the light by atoms when probe light is guided in the higher order modes rather than in the fundamental mode [2]. These results will be useful in implementing higher order modes through ONFs for mode interference-based atom trapping schemes.

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A two-frequency ion trap confining ions with different charge-to-mass ratios

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We describe the theory of two-frequency operation of an ion trap [1] and solve the equations of motion for two species of ions with molecular mass, charge: M_A,+1 and M_B,+33 respectively, where M_A = 138 amu is an isotope of barium and $M_B = 1.4\ 10^6$ amu, e.g., a large protein or molecular complex. The quadrupole electric field is created by RF radiation with angular frequencies ω_1 and ω_2 with $\omega_2 = 100\omega_1$. We obtain a superposition of two almost independent Paul traps whose centres can be made coincident or moved apart, while the effective spring constants can be adjusted to be the same for both species which allows for efficient sympathetic cooling. This approach can be extended to ions with more similar masses to improve the fidelity of quantum logic operations. Manipulation of the orientation of larger particles along the electric field of the trap is also considered.

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Ion trap surface cleaning and microwave-driven gates

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We present our current progress towards performing quantum logic gates on trapped-ion qubits at fidelities suitable for fault-tolerant quantum computing. Our two main technical goals are eliminating the so-called ‘anomalous heating’ of ion motion and improved near-field microwave control of hyperfine ‘clock’ qubits. The effort to reduce the anomalous heating, which limits the fidelity of gates in very small ion traps, is focussed on surface treatment methods to remove contaminants from the trap electrodes. We have shown that argon-ion bombardment can reduce the anomalous heating by a factor of 100 [1], and will report on testing other cleaning methods. Our near-field microwave control work will build on previous work on high fidelity single qubit gates [2], single qubit addressing [3] and two-qubit gates [4].

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Development of Microfabricated 2-D Ion Trap for Quantum Information Processing

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We present a microfabricated ion trap to implement a scalable platform for quantum repeater and quantum computing application. To prevent high-voltage breakdown, we used a 14-μm thick PECVD-deposited SiO_2 dielectric layer which induces less residual stress as compared to the conventionally used tetraethyl orthosilicate (TEOS) films. The trap has one set of RF electrodes, 42 sets of DC control electrodes and slit opening dimensions of 2.3mm x 0.1mm. The RF null is located about 82μm above the trap surface and with the applied RF voltage of 320V peak-to-peak at 25.5MHz, we can trap up to six $^{174}Yb^{+}$ ions and three $^{171}Yb^{+}$ ions. A lifetime of more than 10 hours has been observed with Doppler cooling, and we can shuttle trapped ions along the trap axis. We will report the characterization result of this trap and our working progress in implementation of quantum repeater.

TUESDAY

Grating chips for quantum technologies

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Laser cooled atomic samples have revolutionised atomic physics and are key to new quantum technologies such as frequency metrology and novel atom-based sensors. However, the setups are typically complex and bulky largely due to the multitude of laser beams required.

Micro-fabricated diffractive optical elements [1] can greatly facilitate the miniaturisation of magneto-optical traps (MOTs) for use in ultra-cold atom technology. Such an element can transform a single circularly-polarised input beam into all required beams for an intensity-balanced MOT [1]. This has enabled the realisation of chip-based and sub-Doppler cooled atomic samples, which could subsequently be loaded into a magnetic trap.

Here we present this and more of our latest results on grating-based optical molasses including precise optical characterisation of several new grating designs and an investigation of the phase-space properties in the MOT.

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Double-Loop Microtrap Array for Ultracold Atoms

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A novel kind of magnetic microtrap has been demonstrated for ultracold neutral atoms [1,2]. It consists of two concentric current loops having radii r_1 and r_2. A magnetic field minimum is generated along the axis of the loops if oppositely oriented currents flow through the loops. Selecting r_2/r_1=2.2 maximizes the restoring force to the trap center. The strength and position of the microtrap relative to the atom chip surface can be precisely adjusted by applying an external bias magnetic field. A microtrap array can be formed by linking individual microtraps in series. A linear array of 3 microtraps having r_1 = 300 microns, was loaded with more than 10 ^{587}Rb atoms using three different methods: 1) from a transported quadrupole magnetic trap, 2) directly from a mirror MOT and 3) from an optical dipole trap.

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Sub-micron magnetic lattices for Quantum Simulation

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We use nano-lithography techniques to create lattice potentials in permanent magnetic films at atom chips. These lattices can be created over a large range of length scales and are used to trap mesoscopic clouds of ultracold atoms [1]. We are downscaling the lattice spacing from our current 10um to much smaller lattices for a new series of experiments [2]. On these new atom chips we created lattices with lattice spacing varying from 250nm up to 5um on the same chip. The 50nm thick monocrystaline FePt films are grown with MBE and are then patterned by e-beam lithography to obtain structures with a 20nm resolution. This technique can extend the range of length scales of optical lattices to both smaller and larger sizes, and can be used to study degenerate gases in new regimes and environments. Geometrical interfaces have been constructed to study the role of disorder, frustration and dimensionality.

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Highly Efficient Free-Space Atom-Light Interface

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We present a setup capable of transforming a paraxial Gaussian-beam into a spherical linear-dipole wave. This is accomplished by focusing a radially polarized Laguerre-Gaussian beam with a parabolic mirror covering 94% of the solid angle relevant for a linear dipole. This mode is interfaced to an ion at the focus of the parabolic mirror, providing an ideal probe for the created mode. Reducing our focusing geometry to half solid-angle enables us to monitor the upper-level population of the driven transition by measuring the light scattered by the ion into the complementary solid angle part. By varying the incident power we determine the coupling efficiency to the linear dipole to be 27%. Our setup demonstrates the highest efficiency for coupling between light and a single emitter in free space reported so far. Extrapolating from half to full solid-angle yields an efficiency of 54%.

Hybrid trap for atoms, ions and molecules built within a Fabry-Perot cavity

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The study of two, few and many particle systems, where the interactions are mediated by central potentials ranging from $1/r$ to $1/r^6$ can be realized in cold, dilute gas mixtures of ions, atoms and molecules. To enable these studies in a comprehensive way, we have developed an apparatus capable cooling and trapping ions and ultracold atoms and creating and trapping ultracold molecules[1]. Our scheme allows the trapped overlap of specific numbers of ions, atoms and molecules, in prepared internal states, so that interactions of any combination can be studied. An important feature of the apparatus is that the center of the trapping region lies on the axis of a Fabry-Perot cavity, enabling resonant interrogation of the species within[2]. We present this experiment and the initial results[1],[2],[3] with this hybrid apparatus which demonstrate the capabilities of this system and discuss future prospects.

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Spontaneous coherence of magnons in spin-polarized atomic hydrogen gas

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A macroscopic occupation of the ground state and long-range correlations are the hallmarks of Bose-Einstein condensation. The phenomenon has also been observed in systems of wave-like excitations such as photons, excitons, and spin waves (magnons). Spin waves in cold gases are propagating perturbations of spins, i.e. travelling fluctuations of the macroscopic magnetization. The propagation results from the cumulative effect of the identical spin rotation effect due to exchange interaction. In spin-polarized atomic hydrogen gas, magnons can be trapped and controlled by magnetic forces in a manner similar to ordinary atoms [1]. We demonstrate confinement of magnons in magnetic traps of distinct geometries. We show that at a critical density of H gas magnons accumulate in the ground state and exhibit long-term coherence, profoundly changing the electron spin resonance spectra. We interpret these effects as signs of spontaneous coherence and argue for an explanation in terms of BEC of magnons.

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Modular Quantum Systems with Photons and Phonons

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Distributed, modular systems for quantum information processing require the use of both stationary and flying qubits and no single physical qubit type currently fills both roles. One proposal uses trapped ions as stationary qubits due to their long coherence times and robust control and photons as flying qubits that allow entanglement of stationary qubits in separate modules [1]. We have demonstrated a basic version of this ion-photon system consisting of two modules [2]. By utilizing photonic and phononic buses, we generate entanglement both between two qubits within one module and a second qubit stored in the other. Most importantly, intramodular entanglement generation occurs more quickly than coherence of the entangled state is lost. This feat has only been accomplished in this ion-photon system and indicates that scaling of this system is achievable. Additionally, we discuss control and stability of intramodular [3] and intermodular phases.

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Controlled photon emission of two ions in a cavity as enhanced quantum interface

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Sub- and superradiance are widely studied fundamental effects in quantum optics. We generate sub- and superradiant states of a two-ion crystal coupled to an optical cavity. The ions interact with the cavity via a cavity-mediated Raman transition. In the context of quantum information, the transfer of a qubit state encoded in a single ion onto a single photon within an optical cavity has been recently shown. Here, we encode the qubit state in a superradiant state of a two-ion crystal before performing the transfer. We show an overall enhancement in the process fidelity and efficiency of the mapping process compared to the single-ion case. The results are a proof of principle of how cooperative effects can be utilized to improve the performance of a quantum node of a quantum network.

Transverse electron momentum distribution for arbitrary polarization state of the ionizing laser pulse

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We study evolution of the distribution of electron momenta in the direction perpendicular to the polarization plane with the change of the ellipticity parameter of the driving laser pulse. We show, that the distribution gradually changes from the singular cusp-like distribution for the close to linear polarization to the smooth gaussian-like structure for the close to circular polarization states. In the latter case, when the ellipticity parameter is close to one, the strong field approximation [1] formula for the transverse momentum distribution become quantitatively correct.

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Two-dimensional absorption spectroscopy with attosecond XUV light: Unraveling bound-state electron dynamics in strong laser fields.

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We demonstrate a two-dimensional spectroscopy method to observe dynamics of atomic bound states in strong laser fields. The approach allows to separate different pathways of light-matter interaction, *e.g.* non-resonant interactions and resonant coupling among states, and thus enables us to analyze each type of interaction individually. Furthermore, it is possible to extract amplitude and phase modifications imprinted on a quantum system as it interacts with an ultrashort laser pulse.

The method is based on Fourier analysis of the time-resolved absorption spectrum of an ultrashort excitation pulse, in which the information about the system's evolution is encoded. The underlying analytical framework predicts the building blocks of the spectra, and reveals how amplitude and phase information can be directly retrieved from the experimental spectrum.

We experimentally study the transient coupling, introduced by interaction with a few-cycle near-infrared laser pulse, of doubly-excited states in helium, which are excited by attosecond-pulsed extreme ultraviolet light.

Low-energy enhanced multiphoton above-threshold ionization in a strong laser field of mid-infrared wavelength

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We report about the results of our study of strong-field (multiphoton) above-threshold ionization (ATI) in laser-irradiated atomic species (*Ar*, *Xe*) under conditions of recent experiments [1, 2] observing an unexpected characteristic spike-like low-energy structure in photoelectron energy distribution (PED), which becomes prominent using mid-infrared laser wavelengths ($\lambda > 1.0$ μm) corresponding to intermediate values of the *Keldysh parameter* ($\gamma \leq 1$). The problem is addressed theoretically within the *velocity-gauge* formulation of *strong-field approximation* (SFA) [3] complemented with the *density-functional-theory* (DFT) applied for numerical composition of initial (laser-free) atomic state using the routines of GAUSSIAN-03 code [4]. Our DFt_SFA calculation results clearly demonstrate a remarkably enhanced ionization rate in low-energy domain of PED and fairly well reproduce their low-energy structure and its intensity-dependent behavior observed in relevant experiments (particularly, a noticeable energy shift of maximum ionization rate to higher energies under increasing the laser peak intensity).

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TUESDAY

Pressure optimization of high harmonic generation with argon gas jet

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High harmonic generation (HHG) in a gas jet depends on pressure due to density changes, variation of the matching conditions and absorption. In this work we experimentally studied the pressure dependence of the output of high harmonics at HHG process in Ar gas at moderate peak laser intensities in the interaction region ~1.5×10^{14}W/cm^2. To enable measurements in a broad range of pressures we employed an additional chamber enclosing the gas jet with differential pumping. By varying the Ar gas jet pressure within the range p~0.05-3bar, we observed the maximum HHs output at p~0.5-1bar. Compared to the case without the enclosing chamber, we achieved the HHG enhancement up to four times and extension of the cutoff by two more harmonics from 27th to 29th order.

This work was supported by the by the Robert A. Welch Foundation grant No. A1546 and the Qatar Foundation under the grant NPRP 5-994-1–172.

Effect of different transverse modes of femtosecond pulses on filament propagation

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We experimentally studied femtosecond pulse filamentation and propagation in water for Gaussian, Laguerre-Gaussian, and Bessel beams. Three different transverse modes were created from an initial Gaussian beam by using a computer generated hologram technique. We found that the propagation length of the filament produced by the Bessel incident beam was longer than that for the other transverse modes under the conditions of the same peak intensity, pulse duration, and the size of the central part of the beam. We performed for a Bessel-type beam a more detailed study of the filament length on the number of radial lobes. This length increased with the number of lobes, which implies that they serve as an energy reservoir for the filament formed by the central intensity peak.

This work was supported by the by the Robert A. Welch Foundation grant No. A1546 and the Qatar Foundation under the grant NPRP 6-465-1-091.

Reduced-Density-Matrix Description for Pump-Probe Optical Phenomena in Moving Many-Electron Atomic Systems

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Linear and non-linear (especially coherent) electromagnetic interactions of moving many-electron atomic systems are investigated using a reduced-density-matrix description. Complimentary time-domain (equation-of-motion) and frequency-domain (resolvent-operator) formulations are self-consistently developed. The general non-perturbative and non-Markovian formulations provide a fundamental framework for the systematic introduction of the standard Born (lowest-order-perturbation) and Markov (short-memory-time) approximations. The macroscopic electromagnetic response is described semi-classically, employing a perturbation expansion of the reduced-density operator in powers of the classical electromagnetic field. We obtain compact Liouville-space operator expressions for the linear and general (n'th order) non-linear macroscopic electromagnetic-response tensors, which can be evaluated for a non-local and non-stationary optical medium. Binary atomic collisions and single-photon processes are incorporated as environmental interactions by means of a Liouville-space self-energy operator, for which the tetradic-matrix elements are explicitly evaluated in the isolated-line, lowest-order, and Markov approximations.

Effect of nuclear mass on carrier-envelope-phase controlled electron localization in dissociating molecules

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TUESDAY

Coherent control of molecular fragmentation with few-cycle laser pulses of well-defined carrier-envelope phase (CEP) has become an active research topic in ultrafast science due to its potential application for control of chemical reactions[1-3]. We explore the effect of nuclear mass on the laser-driven electron localization process[4]. We dissociate a mixed H_2/D_2 target with intense, carrier-envelope-phase (CEP) stable 6 fs laser pulses and detect the products in a reaction microscope. We observe a very strong CEP-dependent asymmetry in proton/deuteron emission for low-KER dissociation channels. This asymmetry is much stronger for H_2 than for D_2. We also observe a large CEP offset between the asymmetry spectra for H_2 and D_2. Our theoretical simulations, based on a one-dimensional two-channel model, agree very well with the asymmetry spectra, but fail to account properly for the phase difference between the two isotopes.

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Quantum Secret Sharing Using Multi-Spatial-Mode Entangled Light

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With the advent of quantum cryptography it became possible for two parties to share a secret key that is mathematically provably secure against eavesdropping. A desirable extension of this concept is multi-user quantum secret sharing, in which a message or key is sent to multiple parties who must work together to access it. Here we demonstrate multi-party secret sharing by using a four-wave mixing process in atomic vapor to produce a multiple-spatial-mode continuous-variable entangled state of light. We generate random bit streams by performing quadrature measurements on spatially distinct modes of the light, and combine these bit streams to generate a key. Simultaneously, the entangled pairs of these modes are sent to different receivers who perform similar measurements. While the bit streams produced by the receivers individually are not correlated with the key, these parties can work together and combine their information to reconstruct the key.

Adiabatic state transformation in the presence of classical noise.

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In adiabatic state transformations, the role of classical noise is still not well understood. For quantum simulated annealing, however, recently computed upper bounds[1] for the time cost with randomness introduced in each time step show a quadratic speed in the size of energy gaps up over upper bounds for adiabatic quantum computation. We study of classical noise in adiabatic state transformation by stochastic simulation (for coloured noise) and a master equation approach (for white noise), comparing the cost between the noisy Hamiltonian and the noise-free case. For particular parameter regimes, we find evidence that introducing specific types of noise could improve the final fidelity of state preparation for limited total time, both in in two-level systems, and in the transverse Ising model and Bose-Hubbard model in 1D.

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All optical quantum storage based on spatial chirp of the control field

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We suggest an all-optical quantum memory scheme which requires neither synchronization and temporal manipulation on the control field and medium nor the presence of the Stark or Zeeman effect in the atomic medium. The scheme is based on the off-resonant Raman interaction of a signal quantum field and a strong control field in a three-level atomic medium in the case, when the control field has a spatially varying frequency across the beam, called a spatial chirp. We show that the effect of such a spatial chirp is analogous to the effect of a controllable reversible inhomogeneous broadening (CRIB) of the atomic transition used in the gradient echo memory (GEM) scheme. We find that for the optimal conditions the proposed spatial-chirp memory scheme is capable of almost one hundred percent efficiency in the retrieval of the stored quantum signal. This scheme is also analogous to phase matching control (PMC) memory schemes [1-4].

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TUESDAY

Rydberg Quantum Information using a Magnetic Film Atom Chip

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We present our ongoing research with two-dimensional atomic ensembles in a lattice of Ioffe-Pritchard type microtraps arrays created by a patterned permanent-magnetic film atom chip [1]. We recently demonstrated the loading of ultracold ^{87}Rb atoms in 600 lattice sites of square and hexagonal structures simultaneously, with 400 atoms/trap and T=30 μK on average [2]. This is an easily scalable platform well suited for quantum information using Rydberg dipole blockade in atomic ensembles [2]. We present results of coherent Rabi oscillations between qubit states and initial experiments towards Rydberg mesoscopic ensembles.

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Nanophotonic and CMOS-integrated architectures for trapped ion quantum information processing

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We present an integrated optics architecture enabling scalable control and measurement for quantum information processing in planar ion traps. Single-mode waveguides distribute light to various locations in a dielectric layer in the same chip as the trap electrodes, and focusing grating couplers direct the light, through gaps in the trap electrodes, to micron-scale focuses at the ion locations. Recent advances in CMOS photonics suggest possible creation of such systems in foundry processes, which would allow practical integration of many couplers, avalanche photodiodes for readout, and electro-optic modulators, and control electronics together with the trap electrodes; additionally, the optics approach proposed would bring performance advantages, including tighter focuses and attendant advantages for individual addressing and laser power requirements, higher collection efficiencies, phase stability owing to reduced free-space path lengths, and pointing stability from inherent alignment. We present also experimental progress to these goals.

Experimental test of state-independent quantum contextuality of an indivisible quantum system

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Since the quantum mechanics was born,quantum mechanics was argued among scientists because the differents between quantum mechanics and the classical physics. Because of this,some people give hidden variable theory. One of the hidden variable theory is non-contextual hidden variable theory, and KS inequalities are famous in non-contextual hidden variable theory.

But the original KS inequalities have 117 directions to measure, so it is almost impossiable to test the KS inequalities in experiment. However, about two years ago, Sixia Yu and C.H.Oh point out that for a single qutrit, we only need to measure 13 directions, then we can test the KS inequaties. This makes it possiable to test the KS inequalities in experiment.

We use the polarization and the path of single photon to construct a qutrit, and we use the half-wave plates, the beam displacers and polar beam splitters to prepare the quantum state and finish the measurement. And the result prove that quantum mechanics is right and non-contextual hidden variable theory is wrong.

Transfer and qubit fidelity of single atoms in a ring lattice

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Controllable transfer of atomic qubits opens a route to quantum information storage and processing. We demonstrate transferring of single atoms in a ring lattice with an auxiliary optical tweezers [1]. Single atoms follow the deeper tweezers and move to the determined position with high efficiency of 95% when they cross the static lattice. Comparison with other schemes [2, 3], it is more convenient for application, especially for single atoms array. Qubit fidelity is analyzed by quantum state tomography during the transportation. Additionally, the coherence properties of single atoms are investigated in detail via spin echo techniques. The reduced fidelity results from the instability of the movable tweezers and the heating of atoms. Dephasing in this process could be suppressed by stabilizing the laser intensity and by reducing the pointing fluctuations. Application of this scheme in quantum information processing is prospected.

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Scalable Source of Multipartite Continuous Variable Entangled Beams of Light

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The development of efficient and scalable sources of multipartite entanglement is required for the further development of quantum information. We propose a scalable configuration based on cascaded four-wave mixing (FWM) processes for the generation of multipartite CV entanglement. The FWM process is based on a double-lambda configuration in rubidium vapor and has been previously used to generate highly entangled twin beams. In the proposed configuration, one of the twin beams is used to seed another FWM process. We have experimentally verified that two cascaded FWM processes lead to the generation of three beams that contain quantum correlations in the form of intensity-difference squeezing and show that the level of squeezing produced by the first FWM process is increased by the second one. We derive a necessary criterion for the presence of multipartite entanglement that shows that one should expect the beams generated by the cascaded FWM processes to be entangled.

Photon-added nonlinear coherent states for a one mode field in a Kerr medium

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We construct deformed photon added nonlinear coherent states by application of a deformed creation operator upon the nonlinear coherent states obtained as eigenstates of the deformed annihilation operator and by application of a deformed displacement operator upon the vacuum state. We evaluate some statistical properties like the Mandel parameter, Husimi and Wigner functions for each of these states and analyze their differences [1]. We give closed analytical expressions for them.

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Advanced single photon sources with fiber-based optical microcavities

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Fiber-based optical microcavities [1,2] combine small mode volume and large quality factors with full tunability and open access. We use enhanced light-matter coupling in the cavity to realize improved single photon sources with colour centers in diamond [3] in two complementary regimes: First, we demonstrate broadband Purcell enhancement of fluorescence from nitrogen-vacancy centers in diamond nanocrystals coupled to a low Q cavity with sub-λ^3 mode volume. Second, we discuss the generation of indistinguishable single photons under ambient conditions by coupling the emission from silicon-vacancy centers to high Q ($>10^6$) cavities. We report on first experimental steps in this direction.

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Quantum optics with hot Rydberg atoms

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The exceptionally strong interaction between highly excited Rydberg atoms enables applications in fields such as quantum optics, quantum computing, quantum simulation and metrology. If however they are to be used routinely in applications, a major requirement is their integration into technically feasible, miniaturized devices. Here we give an overview on our experiments on thermal Rydberg atoms confined in microscopic vapor cells or hollow core fibers [1]. We will present data on the coherent excitation to Rydberg states and how the Rydberg-Rydberg interaction alters the excitation dynamics [2]. We also report on the development of complex vapor cells e.g. including conductive structure for manipulating and detecting Rydberg atoms [3]. Finally, we will present our progress towards a room temperature single photon source.

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Cross-Modulation of Two Laser Beams at the Individual Photon Level

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Deterministic photon-photon interactions are a long-standing goal in optical science. Using an atomic ensemble inside a cavity, we demonstrate the mutual cross modulation of two continuous light beams at the level of individual photons. The originally uncorrelated beams derived from independent lasers become anticorrelated, as evidenced by an equal-time cross-correlation function $g^{(2)} = 0.89(1)$, showing that one photon in one beam extinguishes a photon in the other beam with a probability of 11(1)%. We also report recent progress using this approach for non-destructive continuous detection of traveling optical photons.

Single Photon Transistor in Circuit Quantum Electrodynamics

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Photons are the most suitable carrier for transmitting information over long distances as they are largely immune to environmental perturbations, and can propagate with very low loss and long-lived coherence in a wide range of media. The use of photons in information processing however still suffers from the inability to realize controlled, strong interactions between individual photons. For this reason we introduce a circuit quantum electrodynamical setup for a "single-photon" transistor. In our approach photons propagate in two open transmission lines that are coupled via two interacting transmon qubits. The interaction is such that no photons are exchanged between the two transmission lines but a single photon in one line can completely block respectively enable the propagation of photons in the other line. High on-off ratios can be achieved for feasible experimental parameters.

TUESDAY

Characterization of Non-Classical Photonics States Retrieved from a Cold Atomic Memory and Quantum Statistics of Light Transmitted through Intracavity Rydberg medium.

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Quantum states of light are one of the foremost and robust candidates for quantum information transportation and processing. Cold atomic ensembles are a prime choice to store and manipulate quantum states of light [1]. However, very often the light states stored or engineered in such systems are characterized only partially using photon counting statistics [2-4]. We demonstrate an on-demand retrieval of single photons by implementing the DLCZ protocol [5] in a cavity enhanced cold atomic memory . Single photon states were recovered with high efficiency (up to 82%) in a well defined spatio-temporal mode and consistently characterized by photon counting and homodyne tomography [6].

We theoretically investigate the quantum statistical properties of light transmitted through a cavity-enhanced atomic medium with strong optical nonlinearity induced by Rydberg-Rydberg van der Waals interactions [7]. Currently, an experiment is in progress to characterize the transmitted light by measuring the second order correlation function.

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Reversing the temporal envelope of an heralded single photon using a cavity

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We demonstrate a way to prepare single photons with a temporal envelope that resembles the time reversal of photons from the spontaneous decay process. We use the photon pairs generated from a time-ordered atomic cascade decay as a starting point: the detection of the first photon of the cascade is used as a herald [1,2]. We show how coupling the heralding photon into an asymmetric Fabry-Perot cavity reverses the temporal shape of the heralded photon from a decaying to a rising exponential envelope. A single photon with such an exponentially rising temporal envelope would be ideal for interacting with two level systems. Using the analogy between an atom and a cavity [3] we demonstrate a proof-of-principle experiment on how these photons can be used for strong interaction with a single atom.

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Phase-dependent double-Λ electromagnetically induced transparency

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We theoretically investigate a phase-dependent double-Λ electromagnetically induced transparency (EIT) system. The property of the double-Λ EIT medium with a closed-loop configuration depends on the relative phase of the applied laser fields. This phase-dependent mechanism makes the double-Λ medium is different form the conventional Kerr-based nonlinear medium which only depends on the intensities of the applied laser fields. A steady-state analytical solution of the double-Λ EIT system is obtained by solving the Maxwell-Bloch equations. Additionally, we experimentally demonstrate an efficient all-optical π phase modulation based on the double-Λ EIT scheme in cold Rubidium atoms.

Observation of Spinor Slow Light

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We report the first experimental demonstration of two-component or spinor slow light (SSL) using a double tripod (DT) atom-light coupling scheme [1]. Based on the interaction between the two slow light components, we observed the neutrino-type oscillations controlled by the two-photon detuning. In a proof-of-principle measurement, our data showed that the DT scheme for the light storage behaves like the two outcomes of a Mach-Zehnder interferometer enabling measurements of the frequency detuning. We also experimentally demonstrated a possible application of the DT scheme as quantum memory/rotator for the two-color qubit. Furthermore, the SSL may lead to interesting physics such as Dirac particles and spinor Bose-Einstein condensation of dark-state polaritons. It can also be used to achieve high conversion efficiencies in the sum frequency generation and is a far more superior method than the widely-used double-Λ scheme. This work opens up a new direction in the EIT/slow light research.

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TUESDAY

Quantum Optics and Cavity QED Tu-090

Three-photon electromagnetically induced absorption in a ladder-type atomic system

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We report on three-photon electromagnetically induced absorption (TPEIA) due to three-photon coherence in ladder-type atomic systems for the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition in ^{87}Rb atoms. When a counterpropagating coupling field was added to the typical ladder-type electromagnetically induced transparency (EIT) experiment, both EIT and two-photon absorption (TPA) switched to TPEIA.Considering three-photon coherence in a Dopplerbroadened three-level ladder-type atomic system, the spectrum of the switch from EIT and TPA to TPEIA was numerically calculated and could be understood by decomposing the calculated spectrum into two-photon coherence and three-photon coherence components.

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Line Properties of the Ladder-type Electromagnetically Induced Transparency

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The relative intensities and line shape of the probe transmission in a ladder-type electromagnetically induced transparency (EIT) system by considering the optical pumping effect thoroughly are elucidated. The observed EIT spectra reveal a different probe or coupling power dependence for various transmission peaks. In addition to causing quantum interference, the probe, and coupling laser fields realign the population of Zeeman sublevels in the ground state through optical pumping. Analytical simulation results show a good agreement with the experimental observations.

Investigation of dynamical features in Λ-EIT atomic systems through noise correlation spectroscopy

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We present a study of a cold Rubidium ^{87}Rb ensemble under eletromagnetic induced transparency (EIT). Using noise correlation spectroscopy, we investigate the asymmetric atomic response to an increasing or decreasing scanning in the detuning of a probe in the EIT process.

The Λ-EIT involves Zeeman sublevel coupled by two beams with orthogonal circular polarizations coupling the transition F=1 -> F'=1. A repump coupling the transition F=2 -> F'=2 is added to recycle the population.

Experimentally, we explored the angle between the probes and repump detuning, intensity and incidence direction. Additionally, spectra in time domain were studied.

Our theoretical approach[1] models the system simply as a Λ coupling in a 3 level atom. Although this model contains the basic features of EIT, it is not enough to explain atomic response observed. As we wish to fully understand the dynamics and obtain the characteristic time scales of relaxation processes, we present here a more sophisticated model.

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TUESDAY

Electromagnetically induced photonic bandgap in cold ^{87}Rb atoms

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An Electromagnetically induced photonic bandgap is formed in cold ^{87}Rb atoms using configuration of Λ-type electromagnetically induced transparency in which the strong coupling beam is replaced by a standing-wave. When the probe light is propagating along the standing-wave, we are able to observe the transmission and the reflection behaviors of the weak probe beam. We studied the properties of electromagnetically induced photonic band gaps as the frequency detuning, polarization, or intensity of the coupling beam.

TUESDAY

Synchronization in Superradiant Lasers

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Superradiant lasers using cold atoms operate in a unique regime of laser physics where laser coherence is generated by spontaneous synchronization of the optical dipoles of an ensemble of atoms. Our rubidium superradiant laser offers unique access to this atomic synchronization process. We have recently studied superradiant synchronization in two experiments, observing for the first time both synchronization of a lasing superradiant ensemble to an external driving field and spontaneous synchronization of two superradiant ensembles. Here we present recent results from the two experiments with applications for the fundamental study of non-equilibrium phase transitions, synchronization of quantum oscillators, and possible generation of exotic many-body states in an open quantum system.

Imaging the Rydberg Electron Wavefunction

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An electron excited to a Rydberg state has an orbital radius larger than optical wavelengths and polarizes 1000s of ground state atoms in a dense medium such as a BEC. The interaction of the electron with the ground state atoms can be described by a pseudopotential linearly dependent on the ground state atom density. This interaction energy alters the density of the surrounding ground state atoms offering the possibility to image the probability density of the Rydberg electron imprinted in a dense medium [1]. We report on the progress of imaging the electron wavefunction of a single Rydberg atom in a ^{87}Rb BEC with 1μm resolution. The density modulation signal will increase due to multiple Rydberg excitations created using an excitation laser focused through the center of the BEC. First experiments concentrate on nS Rydberg states with n in the range of 100-160.

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TUESDAY

Dipolar transport in ultracold Rydberg gases

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Interfacing laser light with electronically highly excited (Rydberg) atoms allows to engineer synthetic systems for simulating coherent-quantum and open-system many-body dynamics. Rydberg atoms experience state changing interactions similar to Förster processes in complex molecules, offering a model system to study the nature of dipole-mediated energy transport in a controlled many-body system. We apply a new imaging technique to monitor the migration of Rydberg excitations with high time and spatial resolution [1,2]. The many-body dynamics is determined by continuous spatial projection of the electronic quantum state which establishes an environment for the transport dynamics [2]. With the available control of interactions and environment via the laser fields, we show that this system opens the way to studying the transition from classical to quantum transport as well as to investigations of dipolar transport phenomena which could ultimately shed new light on the nature of energy and spin transport in complex quantum systems.

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Spin squeezing and supersolids using Rydberg-dressed strontium atoms

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Coherent excitation of cold atoms to Rydberg states provides a new platform for quantum many-body physics. We demonstrate the utility of divalent atoms in this pursuit, showing that laser excitation of the second valence electron enables spatially resolved, state-selective detection of Rydberg atoms with single-atom sensitivity [1] and full access to counting statistics [2]. Strontium's narrow intercombination lines not only provide the option to cool to the photon recoil limit but also enable two-photon excitation to the Rydberg state with low decoherence, providing an ideal system to investigate "Rydberg dressing". Here, a strong, off-resonant coupling to the Rydberg state introduces a new, tunable, soft-core interaction between the atoms, with potential for the formation of a Rydberg supersolid phase [3]. With the MPIPKS Dresden we show that applying this dressed interaction to strontium lattice clocks can also lead to the generation of significant spin squeezing that could be used to improve the signal-to-noise ratio [4]. We will present the first indications of Rydberg Blockade in a divalent atom in addition to the status of experiments seeking to observe Rydberg dressing.

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Ultralong Range Rydberg Molecules of Strontium

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We report the formation of ultralong range Rydberg molecules in a thermal gas of neutral strontium. This work serves as an important first step in characterizing electron-ground state atom interactions in strontium. Using two photon excitation through the metastable $^3P_1$ state, we create molecules in the $5sns^3S_1$ Rydberg series in the vicinity of n = 35. Molecule formation is detected as a loss of atoms from an optical dipole trap. Understanding these molecules lays the foundation for our future work in Rydberg excitation and Rydberg dressing of a Bose Einstein condensate of strontium. I will also describe progress towards these ends.

Ultrafast coherent control of an ultracold Rydberg gas

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TUESDAY

We investigate many-body interactions in an ensemble of ultracold Rydberg atoms by means of ultrafast coherent control with attosecond precision [1]. A picosecond laser pulse produces Rydberg electronic wave-packets in a cloud of laser-cooled Rb atoms prepared in an optical dipole trap. The bandwidth of our picosecond laser pulse is larger than that of the CW or nanosecond-pulsed laser employed in previous experiments with ultracold Rydberg atoms [2,3], so that our Rydberg-blockade radius is significantly smaller. This allows for a high density of Rydberg atoms and consequently for strong many-body interactions, which modulate the temporal evolution of the wave-packets. The strength of the interactions is actively tuned by changing the atom density and the principal quantum number. In this presentation, we will discuss the atom-density dependence of the Rydberg wave-packet interferogram. This technique could be a novel approach to investigating quantum many-body dynamics.

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Dynamical crystallization in a low-dimensional Rydberg gas

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Rydberg gases o er the possibility to study long-range correlated many-body states due to their strong van der Waals interactions. In our setup, we optically excite Rydberg atoms and detect them with submicron resolution, which allows us to measure spatial correlations of resulting ordered states. Starting from a two dimensional array of ground state atoms in an optical lattice, we couple to a Rydberg state in a two-photon excitation scheme. Using numerically optimized pulse shapes for coupling strength and detuning, we deterministically prepare the crystalline state in this long-range interacting many-body system. Control of the spatial con guration of the initial state is of great importance for the investigation of the phase diagram. To achieve this, we developed an experimental scheme based on single site addressing allowing for preparation of initial states with sub-Poisson number uctuations.

Rydberg blockade in an optical lattice

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Ultracold Rydberg atoms are a promising system to study quantum many body effects due to their strong Rydberg interactions. The strength of the interaction is tunable via the principal quantum number of the Rydberg state, and we choose a regime where only nearest neighbors in our optical lattice are strongly blockaded. We perform fluorescence spectroscopy of the 18S Rydberg level in ultracold Rb-87 by exciting a two-photon transition with intermediate detuning near the D1 line and detecting photons emitted on the D2 line with a single photon avalanche diode. We use this technique to measure a magic wavelength, where there is no differential light shift between the ground and Rydberg state, near 1064 nm to better than 1 GHz. We also report initial progress toward spectroscopy in a 3D optical lattice in which the Rydberg blockade effect should allow us to generate collective states that exhibit large spatial and temporal correlations.

Tune-out wavelengths for metastable helium

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Tune-out wavelengths occur near atomic transitions where the opposite sign of the respective contributions to the dynamic polarizability of the atom cancel to yield a net zero polarizability [1]. Mitroy et al. [2] have estimated the locations of the tune-out wavelengths associated with the metastable helium at the 0.1% level in order to provide a guide to experimental investigations. If the tune-out wavelength can be determined to an absolute accuracy of 100fm (~0.2 ppm), then the fractional uncertainty in the derived structure information would be 1.8 ppm [2]. We will employ our metastable helium facility used in previous precision measurements [3] to determine the effect of a light field near the 413nm tune-out wavelength on the trap frequency, and later employ our new atom interferometer facility to accurately measure the tune-out wavelength of light illuminating the metastable helium atoms for which there is no change in the interferometric fringe position.

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Magic polarization to eliminate Stark-induced dephasing in an optical trap

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We demonstrate that the differential ac-Stark shift of a ground hyperfine transition in an optical trap can be eliminated by using properly polarized trapping light. We use the polarization dependence of the Stark shift via vector polarizability that resembles a Zeeman shift. We study a Zeeman-sensitive transition from the $|2S_{1/2}, F = 2, m_F = -2\rangle$ to the $|2S_{1/2}, F = 1, m_F = -1\rangle$ state of ^{7}Li. By using magic polarization we observed 0.59 ± 0.02 Hz linewidth for Rabi transition with interrogation time 2 s and 0.82 ± 0.06 s coherence time for a superposition state. These are improvements over previous results by at least two orders of magnitude. We hope that the magic polarization brings breakthroughs in precision spectroscopy and quantum information processing just as the magic wavelength did in frequency metrology and cavity quatum electrodynamics.

Magic Frequencies in Atom-Light Interaction for Precision Probing of the Density Matrix

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We analyze theoretically and experimentally [1] the existence of a magic frequency for which the absorption of a linearly polarized light beam by a vapor of alkali-metal atoms is independent of the population distribution among the Zeeman sublevels and the angle between the beam and an external magnetic field, which defines the quantization axis. From a fundamental point of view, the magic frequency represents a unique cancellation of the contributions of higher moments of the atomic density matrix to light absorption, so that light-matter interaction becomes rotationally invariant although the atomic sample as well as the light beam and its polarization all have a well-defined direction. The phenomenon is described using the Wigner-Eckart theorem and inherent properties of Clebsch-Gordan coefficients. One important application is the robust measurement of the hyperfine population. We experimentally demonstrate the magic frequency on an ensemble of rubidium atoms inside a vapor cell.

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Tailoring light to enhance forbidden atomic transitions rates

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The coupling between the electric dipole moment **d** of an atom to the electric field **E** of an electromagnetic wave, **d .E**, yields optical dipole transition amplitudes, so that the corresponding transition rates |**d .E**|^2 are proportional to the intensity of the pump field. Quadrupole and magnetic dipole atomic moments couple to the derivatives of **E**. We make a comparative study of different vectorial modes of the electromagnetic field that, having greater values of the derivatives of **E** with respect to standard paraxial Gaussian pump beams, enhance the quadrupole and magnetic dipole transition rates. We take polarization, focusing and topological structure (optical vortices and phase dislocations) as the relevant properties of the pump beams. The feasibility of the realization of optimal pump beams and the expected results for specific atomic transitions is also discussed.

Time-resolved measurement of velocity-changing collisions in a paraffin-coated alkali vapor cell

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A paraffin coating on the walls of an alkali vapor cell might increase a residual gas pressure. In order to find out whether paraffin-coated cells contain a non-negligible buffer gas, we measure the effect of velocity-changing collisions (VCCs) on the microsecond time scale. The polarization of atoms that move perpendicular to laser beams is produced and measured by means of velocity-selective optical pumping. In addition to collisions with coated walls, VCCs with a buffer gas occur and affect the signals of the polarization if the cell contains a buffer gas. We can distinguish these collisions by time-resolved measurement because VCCs occur before wall collisions. Comparing the measurements for coated cells with that for non-coated cells, we can determine whether the coated cells contain a buffer gas.

Atom-surface interactions using a quadrupole oscillator strength sum rule

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Characterizations of the long-range potentials for interactions between atoms or molecules and surfaces are of key interest for collisional and trapping studies. Knowledge of the electric dipole oscillator strength distribution of the atom or molecule provides one route to obtaining the interaction coefficient. In this paper an electric quadrupole oscillator strength sum rule is related to the atom-surface interaction. The utility of the approach for calculating interactions between various atoms and molecules and different surfaces is explored.

Adsorbate Electric Fields on a Cryogenic Atom Chip

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We investigate the behaviour of electric fields originating from adsorbates deposited on a cryogenic atom chip as it is cooled from room temperature to cryogenic temperature. Using Rydberg electromagnetically induced transparency we measure the field strength versus distance from a 1mm square of YBCO patterned onto a YSZ chip substrate. We find a localized and stable dipole field at room temperature and attribute it to a saturated layer of chemically adsorbed rubidium atoms on the YBCO. As the chip is cooled towards 83K we observe a change in sign of the electric field as well as a transition from a localized to a delocalized dipole density. We relate these changes to the onset of physisorption on the chip surface when the van der Waals attraction overcomes the thermal desorption mechanisms [1] .

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TUESDAY

Relaxation of Cs atomic polarization at surface coatings characterized by x-ray photoelectron spectroscopy

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We study anti-relaxation surface coatings in order to preserve atomic spin polarization in alkali vapor cells. The polarization of the alkali atoms relaxes due to the collisions with the cell wall. However anti-relaxation surface coatings reduce the effects of spin relaxation at the wall of the cell. The most effective known anti-relaxation coating is paraffin, with which polarized alkali atoms may collide up to 10000 times before depolarizing. Its effectiveness varies considerably depending on the preparation skill of the individual involved. Relationship between the effectiveness and surface conditions had not been extensively studied. We made paraffin and diamond-like carbon (DLC) coated substrates by vacuum vapor deposition, and measured relaxation times for Cs vapor. We confirmed the anti-relaxation effect only with paraffin. According to x-ray photoelectron spectroscopy, effective anti-relaxation substrates had high carbon coverage.

Raman spectroscopy and NMR investigation of hydrocarbon anti-relaxation coatings upon interaction with an alkali-metal vapor

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TUESDAY

New alkene-based anti-relaxation coating of alkali metal vapor cell demonstrated up to 10 times longer relaxation time then the same time for classical alkane-based coating [1]. The results of experimental investigations of the influence of alkali-metal vapor on different types of coating materials, via Raman spectroscopy and Nuclear Magnetic Resonance (NMR) Spectroscopy are presented. Standard coated alkali- metal vapor cells, coated glass wafers, and the same material inside special vacuum tubes were used as experimental samples. Alkene-based anti-relaxation - coating material from [1] was studied with the NMR method. Isomerization of alkene - double bond moving from the "alpha" position towards the center of the molecule was found. This work considerably extends the earlier studies of the anti-relaxation coatings by a variety of surface-science techniques [2].

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Nonlinear spectroscopy of atoms inside a porous sample

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The nonlinear response of Rb vapor inside the pores of a ground glass sample made of grains of a few tenth of micrometers was studied and shown to be affected by confinement and the spatial randomness of the light scattered by the sample. Sub-Doppler resonances were observed in Hanle spectroscopy and in a saturation-absorption-like pump-probe experiment arising from atoms near the sample surface. Specificities in the spectrum reveal the atomic confinement [1]. The spectroscopic examination of scattered light that has traversed the bulk of the sample does not show narrow Sub-Doppler resonances. This negative result is interpreted as a consequence of the speckle nature of the light inside the sample. Nonetheless, broad pump-probe spectral features are observed as a consequence of hyperfine optical pumping. The observed spectra are in good agreement with a simple model for two-photon interaction of atoms with thermal velocity distribution with random light.

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Cell influence on the absolute frequency of cesium atom 6S-8S hyperfine transition

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Glass cells, like iodine cell, rubidium cell and so on, have been used for secondary standard for several of ten years. It is long believed that some unclear effects obstruct the atomic frequency measurements from cells since 10 kHz discrepancy between secondary standards were easy to be found. Here we report on one significant fact. We examined 10 cells for obtaining the absolute frequency of cesium atom 6S-8S hyperfine transition and, to our surprise, the frequency measurement results scattered over 400 kHz! We found that the frequency deviation determined from each cell has correlation with its linewidth [1]. To precisely measure the aforementioned linewidth, we develop a novel approach of stabilizing laser frequency by two-photon interfered spectrum that leads to higher resolution than previous result [2].

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Revised and extended analysis of trebly ionized selenium: Se IV

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The fourth spectrum of selenium has been investigated in the wavelength region 300-2080Å using triggered spark source. The ground configuration of Se IV is $4s^2 4p$ and its outer excitation is basically one-electron system with doublet structure while inner excitation leads to a three-electron system making structure more complex. We have studied the $4s^2np(n=4\text{-}7)+4s^2 nf(n=4\text{-}6)+4p^3+4s4p(5s+6s+4d+5d)$ configurations in the odd parity system and $4s^2ns(n=5\text{-}7)+4s^25g$ configurations in the even parity matrix. In one electron spectrum, the levels of $4s^2$ (5s,6s,4p,5p,6p,4d,5d,4f and 5g) configurations are being confirmed but revised the levels of $4s^2$ (7s,7p,6d and 5f) configurations. In three-electron system, $4s4p^2\ {}^4S_{3/2}$ and all levels of $4p^3$ configuration have been revised. The 4s4p(4d+5d+5s+6s) configurations have been studied for the first time. Forty-six odd and seventeen even parity energy levels are now known based on the identification of three-hundred transitions. The Ionization limit was found to be $346721\pm265cm^{-1}(42.988\pm0.033eV)$. The analysis is supported by Hartree-Fock calculations. Parametric values of energy levels agreed well with the experimental values.

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The fourth spectrum of tin: Sn IV

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The spectrum of trebly ionized tin (Sn IV) has been investigated with the help of spectral recordings made on a 3m normal incidence vacuum spectrograph of Antigonish laboratory in Canada using a triggered spark light source. The ground configuration of Ag-like tin is $4d^{10}5s$. The outer electronic excitation gives rise to $4d^{10}n\ell$ configurations with doublet structure, while inner electron excitation leads to form the configurations like $4d^95s$ [5p+4f], $4d^95s^2$ and $4d^95p^2$. We have confirmed all the reported levels [1, 2] belonging to one electron part but could not confirm all the levels of doubly excited configurations. The $4d^95s5p$- $4d^95p^2$ transitions lie around 1000-1500Å was turn out to be very helpful to confirm the reported levels of $4d^95p^2$ as well as to establish the new levels of $4d^95s5p$ with $J\geq 5/2$. The Hartree-Fock calculations by Cowan's code support the analysis.

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A New Simple Atom for Atomic Physics: e^+ bound to H^- in atomic state, H^{-+}

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An H^- ion beam is directed through a sample of trapped e^+ from a radioactive source, producing long lived H^{-+} atoms. For production, ions are decelerated to ~50eV by an electric field from applied potentials on cylindrical electrodes. These electrodes along with an axial magnetic field produce a Penning trap for ~$10^7 e^+$ slowed and captured in this Surko-style e^+ accumulator. H^{-+} travel 2 meters and into a metal plate where back-to-back e+ annihilation gammas emitted are detected in coincidence. Typically systems with antimatter bound to matter have short lifetimes (and hence wide transition widths) due to annihilation. Rydberg states of H^{-+} have long radiative lifetimes and hence narrow transitions. The 2 meter transit indicates a survival time of ~5microseconds

We will also present research toward measurements of Rydberg positronium atomic structure.

TUESDAY

Solitons, Interactionless BECs and Simultaneous Dual Isotopes in Atom Interferometry

Gordon McDonald[1], Carlos Kuhn[1], Kyle Hardman[1], Shayne Bennetts[1], Patrick Everitt[1], Paul Altin[1], John Debs[1], John Close[1], Nicholas Robins[1]

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We demonstrate the first realisation of a solitonic atom interferometer, using a tunable-interaction condensate of Rubidium-85 in a horizontal optical waveguide [1]. By balancing the inherent matter-wave dispersion with a small attractive inter-atomic interaction, a non-dispersive cloud - a bright soliton - can be formed. We construct a Mach-Zehnder interferometer using this variable-interaction-strength condensate . It is found that the soliton interaction strength maximises the coherence time of the interferometer, over all other possible interaction strengths including an interactionless condensate.

Due to the sympathetic cooling process we employ to generate condensates of Rubidium-85, we can also produce dual condensates of both Rubidium-85 and Rubidium-87 in the same trap [2]. By loading both of these into the optical waveguide we can construct a simultaneous Mach-Zehnder interferometer on both isotopes. Such a scheme is proposed for Weak Equivalence Principle measurements. This allows cancellation of common-mode vibration noise sources. Also, we measure the phase shift on an interactionless Rubidium-85 Mach-Zehnder interferometer due to a variable number of coincident Rubidium-87 atoms, which should allow a precision measurement of the inter-isotope scattering length.

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Compact atom interferometer inertial sensor with radially expanding atom ensemble

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We present our work toward a novel compact atom interferometer inertial sensor based on a single radially expanding ensemble of laser-cooled atoms interrogated by pulsed stimulated Raman transitions. The sensor design emphasizes small size and simplicity of operation, while potentially achieving a performance level suitable for inertial navigation. The expansion of the atom ensemble together with spatially-resolved detection enables the separation of acceleration-induced phase shifts from rotation-induced phase shifts, allowing acceleration and rotation to be independently measured. In addition, the ability to spatially resolve phase shifts across the cloud enables us to mitigate the effect of imperfections like magnetic field gradients, residual light shifts, and imperfections in the interrogation beams.

Agile narrow linewidth single source laser system for onboard atom interferometry

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Atom interferometers have demonstrated excellent performance for precision acceleration and rotation measurements [1]. Many researches have been made the last few years to develop transportable laser systems [2] and particularly to make the laser setup as compact and immune to perturbations as possible [3].

We realized a compact and robust laser system for rubidium atom interferometry based on a frequency-doubled telecom laser. Our frequency stabilization architecture allows us to tune dynamically the laser frequency over 1 GHz in few ms using only one laser source. Each laser frequency used for atom interferometry is created by changing dynamically the frequency of the laser or by creating sidebands using a phase modulator. We take advantage of the maturity of fiber telecom technology to make the setup compact, immune to vibrations and thermal fluctuations. The source provides spectral linewidth below 10 kHz required for precision atom interferometry, and particularly for atom gravity gradiometer.

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A Mobile, Dual-Species Atom Interferometer for Equivalence Principle Tests in Micro-Gravity

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The ICE experiment is a compact and transportable atom interferometer designed to make precise tests of the weak equivalence principle (WEP) using two atomic species: ^{39}K and ^{87}Rb. The WEP states that two massive bodies will undergo the same gravitational acceleration regardless of their mass or composition. An atom-interferometric test of the WEP involves precisely measuring the relative acceleration of two different atoms. Since potassium and rubidium differ greatly in mass, but have similar internal structure, they are ideal choices for this type of test. Recently, we demonstrated the first airborne matter-wave interferometer, which operated in the micro-gravity environment created during the parabolic flights of the Novespace Zero-g aircraft [1]. The 20 seconds of 0g produced during each parabola allows us to extend the interrogation time and therefore the sensitivity of our interferometer. Here, we present our recent experimental results, including some of the first interferometric measurements with ^{39}K [2].

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TUESDAY

Matter-wave laser Interferometer Gravitation Antenna (MIGA) experiment for fundamental physics and geoscience

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The MIGA experiment will implement a hybrid sensor coupling laser and matter-wave interferometry to study sub-Hertz variations of the strain tensor of space-time and gravitation. An array of atomic interferometers will be simultaneously manipulated by the resonant optical field of a 200 m cavity. The system will use as gravity sensors both the suspended cavity mirrors, whose relative motion is optically monitored, and free falling atomic ensembles, probed with matterwave interferometry techniques. The experiment will be located underground at the LSBB laboratory in Rustrel (France), far from major anthropogenic disturbances and in an environment with a very low background noise [1]. The presence on site of several instruments to monitor the geophysical site (inclinometers, accelerometers, magnetometers, seismometers…) will be exploited to push the experimental sensitivity. We will report on the status of the small scale prototype that we will use to study cavity aided atom interferometry.

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Ytterbium Bose-Einstein condensate interferometer: current results and new construction.

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We present the first ytterbium matter-wave interferometer using a Bose-Einstein condensate (BEC) source in a contrast interferometer geometry. We measure h/m, where h is Planck's constant and m is the mass of an ytterbium atom, in order to determine the fine structure constant α. We demonstrate theoretical understanding and experimental control over our two main sources of systematic error: atomic interactions and diffraction phases. Based on our findings, we present our plans for increasing the precision of our α measurement to the level of one part in ten billion. We also observed that the interferometer signal is sensitive to the condensate critical temperature, and we propose BEC interferometry as a tool for studying phase transitions. We will describe some of the features of a new apparatus for our next generation of measurements that is currently under construction.

Dynamic algebraically precise atom chip potentials

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Precision potentials for cold atom experiments are often limited by the placement of individual conductors and the resulting magnetic field shape. Traps and guides are typically created to achieve a singular purpose, with new experiments requiring redesigned coils or atom chips. We present a method to create customized, dynamic, and algebraically precise potentials over large distances along the axis of a cold atom waveguide near the surface of an atom chip. Our experimental results include demonstrations of a pure harmonic trap and a dynamic double well. We will present our methods for fabricating atom chips and the corresponding experimental setup.

Quantum interference experiments with macromolecules

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The quest for testing the quantum superposition principle in the regime of high mass and complexity has motivated quantum interference experiments with macromolecules.

We present experiments in a Kapitza-Dirac-Talbot-Lau matter-wave interferometer [1,2] and report on the current mass record in de Broglie interference [3].

The sensitivity of molecular coherence to tiny external forces enables the investigation of internal molecular properties through measurements of dephasing and shifts of the molecular interference patterns. This has been exploited for the study of electric polarizability and moments in molecule interferometry in the presence of inhomogeneous electric fields [4,5].

Recently, we were able to demonstrate how to derive absolute photo-absorption cross sections from quantum interferometry [6]. The recoil imparted on each molecule upon absorption of a single photon leads to an effective reduction in quantum fringe visibility. This allows us to extract the cross section with high accuracy and independent of the molecular beam density.

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Atom interferometry of trapped BECs with tunable interactions

Andreas Trenkwalder[1], Giacomo Spagnolli[1], Giacomo Colzi[1], Giulia Semeghini[1], Manuele Landini[1], Giovanni Modugno[1, 2], Massimo Inguscio[1, 2], Marco Fattori[1, 2]

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We present a new atom interferometry experiment with BECs of 39K atoms with tunable interactions. The setup consists of an array of double-well potentials which we can operate in parallel. The tunability of interactions allows to obtain long coherence times and the possibility of using entangled states has the potential to increase the sensitivity beyond shot noise towards the Heisenberg limit.

TUESDAY

Generation 2 of the ACME electron EDM search

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We present a proposal to upgrade the ACME experiment to make a new measurement of the electron's electric dipole moment (eEDM). We plan a number of improvements to increase statistical sensitivity and suppress known systematic effects. Statistical sensitivity improvements include an upgraded molecular beam source, a molecular electrostatic guide, and a coherent state preparation scheme. We estimate a signal sensitivity improvement of at least an order of magnitude over our previous limit [1].

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Measuring the Xe-129 Permanent Electric Dipole Moment

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We describe a new, ongoing measurement of the permanent electric dipole moment of the Xe-129 nucleus. Our technique, which extends sensitivity to beyond-Standard-model physics and makes Xe-129 available as a magnetometer species for other experiments, employs a cohabiting He-3 magnetometer and a magnetic environment with the lowest residual field and gradients yet produced over a cubic-meter volume.

The noble gas nuclear spins are prepared by spin-exchange optical pumping, and probed using sensitive magnetometry in a highly stable magnetic environment with both active and passive shielding. Novel cell design, magnetic shielding, SQUID detection, and next-generation optical magnetometry are discussed.

Cold and intense sources of large and heavy molecules for precision measurement of the electron EDM and parity violation

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Measurements of heavy polar molecules, such as YbF, enable a very precise determination of the electic dipole moment of the electron [1]. Here we describe new cryogenic buffer gas sources that we have developed, which provide beams of molecules that are significantly slower and more intense than the supersonic beams used previously [2]. The use of such a buffer gas beam, in combination with laser cooling, is expected to reduce the statistical uncertainty of measurements of the electron EDM being carried out at Imperial College London by several orders of magnitude [3].

Similarly, polyatomic molecules possessing chirality can be used to carry out sensitive and direct tests of parity violation. Recent proposals for such experiments have suggested that chiral derivatives of methyltrioxorhenium (CH_3ReO_3), or MTO, can be particularly sensitive probes of parity violation [4,5]. We have developed a simple source of buffer gas cooled MTO molecules in a closed cryogenic cell. To demonstrate the low temperatures achieved, we have carried out high-resolution spectroscopy of the Re-O antisymmetric stretching band at 10.2μm. We will present these results, along with plans to build a slow and intense beam of buffer gas cooled MTO molecules for use in a measurement of parity violation.

TUESDAY

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Interrogating the atomic nucleus with laser spectroscopy: francium (Fr) hyperfine anomaly and isotope shift measurements.

Jiehang Zhang[1], Michael Tandecki[2], Robert Collister[3], Seth Aubin[5], John Behr[2], Eduardo Gomez[4], Gerald Gwinner[3], Luis Orozco[1], Matthew Pearson[2], Gene Sprouse[6]

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We present laser spectroscopy of francium. The experiment uses laser cooling and trapping techniques in an accelerator-based radioactive isotope facility at TRIUMF, Canada. We use RF modulation techniques to carry out precise measurements of $7P_{1/2}$ state (*D1* line) hyperfine splitting in isotopes $^{206\text{-}213}$Fr and ^{221}Fr, including the long-lived isomer of ^{206}Fr, we observe the effect of the spatial distribution of the neutron magnetization: the hyperfine anomaly (Bohr-Weisspkof effect). This measurement provides a sensitive probe of the neutron wavefunction for testing theories near the doubly "magic" ^{208}Pb region. The isotope shift with its sensitivity to electron correlations is used to benchmark *ab-ibitio* atomic theory calculations. These important tests for both the atomic and nuclear theory are needed for extracting weak interaction parameters from atomic parity non-conservation (APNC) measurements. Supported by NRC, TRIUMF, and NSERC from Canada, DOE and NSF from the USA, and CONACYT from Mexico.

TUESDAY

Precision Measurement of Li Hyperfine & Fine Structure Intervals

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A number of experiments have precisely measured fine and hyperfine structure splittings as well as isotope shifts for several transitions at optical frequencies for ^{6,7}Li [1]. These data offer an important test of theoretical techniques developed by two groups to accurately calculate effects due to QED and the finite nuclear size in 2 and 3 electron atoms. The work by multiple groups studying several transitions in both Li^+ and neutral Li permits a critical examination of the consistency of separately, the experimental work as well as theory. Combining the measured isotope shifts with the calculated energy shifts passing these consistency tests permits the determination of the relative nuclear charge radius with an uncertainty approaching 1 x 10^{-18} meter which is more than an order of magnitude better than obtained by electron scattering. Propsects for a precision measruement of the fine structure constant are also discussed.

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TUESDAY

Nuclear Spin Dependent Parity Violation in Diatomic Molecules

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Nuclear spin-dependent parity violation (NSD-PV) effects arise from exchange of the Z^0 boson between electrons and the nucleus, and from interaction of electrons with the nuclear anapole moment (a parity-odd magnetic moment induced by electroweak interactions within the nucleus). We study NSD-PV effects using diatomic molecules. Here, observable signals from NSD-PV are amplified by many orders of magnitude when two levels of opposite parity are brought close to degeneracy in a strong magnetic field. We present preliminary results that demonstrate statistical sensitivity to NSD-PV effects surpassing that of any previous atomic parity violation measurement, using the test system ^{138}Ba^{19}F. We also discuss systematic errors in the current measurements, and short-term prospects for measuring the nuclear anapole moment of ^{137}Ba with this method. Over the long term, our technique is sufficiently general and sensitive that it should apply to measurements of the NSD-PV couplings for a wide range of nuclei.

Shifts due to quantum-mechanical interference from distant neighboring resonances

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Quantum-mechanical interference with distant neighboring resonances is found to cause shifts for precision saturated fluorescence spectroscopy of the atomic helium 2 ^3S-to-2 ^3P transitions. The shifts are significant (larger than the experimental uncertainties for measurements of the intervals) despite the fact that the neighboring resonances are separated from the measured resonances by 1400 and 20000 natural widths. The shifts depend strongly on experimental parameters such as the angular position of the fluorescence detector and the intensity and size of laser beams. These shifts must be considered for the ongoing program of determining the fine-structure constant from the helium 2 ^3P fine structure. The work represents the first study of such interference shifts for saturated fluorescence spectroscopy and follows up on our previous study of similar shifts for laser spectroscopy.

This work is supported by NSERC, CRC, ORF, CFI, NIST and SHARCNET.

Buffer gas cells and quantum cascade lasers: towards measuring parity violation in chiral molecules using vibrational spectroscopy

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TUESDAY

The weak interaction should cause parity violating frequency shifts between the rovibrational spectra of two enantiomers of a chiral molecule. However, these effects have never been observed. We report on our latest progress towards making this observation.

On the source side, we report the creation of an 8 K buffer gas cell of methyltrioxorhenium (MTO), a molecule of interest for the project. An MTO target is ablated in the cell using an Nd:YAG laser, and the resulting plume is cooled by the helium buffer gas. This is the first buffer gas cell of organometallic molecules, and is a stepping-stone towards a key goal of making a beam.

We also report the locking of a 10µm QCL onto our narrow linewidth CO_2 laser. The result is a QCL with a 10 Hz linewidth, the narrowest to date [1].

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Progress in barium tagging for the next generation ^{136}Xe double beta decay experiment

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The "ideal" next-generation neutrinoless double beta decay experiment would have tonne-scale mass and perfect discrimination against all background events. This is uniquely conceivable in a liquid or gas ^{136}Xe double beta decay experiment through detecting, or "tagging", the ^{136}Ba daughter atom or ion at the site of the decay.[1],[2] The next-generation ^{136}Xe experiment, nEXO, could probe the region of normal neutrino mass hierarchy with the implementation of barium daughter tagging in its second stage of operation.

Within the EXO Collaboration, efforts to demonstrate barium atom tagging in liquid xenon include using laser fluorescence of single Ba atoms captured in solid xenon on an optical probe and thermal ionization or laser ablation and resonance ionization of single Ba atoms captured on a tip. Barium tagging research in xenon gas includes extraction of single Ba ions from high pressure Xe gas and transport to an ion trap.

Supported by NSF and DOE.

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Towards an improved measurement of the n=2 triplet P fine structure of helium

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A comparison of precise experimental and theoretical determinations of the n=2 triplet P fine structure of helium allows for a precise determination of the fine-structure constant. An improved experiment is in progress which uses transverse laser cooling to prepare a more intense beam of thermal metastable helium atoms. Fine-structure transitions are driven using microwaves in a separated-oscillatory-field configuration. A new detection technique via an intermediate transition to the 3S state eliminates the largest systematic effect in our previous measurement and improves the signal-to-noise ratio.

We acknowledge funding from NSERC, CFI, CRC, ORF, and NIST.

Neutrino spectroscopy with atoms and molecules

Takahiko Masuda, for the SPAN collaboration

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This poster describes a new experimental method using atoms and molecules which is aiming at the measurement of unknown parameters of neutrinos: the absolute mass, the particle type (Majorana or Dirac), and the CP-violating phases. The process we use is a cooperative de-excitation of a collective body of atoms in a metastable level emitting a neutrino pair associated with a photon. An observable of this experiment is wavelength of the photon which is emitted with a neutrino pair, and the spectra of the photon have information of the neutrino properties. One important item of this experiment is the amplification of emission rate using macro-coherence in target media. We thus performed an experiment to validate this amplification mechanism with para-hydrogen gas target and two monochromatic lasers. The experimental concept of neutrino spectroscopy, expected spectra of photon energy, and the current status of the experiment will be discussed.

The Cold Atom Gravimeter at the μ-Gal-Level for Field Applications

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Recently, the novel inertial sensors based on atom interferometer have a rapid development. The mobile atom gravimeter has become a reality. We have realized a high precision atom gravimeter for field applications. Currently, with the interrogation time and the repetition rate 2.2 Hz, a sensitivity of has been reached in our experiment. The tidal phenomenon is observed continuously over 128 h based on our atom gravimeter. Moreover, a whole seismic wave occurred in Pakistan was recorded in detail with our atom gravimeter and the results are very consistent with that recorded by a traditional seismic detector. Finally the absolute gravity value at the location of our laboratory has been measured, the uncertainty of the measurement is about . The current performance of our gravimeter meets the most of the field applications.

Critical Nuclear Charge and Electron Charge Distribution for Two-Electron Atoms

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The critical nuclear charge Z_c required to bind a nucleus plus two electrons in a heliumlike atom has been calculated to high precision, thereby resolving a long-standing discrepancy in the literature [1]. The result is $Z_c = 0.911028224077255 73(4)$, corresponding to $1/Z_c = 1.097660833738559 80(5)$. The outer electron remains localized near the nucleus, even at $Z = Z_c$, and the bound state evidently changes smoothly into a shape resonance for $Z < Z_c$. A qualitative polarization potential is proposed to account for the resonance, and the radial distribution function for the electron density is calculated.

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ATOMIC CLOCKS

Progress Toward a Spin Squeezed Optical Atomic Clock Beyond the Standard Quantum Limit

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State of the art optical lattice atomic clocks have reached a relative inaccuracy level of 10^{-18} [1,2], already making them the most stable time references in existence. One restriction on the precision of these clocks is the projection noise caused by the measurement of the atomic state. This limit, known as the standard quantum limit (SQL), can be overcome by entangling the atoms. By performing spin squeezing [3], it is possible to robustly generate such entanglement and therefore surpass the SQL of precision in optical atomic clocks [4]. I will report on recent experimental progress toward realizing spin squeezing in an ^{171}Yb optical lattice clock. A high-finesse micromirror-based optical cavity mediates the atom-atom interaction necessary for generating the entanglement. By exceeding the SQL in this state of the art system, we are aiming to advance precision time metrology and expand the boundaries of quantum control and measurement.

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TUESDAY

Near-Heisenberg-Limited Atomic Clocks in the Presence of Decoherence

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The ultimate stability of atomic clocks is limited by the quantum noise of the atoms. To reduce this noise it has been suggested to use entangled atomic ensembles with reduced atomic noise. Potentially this can push the stability all the way to the limit allowed by the Heisenberg uncertainty relation, which is denoted the Heisenberg limit. In practice, however, entangled states are often more prone to decoherence, which may prevent reaching this performance. We present an adaptive measurement protocol that in the presence of a realistic source of decoherence enables us to get near-Heisenberg-limited stability of atomic clocks using entangled atoms. The protocol may thus realize the full potential of entanglement for quantum metrology despite the detrimental influence of decoherence [1].

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Hunting for topological dark matter with atomic clocks

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The cosmological applications of atomic clocks so far have been limited to searches of the uniform--in--time drift of fundamental constants. Here we point out that a transient in time change of fundamental constants can be induced by dark matter objects that have large spatial extent, and are built from light non--Standard Model fields. The stability of this type of dark matter can be dictated by the topological reasons.

We point out that correlated networks of atomic clocks, some of them already in existence (e.g., GPS), can be used as a tool to search for the topological defect dark matter, thus providing another important fundamental physics application to the ever-improving accuracy of atomic clocks. During the encounter with a topological defect, as it sweeps through the network, initially synchronized clocks will become desynchronized. Time discrepancies between spatially separated clocks are expected to exhibit a distinct signature, encoding defect's space structure and its interaction strength with the Standard Model fields.

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Trapping Ra^+: Optical Clock and Atomic Parity Violation

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We study single trapped Ra^+ ions for a precision measurement of the Weinberg angle at low energy, testing the electroweak running. Ra^+ has the largest atomic parity violation effect for a simple electronic structure. In addition, the electric quadrupole transitions 7s $^2S_{1/2}$ – 6d $^2D_{3/2}$ at 828 nm and 7s $^2S_{1/2}$ – 6d $^2D_{5/2}$ at 728 nm to the low-lying metastable D-states of Ra^+ are excellently suited for an optical clock. In specific radium isotopes the lack of a linear Zeeman and/or electric quadrupole shift promises a robust clock operating at a relative uncertainty level of 10^{-18} [1]. The heavy Ra^+ ion is sensitive to a changing fine structure constant and has easily accessible transition wavelengths. Relevant transitions have been studied using laser spectroscopy of short-lived Ra^+ [2] and current experiments are focused on trapping single Ba^+ ions as precursor to Ra^+. Work toward single ion trapping of Ra^+ is in progress.

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Sorting ions in an two-species ion chain by amplitude-modulated laser beams for a new In^+ optical clock

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We have proposed a new implementation of an In^+ optical clock based on In^+ ions sympathetically cooled with Ca^+ ions in a linear trap [1]. This implementation can be extended to a multi-ion clock with enhanced stability, provided that In^+ and Ca^+ can be sorted in proper orders. Sorting ions in a non-segmented trap is not a trivial task, but this might be possible by selectively destabilizing undesired orders. Different eigenmode frequencies of collective motion of ions dependent on the ion order enable the selective destabilization by a laser beam with amplitude modulation at the eigenfrequencies. Once the order is changed to the desired order by destabilization, the ion chain doesn't interact with the AM frequency anymore and stays as it is. A principle of proof experiment is successfully demonstrated with an ion chain consisting of two Ca^+ and one In^+. The status of In^+ clock development is also reported.

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Agile coherent control of ions in a microfabricated trap

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Using an agile laser system [1], we have demonstrated coherent control on the $S_{1/2}$ – $D_{5/2}$ optical qubit transition (674 nm) of $^{88}Sr^{+}$ ions confined in our microfabricated ion trap [2]. We use amplitude-shaped pulses to minimise off-resonant excitation of other Zeeman transitions in the ion's spectrum. When combined with the laser's phase agility, this enables tailoring of the spectral lineshape in Rabi and Ramsey excitations. A spin echo sequence was used to demonstrate an improved coherence time over our previous work. Frequency-resolved optical pumping on the 674 nm transition has also been investigated, and resolved sideband cooling of the ion's motional modes is in progress. This agile coherent control will be used to implement the Mølmer - Sørensen entangling gate [3,4] on $^{88}Sr^{+}$. Entangled states in the microfabricated trap will be used to explore applications in quantum metrology experiments.

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Highly-charged ions for atomic clocks, quantum information, and search for α-variation

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We propose 10 highly-charged ions as candidates for the development of next generation atomic clocks, quantum information, and search for α-variation. These are the only highly-charged ions that have the long-lived metastable states with transition frequencies to the ground state between 170-3000 nm, relatively simple electronic structure, high sensitivity to α-variation, and stable isotopes. We find that only the ions in four isoelectronic sequences, Ag-like, Cd-like, In-like, and Sn-like satisfy these criteria. We predict their properties crucial for the experimental exploration. We find that Pr^{+9} ion is a particular attractive candidate for these applications as it possesses a unique metastable level structure with optical transitions not present in any neutral and low-ionization state systems. Highly-charged ions are less sensitive to external perturbations than either neutral atoms or singly-charged ions due to their more compact size, potentially leading to reduced decoherence effects and smaller ultimate clock uncertainties.

High power, very narrow linewidth, micro-integrated diode laser modules designed for quantum sensors in space

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We report on the development of very robust, energy efficient, micro-integrated Master-Oscillator-Power-Amplifier (MOPA) and Extended-Cavity-Diode-Laser (ECDL) modules for the deployment of cold atom based quantum sensors in space. The micro-optical benches, not larger than 80x25 mm^2, include an electrical interface that allows for high modulation bandwidth, a feature especially useful for spectroscopy applications. With MOPAs and ECDLs designed for rubidium BEC and atom interferometry experiments at 780 nm we achieved an intrinsic linewidth of 35 kHz at 1.4 W and of 2 kHz at 35 mW, respectively. Due to individual temperature control of the external Bragg grating ECDLs can be tuned continuously by more than 30 GHz [1] . The technology can be transferred to all wavelengths accessible by laser diodes, e.g. 767 nm [2] for spectroscopy with potassium.

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Towards a fully-miniaturised magneto-optical trap system for portable ultracold quantum technology

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We present progress on work carried out in the development of enabling technologies for integrated atom chips [1]. Cold atom experiments have flourished with the advent of atom chips, whose construction readily lends itself to integration with larger systems and future mass production. To bring these experiments out of the lab and make use of them in new settings, the complex surrounding infrastructure (including vacuum systems, optics, and lasers) also needs to be miniaturized and integrated. The ideal solution would seem to be an Integrated Atom Chip incorporating the vacuum system, atom source and optical geometry into a permanently sealed micro-litre system capable of maintaining 10^{-10} mbar for more than 1000 days of operation with no active pumping systems. The primary focus of the project so far has been on the design and construction of a silicon die bonding system capable of producing such devices with high longevity and hermeticity.

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Locking Raman laser frequency of up to 40 GHz offset for atom interferometers

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Laser frequency stabilization is widely used in the study of atomic and molecular physics [1, 2], measurements of fundamental physical constants [3, 4], and precision spectroscopy [5]. Optical phase locked loops (OPLLs) allow one laser to track another with a fixed frequency difference and a maximum tuning range of 40 GHz [6]. We demonstrate a method to lock a laser frequency of up to 40 GHz offset to a reference using a 10 GHz electro-optic modulator (EOM) [7]. Offsetting is provided by the EOM sidebands, and first- to fourth-order sidebands are generated by changing the power of the EOM's driving frequency. By scanning the driving frequency across the 10 GHz bandwidth, the output laser frequency can be tuned over an 80 GHz range (−40 to 40 GHz) by locking a sideband to the reference. This method provides simple, stable, and low-cost generation of Raman laser pairs for atom interferometers.

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Optical phase locking of two extended-cavity diode lasers : direct modulation and serrodyne modulation

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We present two methods for optical phase locking of two extended-cavity diode lasers with ultra low phase noise. The frequency difference between two lasers is 6.9 GHz, which is close to the ground-state hyperfine splitting of ^{87}Rb. First method is a direct modulation scheme, where the phase error signal is electrically fedback to the injection current of a slave laser. Second method is a serrodyne modulation scheme, where the phase error signal is fed into an electro-optic modulator after the slave laser. In both cases, the bandwidth of the optical phase locking loop is extended up to 8 MHz and the residual phase noise of two phase-locked lasers reaches below -120 dBrad^2/Hz in the offset frequency range of 100 Hz to 300 kHz. These schemes will be employed to enhance the sensitivity limit in atom interferometer.

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A Dynamic Magneto-Optical Trap for Atom Chips

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We demonstrate a new mirror magneto-optical trap which relies on time varying optical and magnetic fields in an analogous configuration to the quadrupole ion trap. The AC operation of the trap removes the requirement of an in plane laser beam seen in other mirror MOTs, and as a result is advantageous in applications where optical access is restricted to a single window. Due to the planar nature of this design it is particularly well suited for use in atom chips, and unlike some other traps this dynamic MOT works independently of the wavelength of the light used, allowing for multiple atomic species to be trapped simultaneously.

Holographic Laguerre-Gaussian beams for long-distance channeling of a 2D-MOT generated cold atom beam.

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A 2D-MOT is an efficient sources for cold atoms experiments. Unfortunately, the divergence (≈ 40 mrad) of the atom beam is problematic if the 2D-MOT has to be far from the main science area. We have demonstrated a reduction in the size of the beam from 12 mm to 1 mm 300 mm away from our 2D-MOT output by guiding the atomic beam in a blue detuned holographically generated Laguerre-Gaussian (LG) mode. As the atoms are guided in the dark center of the donut shaped LG beam, heating is low compared to a red detuned guide, allowing a longer guiding distance. Holography could generate in principle any laser beam shapes. As cold atoms are sensitive to perturbations, the generated light field must be precisely defined. Unfortunately, spatial light modulators (SLM) suffer from defects that need to be corrected for high-fidelity holography. We have also demonstrated an active and in-situ SLM correction.

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TUESDAY

Fermi Gases Th-001

Boltzmann-Vlasov approach and Fermi surface anisotropy in dipolar Fermi gases

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We study harmonically trapped three-dimensional ultracold Fermi and Bose gases in the presence of the short-range contact and the long-range anisotropic dipole-dipole interaction. The dynamics of such quantum systems can be described by the Boltzmann-Vlasov equation. Dipole-dipole interaction breaks rotational symmetry in momentum space and gives rise to an elliptic Fermi surface. We calculate time-of-flight expansion all the way from in a collisionless to the hydrodynamic regime and show that momentum distribution is stretched along the orientation of dipoles, arising dominantly from the Fermi surface anisotropy. This result agrees with a recent experiment done in a collisionless regime by probing the momentum distribution of an atomic gas via time-of-flight expansion measurements.

Specific heat and strong-coupling effects in the BCS-BEC crossover regime of an ultracold Fermi gas

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We theoretically investigate the specific heat in the normal state of an ultracold Fermi gas. Using a strong-coupling BCS-BEC crossover theory, we clarify how strong pairing fluctuations affect this quantity in the whole BCS-BEC crossover region. Recently, the specific heat has been measured in the unitarity limit of this system[1], exhibiting a lambda-like temperature dependence near the superfluid phase transition temperature, as opposed to the well-known T-linear behavior obtained in normal Fermi liquids. We examine whether this anomalous temperature dependence is due to strong pairing fluctuations. We also discuss effects of the so-called pseudogap phenomenon on the specific heat. Since the existence of strong pairing fluctuations is a crucial key in understanding the BCS-BEC crossover physics, our results would be helpful in elucidating their effects on the thermodynamic properties of an ultracold Fermi gas.

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Perron-Frobenius theorem on the superfluid transition of an ultracold Fermi gas

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The Perron-Frobenius theorem is applied to identify the superfluid transition of the BCS-Bose-Einstein condensation (BEC) crossover [1]. According to the quantum cluster expansion method of Lee and Yang [2,3], the grand partition function is expressed by the Lee-Yang graphs. A singularity of an infinite series of ladder-type Lee-Yang graphs [4] is analyzed. We point out that the singularity is governed by the Perron-Frobenius eigenvalue of a certain primitive matrix which is defined in terms of the two-body cluster functions and the Fermi distribution functions. As a consequence, it is found that there exists a unique fugacity at the phase transition point, which implies that there is no fragmentation of BEC of dimers and Cooper pairs at the ladder-approximation level of Lee-Yang graphs. An application to a Bose-Einstein condensate of strongly bounded dimers is also made.

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Numerical Analysis of Fermion Transport Based on Nonequilibrium Thermo Field Dynamics

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We discuss the properties of transport of two-component fermion system. In recent experiments, the nonequilibrium processes of cold atomic gases are observed in detail. Especially for two-component fermion system with a harmonic confinement potential, the dependence of the transport properties on various inter-component interaction strengths were reported [1,2]. In this theoretical study, we analyze the quantum transport equation for the two-component fermion gas in a harmonic potential. To derive the quantum transport equation, we employ Thermo Field Dynamics (TFD), which is a real-time formalism of quantum field theory under thermal situation [3,4]. Because TFD has an advantage in defining an explicit quasi-particle picture even in nonequilibrium situations, it is appropriate to investigate the nonequilibrium process. We compare our numerical results with those of the experiments [1,2] to understand the properties of transport.

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Triplet pair correlation in a trapped s-wave superfluid Fermi gas at T=0

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We theoretically investigate effects spatial inhomogeneity of a system on the character of pair correlation in an s-wave superfluid gas of Fermi atoms trapped in a harmonic potential. Within the framework of real-space Boboliubov-de Gennes coupled equations at T=0, we examine to what extent the local breakdown of the spatial inversion symmetry by the harmonic trap potential (except at the trap center) induces the spin-triplet Cooper-pair amplitude in a s-wave superfluid Fermi gas (which is characterized by the ordinary s-wave superfluid order parameter)[1]. We also identify the region where the spin-triplet pair-amplitude is maximally induced in the BCS-BEC crossover region. Since the so-called non-centrosymmetric pairing state has recently attracted much attention in the field of metallic superconductivity, our result would be useful in exploring this novel pairing state in cold Fermi gas system.

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Diagrammatic Monte Carlo study of the Fermi polaron

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We study the properties of the two-dimensional Fermi polaron model in which an impurity attractively interacts with a Fermi sea of particles in the zero-range limit. We use a diagrammatic Monte Carlo (DiagMC) method which allows us to sample a Feynman diagrammatic series to very high order. The convergence properties of the series and the role of multiple particle-hole excitations are discussed. We study the polaron and molecule energy as a function of the coupling strength, revealing a transition from a polaron to a molecule in the ground state. For all considered interaction strengths, the polaron Z factor from the full diagrammatic series almost coincides with the one-particle-hole result. We also formally link the DiagMC and the variational approaches for the polaron problem at hand.

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Strongly dipolar Fermi gases of erbium atoms

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We report on the observation of few- and many-body dipolar phenomena in a quantum degenerate Fermi gas of strongly magnetic erbium atoms. We demonstrate a new evaporative cooling scheme where spin-polarized fermions are directly cooled down to 0.1 times the Fermi temperature via universal dipolar scattering [1]. In cross-dimensional rethermalization measurements, where the sample is driven out of equilibrium, we reveal the anisotropic character of the interaction and observe that the system relaxes to equilibrium with speeds that strongly depend on the dipole orientation [2]. Furthermore, we show that the Fermi surface of our sample is deformed to an ellipsoid by the many-body DDI and that the magnitude of the deformation is tunable via an external trapping potential. The observed Fermi surface deformation represents a crucial step for exploring exotic quantum nematic phases in the ultracold regime [3].

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Quantum Monte Carlo simulations of muticomponent Fermi systems

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In cold atomic systems, several species of atoms have multiple low-lying hyperfine states. By loading these atoms into optical lattices, we can realize the multicomponent Fermi systems. Recently, six-component Fermi systems were experimentally realized[1], and have attracted much interest.

These backgrounds motivate us to study quantum condensed phases and quantum phase transitions which can be observed in attractively interacting multicomponent Fermi systems. For this purpose, we apply the Quantum Monte Carlo scheme[2] to the multicomponent Hubbard model with attractive interaction, and calculate the pair-correlation function and the charge-correlation function. In this poster presentation, we will show the results of these two functions and discuss how the fluctuations of pair-correlation and charge-correlation lead to the pseudo-gap formation.

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Decoherence of many fermions in an optical lattice due to spontaneous emissions

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A key experimental challenge in reaching low-entropy states with ultra cold fermionic atoms in optical lattices arises from various heating and decoherence mechanisms. We investigate how many-body states are affected by spontaneous emission processes at a rate that can be comparable to the typical dynamical timescales in systems of two-component fermions. Deriving a many-body master equation, we show that magnetic order for strong repulsive interactions can be robust against this decoherence mechanism, in a way that also generalizes to group-II species exhibiting SU(N) magnetism. For attractive interactions, decay rates are faster, and are enhanced by superradiance. We also consider effects of lattice atoms immersed in a Bose-Einstein condensate, analysing changes in properties of lattice atoms due to this entanglement with the condensate for various interaction strengths.

BOSE GASES

Faraday waves in collisionally inhomogeneous multi-component Bose-Einstein condensates

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Faraday (density) waves in Bose-Einstein condesates (BECs) can be excited by harmonic modulation of the interaction or the trapping potential. We will study the emergence of Faraday waves in binary non-miscible BECs [1]. We will show that the excited waves are of similar periods, emerge simultaneously, and do not impact the dynamics of the bulk. We will derive analytically their spatial periods and analyze the behavior of the system driven at resonant frequencies, which turns the two components miscible.

We will also investigate Faraday waves in multi-component BECs with spatially inhomogeneous interactions [2]. In the regime of weak inhomogeneity, we will show that the properties of generated waves are similar to the homogeneous case, while in the strong inhomogeneity regime the periods of density waves strongly depend on the typical length scale of the inhomogeneity. We will derive variational theory for spatial periods of density waves for both cases.

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Stochastic Coupled Growth of 2-Component Bose-Einstein Condensates

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We investigate [1] the competing growth dynamics of highly immiscible two-component condensates |1>, |2> under realistic experimental conditions (partly motivated by the Durham Rb-Cs mixture experiment [2,3]). Our modelling is performed via fully three-dimensional coupled stochastic projected Gross-Pitaevskii equations, with dynamics induced by sudden temperature and chemical potential quenches. In brief, we typically find one of the two components (|1>, Rb) to condense faster than the other (|2>, Cs), which is sympathetically cooled, in agreement with experimental observations. The condensing component |1> exhibits spontaneous appearance of one, or more, dark solitons [via the Kibble-Zurek mechanism], with component |2> gradually condensing in phase-separated regions of low mean-field potential, so either within the dark soliton(s), or around the edges of the emerging condensate in component |1>. The ensuing dynamics can lead to a very rich structure, with observations of emerging immiscible profiles over experimental timescales depending sensitively on the extent to which the stochastically-generated dark soliton(s) in |1> fill in by condensing |2> atoms (thus leading to spontaneously-generated dark-bright soliton(s)) before the dark soliton(s) themselves decay stochastically [4].

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Creation of Topological Monopole Defects In a Quantum Field

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Among all types of topological defects, point defects play an especially important role because they correspond to stable elementary particles in grand unified gauge theories. Lack of experimental evidence of monopoles in real electromagnetic fields has striven the search for monopole analogues in other systems. In our studies we use dilute alkali Bose-Einstein condensates (BEC) as a platform to observe topological point defects. These systems are interacting quantum gases amenable to theoretical analysis, and thus provide unique possibilities for testing the fundamental principles and theories of many-particle quantum physics. Recently, we demonstrated a method to create Dirac monopoles in a synthetic magnetic field of BEC [1,2]. In our current studies, the method is modified to observe topological point defects reminiscent to those predicted theoretically by 't Hooft and Polyakov as quantized magnetic charges. The experiments show excellent quantitative agreement with simulations without any free parameters.

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Observation of Dirac monopoles in a synthetic magnetic field

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The spin degree of freedom of an atomic Bose-Einstein condensate (BEC) generates synthetic electromagnetic fields that can be manipulated by real time-varying magnetic fields. We present the experimental creation and observation of Dirac monopoles in the synthetic magnetic field of a ^{87}Rb BEC [1]. This constitutes the first time Dirac monopoles are observed in a system governed by a quantum field. The experiments are accurately simulated using a mean-field approach, and a very good quantitative agreement is obtained without any fitting parameters.

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Spin-nematic order and phase locking in antiferromagnetic spinor condensates

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We study the equilibrium state of a spin-1 Bose-Einstein condensate of sodium with antiferromagnetic interactions. The equilibrium populations in the mean field ground state are determined by the competition between the antiferromagnetic interactions that tend to minimize the total spin of the system, and the quadratic Zeeman effect which favors atoms in the $m_F = 0$ state. In order to minimize the magnitude of the transverse spin, antiferromagnetic interactions lock the relative phase $\Theta = \Phi_{+1} + \Phi_{-1} - 2\Phi_0$ to π. By applying a spin rotation along the transverse direction, we map the transverse spin fluctuations to the variance of $\boldsymbol{S_z}$ and measure them directly. We verify the phase locking due to antiferromagnetic interactions at several points on the phase diagram of the system.

Quantum fluctuation of soliton in Bose-Einstein condensate beyond Bogoliubov approximation

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The system of Bose-Einstein condensate (BEC) has a zero mode associated with the spontaneous breakdown of the global phase symmetry. However, the treatment of the zero mode is difficult because of its singular property, and has often been neglected. To remove this singularity, we have recently proposed the new treatment of the zero mode, and been able to introduce a ground state of the zero mode [1]. Using this ground state, we have evaluated the quantum fluctuation for the phase of BEC. When a dark soliton exists in BEC, an additional zero mode which is associated with translational symmetry appears. It is well known that this zero mode contributes to the fluctuation of position and momentum of the soliton [2]. Using the method of Ref. [1], we evaluate the quantum fluctuations of position and momentum and compare with the result of Ref. [2].

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Classical and quantum reflection of bright matter-wave solitons

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Bright solitons are non-dispersive wave solutions, arising in a diverse range of nonlinear, one-dimensional (1D) systems, including atomic Bose-Einstein condensates with attractive interactions.

We report the controlled formation of a bright solitary matter-wave [1] from a Bose-Einstein condensate of ^{85}Rb [2]. We demonstrate the reflection of the solitary wave from a broad repulsive Gaussian barrier and contrast this to the case of a repulsive condensate, in both cases finding excellent agreement with theoretical simulations using the 3D Gross-Pitaevskii equation. For an attractive potential we identify a regime where quantum reflection of the solitary wave is possible.

These results pave the way for new experimental studies of bright solitary matter-wave dynamics to elucidate the wealth of existing theoretical work and to explore an array of potential applications including novel interferometric devices, the realisation of Schrödinger cat states and the study of short-range atom-surface potentials [3].

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Bright solitons in quasi-one-dimensional dipolar condensates with spatially modulated interactions

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We introduce a model for the condensate of dipolar atoms or molecules, in which the dipole-dipole interaction (DDI) is periodically modulated in space due to a periodic change of the local orientation of the permanent dipoles, imposed by the corresponding structure of an external field (the necessary field can be created, in particular, by means of magnetic lattices, which are available to the experiment). The system represents a realization of a nonlocal nonlinear lattice, which has a potential to support various spatial modes. By means of numerical methods and variational approximation (VA), we construct bright one-dimensional solitons in this system and study their stability. In most cases, the VA provides good accuracy and correctly predicts the stability by means of the Vakhitov-Kolokolov criterion. It is found that the periodic modulation may destroy some solitons, which exist in the usual setting with unmodulated DDI and can create stable solitons in other cases, not verified in the absence of modulations. Unstable solitons typically transform into persistent localized breathers. The solitons are often mobile, with inelastic collisions between them leading to oscillating localized modes.

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Bose Gases Th-018

Modeling Bose-Einstein Condensates in Non-Uniformly Rotating Reference Frames

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We present the implementation of a method-of-lines approach for numerically approximating solutions of the time-dependent Gross-Pitaevskii equation in non-uniformly rotating reference frames. Implemented in parallel using a hybrid MPI + OpenMP framework, which will allow for scalable, high-resolution numerical simulations, we utilize an explicit, generalized 4th-order Runge-Kutta time-integration scheme with 2nd- and 4th-order central differences to used approximate the spatial derivatives in the equation. The principal objective of this project is to model the effect(s) of rotationally-induced perturbations on quantized vortices within weakly-interacting dilute atomic gas Bose-Einstein condensates in the mean-field limit of the Gross-Pitaevskii equation. Here, we discuss our work-to-date and preliminary results.

Persistent Non-Equilibrium States In Perfectly Spherical Potentials

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Using his transport equation, Boltzmann found that the monopole mode of a gas in an isotropic harmonic potential is *undamped* [1,2]. This elegant many-body dynamical symmetry has never been observed because of the difficulty in realizing a perfectly isotropic harmonic trap. Through a modification to the standard TOP trap, we gain full control over the ellipsoidal parameters of the 3D potential allowing us to achieve spherical symmetry at a level of 0.1%. Damping rates are measured in the presence of controlled symmetry breaking and are explained in the context of monopole/quadrupole mixing.

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Dynaimcs of Breather in linearly coupled Bose-Einstein Condensates

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The emergent sine-Gordon dynamics [1] in weakly coupled Bose-Einstein condensates (BECs) has been actively studied in recent years. An interesting property of sine-Gordon equation is that it possesses a class of solitonic solution [2], called breather, which is a spatially-localized and temporarily-oscillating nonlinear wave. In this presentation, we investigate the evolution of a phase-imprinted sine-Gordon breather in the relative phase of two coupled 1D BECs by numerically integrating the coupled Gross-Pitaevskii equations. We find that, in the weak-coupling regime, the breather-like excitation is long-lived, which loses energy gradually via sound emission. For strong couplings, the breather-like excitation occur in both the relative and total phases when the initial amplitude of the breather is sufficiently small, otherwise the imprinted breather would decay into two dark solitons instantly. The stability of the breather is examined by varying the frequency of the imprinted breather and the coupling energy between the condensates.

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Scissors mode and quantized vortices generated in sodium Bose-Einstein condensates by a rapid modulation of the magnetic field

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When the magnetic field strength at the center of a cloverleaf trap for sodium Bose-Einstein condensates in a few milliseconds using an additional off-axis Helmholtz coil, the center-of-mass oscillation in the radial direction, the m=0 low-lying and high-lying quadrupole modes, and the scissors mode were excited simultaneously in the condensates. The amplitude of the scissors mode was modulated by the frequency of the m=0 low-lying quadrupole mode due to the law of conservation of angular momentum. On the other hand, the sign of the potential was reversed with a reverse time of 11.7 ms through zero, and the potential was hold during 1 ms and returned back rapidly. Thus, the condensates in the m=0 state with a clear quantized vortices was extracted from the condensates in the m = -1 state by the Majorana transition.

Position-dependent spin-orbit coupling for ultracold atoms

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Recently several schemes have been proposed to create the spin-orbit coupling (SOC) of the Rashba-Dresselhaus type for ultracold atoms by illuminating them with several laser beams [1,2]. This leads to a number of distinct phenomena, such as formation of non-conventional Bose-Einstein condensates (BECs) of ultracold atoms affected by the SOC [2,3]. Here we explore effects due to the position-dependence of the SOC for atomic BECs. The position-dependence provides domains of the stripe phases with the stripes oriented in different directions. It is shown that non-trivial structures can be formed at the boundaries of these domains, such as defects or arrays of vortices and anti-vortices.

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Toward simulating artificial gauge fields with atom-chip based quantum simulator

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Quantum degenerate gases are well suited for studying quantum many-body phenomena, both as quantum simulators and also as novel physics systems of their own right. Experimental realizations of artificial gauge fields implemented with Raman-dressed alkali atoms have open-up the possibilities of exploring topological quantum matter with cold atoms. However, one inevitable issue with such scheme is heating effect due to photon-scattering from the Raman lasers, which may hinder future observation of intriguing topological phenomena. We are developing an alternative scheme using RF-dressed states that realize the same kind of Hamiltonian, but have essentially no heating. This scheme works for any alkali atom (boson or fermion) uses an array of ac-current carrying wires on a nanofabricated atom chip to create effective Raman coupling for atoms trapped near the chip surface [1]. We will show the experimental feasibility and report on the progress toward the implementation using rubidium atoms.

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THURSDAY

Roton and phonon modes softening in quantum gases with spin-orbit coupling

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Roton-type excitations emerge from strong or long-range interactions in conventional superfluids. Here we demonstrate a new route to induce roton modes by manipulating the single-particle Hamiltonian in weakly short-range interacting quantum gases. Using Bragg spectroscopy, we measure the excitation spectrum of a spin-orbit coupled Bose-Einstein condensate in the magnetized phase, which possesses a typical phonon-maxon-roton strucure in the spin-orbit coupling direction. It is observed that the roton or phonon mode softens as the condensate is tuned to undergo a relevant quantum phase transition. In addition, the validity of the *f*-sum rule in this system is verified. This work blazes a trail for quantum simulation of strong-correlation physics.

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Bose Gases Th-025

Experimental apparatus for producing the Bose-Einstein condensate of Ytterbium(Yb)

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We report our experimental apparatus for producing ultracold Yb isotopes.The experimental setup consists of three parts: 1. oven and Zeeman slower, 2. main magneto-optical trap chamber, 3. auxiliary science chamber. The oven is designed to have a cold finger inside in order to avoid the nozzle clogging issue, and the Zeeman slower magnetic field profile is set to cross the zero. For magneto-optical trap, two different wavelength lasers (399nm&556nm) are used to increase the capture velocity and trapped atom number. The detailed design of our setup and the performance of our Zeeman slower and magneto-optical trap would be presented

Numerical analysis of quantum transport equation derived from nonequilibrium Thermo Field Dynamics in Markovian approximation

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We study the quantum transport equation derived from nonequilibrium Thermo Field Dynamics (TFD) [1] in the system of cold neutral atomic Bose gas. In our previous works [2], [3], we have applied nonequilibrium TFD to the system with a time-dependent external field. Imposing the renormalization conditions on the improved time-dependent on-shell self-energy, we derived the non-Markovian quantum transport equation and obtained the corrections of the quasiparticle energy. The energy corrections have the off-diagonal hermitian and the imaginary parts, which play crucial roles in the thermal process [2], [3].

Since the cost of numerical calculation of the non-Markovian transport equation is extremely high, we consider it in the Markovian approximation. First, we compare the numerical results of the non-Markovian and the Markovian transport equations for small systems. Then we analyze thermal processes for larger systems, calculating the Markovian transport equation numerically.

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Experimental probing of non-equilibrium Quantum Many-Body Systems

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The study of the non-equilibrium dynamics of isolated quantum many-body systems is a highly active research topic with relevance for many different fields of physics. Despite important theoretical effort, no generic framework exists yet to understand when and how a quantum system relaxes to a steady state.

Over the last years we have developed techniques to experimentally investigate this question. In our experiments we study degenerate 1d Bose gases which are brought out of equilibrium by various types of quantum quenches. The interference of two such gases results in a fluctuating matterwave interference pattern. The noise and correlations in such interference patterns open a probe into the many-body states of the 1d Bose gas, its fluctuations and relaxation. With this method we observe light-cone-like correlation dynamics, thermal-like steady states and the appearance of a unified statistical description for quantum many-body systems.

Creation of excitations from a uniform impurity motion in the condensate

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We investigate a phenomenon of creation of excitations in the homogeneous Bose–Einstein condensate due to an impurity moving with a constant velocity. A simple model is considered to take into account dynamical effects due to motions of the impurity. Based on this model, we show that there can be a finite amount of excitations created even if velocity of the impurity is below Landau's critical velocity. We also show that the total number of excitations scales differently for large time across the speed of sound. Thus, our result dictates the critical behavior across Landau's one and validates Landau's intuition to the problem. We discuss how Landau's critical velocity emerges and its validity within our model [1].

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Structure factor of ultra-cold bosons in two-dimensional optical lattices

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We study the structure factor of the interacting ultra-cold atoms in a square optical lattice. Using a combined Bogoliubov method and the quantum-rotor approach, the Bose-Hubbard Hamiltonian of strongly interacting bosons is mapped onto the U(1)-phase action. This allows to calculate the momentum and energy dependence of the structure factor in the presence of the Mott insulator and superfluid phases. It is shown that superfluidity manifests itself as a sharp coherence peak resulting from the emergence of the long-range order. On the other hand, correlation effects lead to the appearance of a smearing of the excitation spectra of incoherent particles although the remnants of the Bogoliubov band are still present in the part linked to coherent particles.

Quantum state for zero mode of cold atomic gas system with Bose-Einstein condensate

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The quantum state of the zero mode of Bose-Einstein condensate is investigated from the standpoint of quantum field theory. The existence of the condensate, which is associated with the spontaneous breakdown of the global phase symmetry, must involve the zero mode according to the Nambu-Goldstone theorem [1]. However, the zero mode is often neglected (ex. Bogoliubov approximation) because of its infrared singular property. To remove the singularity and handle the zero mode in quantum field theoretical manner, we propose a new unperturbed Hamiltonian [2], which includes not only the first and second powers of the zero mode operators but also the higher ones, and obtain a non-singular stationary quantum state which is appropriate as the vacuum of the condensed system. Using the quantum state, we calculate physical quantities of the condensed system, such as the phase fluctuation, both at zero and finite temperatures.

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Two-particle coalescences for the helium-like ions.

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The two-electron Schrodinger equation at the two-particle coalescences was studied for the atomic three-body systems in S-states [1]. The general differential equation in three variables was reduced to the centrally symmetric field problem for the case of electron-nucleus and electron-electron coalescence lines. New potentials describing attractive and repulsive interactions between the coalesced pair of the electron and nucleus, and the two coalesced electrons, respectively, were derived and studied. Interesting features of these potentials in the vicinity of the triple coalescence point were found. The ground states of the helium atom, the positive ion of hydrogen and the negative ion of lithium were explored, as the typical examples of the helium isoelectronic sequence.

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Full control over two interacting fermions in a single double well

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We have deterministically prepared two fermions in a single double-well potential, having full control over the two-particle quantum state. Starting with two non-interacting atoms in the ground state of a single potential well we can either rapidly switch on a second well and observe tunneling dynamics, or access eigenstates of the double well by means of an adiabatic passage.

After preparing both particles in the ground state of the double well, we introduce interparticle interactions and measure their influence on the particle statistics. For repulsive interactions we find a strong enhancement of singly occupied sites which can be understood as a two-particle analogy to a Mott-insulator. For attractive interactions we observe the onset of the charge-density-wave regime. In a spectroscopic measurement, we study how second-order tunneling affects the energy of the system.

By combining several double-well systems we aim for a bottom-up approach to many-body Hubbard physics.

Ultracold mixtures of metastable He and Rb: scattering lengths from *ab initio* calculations and thermalization measurements

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We have investigated the ultracold interspecies scattering properties of metastable triplet He (He*) and Rb. Ultracold or quantum degenerate He*+Rb mixtures are interesting for few-body physics that require a large mass ratio, such as the observation of multiple Efimov loss features. We performed state-of-the-art *ab initio* quantum chemistry calculations of the relevant interaction potential, and measured the interspecies elastic cross section for an ultracold mixture of ^{4}He* and ^{87}Rb at a temperature of 0.5 mK in a quadrupole magnetic trap. Our combined theoretical and experimental study gives an interspecies scattering length a_{4+87}=+17 $^{+1}{}_{-4}a_0$, which prior to this work was unknown. More general, our work shows the possibility of obtaining accurate scattering lengths using *ab initio* calculations for a system containing a heavy, many-electron atom, such as Rb.

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Efimov Resonances in a Mixture with Extreme Mass Imbalance

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We present the observation of two consecutive heteronuclear Efimov resonances in an ultracold Fermi-Bose mixture of Li-Cs by measuring magnetic field dependent three-body loss coefficients and atom loss spectra near a broad Feshbach resonance [1]. The first Efimov resonance is found at a scattering length of $a^{(0)}$=-320(10)a_0, corresponding to approximately 7(3) times the Li-Cs (Cs-Cs) van der Waals range. The second resonance appears at $a^{(1)}$=-1870(390)a_0, close to the unitarity-limited regime at the sample temperature of 450 nK. Indication of a third resonance is found in the atom loss spectra. The scaling factor of the resonance positions of 5.8(1.0) is close to the predicted universal value of 4.9 for zero temperature mixtures. The refined Feshbach resonance position agrees excellently with an extensive interpretation of the recently observed interspecies Li-Cs Fesbhach resonances [2] by three different theoretical models: coupled channels calculation, asymptotic bound state model, and multi-channel quantum defect theory.

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The influence of confinement, dimensionality, and anisotropy on effective multibody interactions of trapped ultracold bosons.

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Effective multibody interactions can play an important role in the physics of ultracold atoms in optical lattices. Their influence is seen in both the non-equilibrium dynamics of quenched systems, and in precision measurements of atomic Mott-insulator states. Recent studies also suggest they can be used to generate exotic quantum phases. We will discuss our analysis of the effective three- and four-body interactions generated by both contact and effective range two-body interactions. We will also present new results for 1D, 2D isotropic, and 3D cylindrically symmetric harmonic potentials which illustrate the role of confinement and dimensionality on effective interactions, and which may be useful for ultracold atom experiments in highly anisotropic traps.

Towards optical Feshbach resonances with ^{40}Ca

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Ultra-cold quantum gases of alkaline earth elements Ca, Sr and Yb have been the subject of photoassociation investigation due to their narrow singlet-triplet intercombination lines. Of these, calcium offers the narrowest intercombination line with a natural linewidth of 374 Hz only. A quantum degenerate ^{40}Ca gas [1] has been produced in our experiment using forced evaporation in an optical dipole trap. We plan to employ this narrow line for manipulating the scattering length through optical Feshbach resonances (OFR). Compared to the experiments with Yb [2] and Sr [3], where the atom loss limited the possible interaction time, the small linewidth of calcium should reduce the corresponding losses. The binding energies of the most weakly bound molecular states in the relevant potentials were recently measured by single-colour photoassociation spectroscopy and described by a coupled channel model [4]. Based on the model and experimental data we estimated the feasibility of OFR.

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Long range interactions of Sr and Yb in mixed quantum gases.

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A first-principles relativistic method is developed for the accurate calculation of van der Waals coefficients of dimers involving excited-state atoms with a strong decay channel to the ground state. Accurate values of these long-range interaction parameters are needed for efficient production, cooling, and control of molecules. We used the developed methodology to calculate a number of C_6 and C_8 coefficients for Sr-Sr, Yb-Yb, Yb-Rb, and Yb-Li dimers which are of particular interest for development of optical lattice clocks, studies of quantum gas mixtures, and practical realization of quantum simulation proposals. Our calculations include C_6 coefficients for the Sr-Sr and Yb-Yb $^1S_0$+$^3P^o_{0,1}$ and $^3P^o_0$+$^3P^o_0$ dimers, C_8 coefficients for the $^1S_0$+$^1S_0$ and $^1S_0$+$^3P^o_1$ dimers, C_6 coefficients for the Yb-Rb $^3P^o_1$+(5s $^2S_{1/2}$) and $^1S_0$+(5p $^2P^o_{1/2}$) dimers, and the C_8 coefficients for the Yb-Li $^1S_0$+(2s $^2S_{1/2}$) and Yb-Rb $^1S_0$+(5s $^2S_{1/2}$) dimers. We perform detailed uncertainty analysis and provide stringent bounds on all quantities.

THURSDAY

The Degenerate Unitary Bose Gas

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A degenerate Bose gas with fully unitary interactions is generally inaccessible due to its short lifetime at large scattering lengths. However, we observe a metastable state of ultracold trapped ^{85}Rb gas at shorter timescales than the three-body losses. With time-resolved measurements of the momentum distribution of a Bose Condensed gas that suddenly jumps to unitarity, we find that the gas has momentum-dependent dynamics consistent with a universal relation with sample density, while still remaining degenerate. This work opens the door for experimental investigation of unitary regime, thus builds the foundation for future explorations of intriguing strongly interacting quantum liquid.

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Dipolar gases of ground state molecules: NaK in Hannover

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In the coming years, dipolar interactions will be one of the most promising tools in the field of ultracold atoms. Since the first realization of degenerate gases of dipolar atoms and the creation of large diatomic molecular samples in their rovibrational groundstate [1], a lot of experimental and theoretical interest has been focused on long-range interactions, anisotropy, exotic phase transitions and other peculiar phenomena. We will update you on our work in Hannover with details on the NaK experimental apparatus and on our effort to determine the most efficient adiabatic transfer from weakly-bound dimers to ground state dipolar molecules [2].

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Precision measurements with ultracold Sr_2 molecules in optical lattices

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We present high-resolution studies of subradiant states and asymptotic physics with ultracold strontium dimers in an optical lattice. The molecules are photoassociated from ^{88}Sr atoms near a narrow intercombination line. High-Q molecular spectra uncover peculiar physics, including multiply forbidden optical transitions that can be observed just below the atomic threshold. We measure and describe the natural lifetimes of subradiant states in terms of radiative and nonradiative contributions. Near the atomic asymptote, anomalously large linear, quadratic, and higher-order Zeeman shifts are observed. Measurements of linear Zeeman shifts yield nonadiabatic mixing angles of the molecular wave functions. We strongly enable forbidden transitions using small magnetic fields and for the first time, quantitatively compare electric- and magnetic-dipole as well as electric-quadrupole transition strengths in molecules. To characterize the ultranarrow molecular transitions, it is necessary to engineer magic optical lattices where state insensitivity is achieved via polarization and wavelength tuning. Current and future work made possible by this new type of long-lived molecule is discussed.

Rf-induced association of ultracold molecules in ^{87} Rb.

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THURSDAY

Recently two papers [1], [2] proposed radiofrequency-induced coupling of atomic scattering states with a bound molecular state to induce Feshbach resonances at arbitrary magnetic fields. We report the first observation of predicted resonances for a mixture of two states |1, -1> and |2, +1> in ^{87}Rb. Sudden increase of atom losses in narrow ranges of rf-frequencies clearly indicates the molecule association. We successfully created diatomic molecules in five different bound states and mapped their energies in the magnetic field range from 0.15 to 3.3 Gauss. From the interpolated data we determine zero-magnetic field energies of molecules with high precision (uncertainty is better than 0.1%). We also worked out a simple theory on the molecule formation rate and developed an explanation for observed asymmetries of observed resonant curves. New method of molecule association can be employed with any other mixtures of atoms and used for creation and studying new molecules.

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Photoassociative production of Feshbach molecules of ytterbium by using the ultranarrow $^1S_0$ -$^3P_2$ transition

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Feshbach resonance, which is one of the most important experimental tools for ultracold atoms, is not available in the ground state of Yb. Recently it was found that Feshbach resonances exist between the ground $^1S_0$ and the excited metastable $^3P_2$ states [1].

In this poster, we will present the production of $^1S_0$+$^3P_2$ Feshbach molecules and determination of their bound energies by means of photoassociation. For fermionic ^{171}Yb, we find 11 resonances below 8G, which are considered to be induced by the presence of anisotropic interactions [2]. We succeed to create Feshbach molecules for these resonances via photoassociation. Enhanced Franck-Condon factor in the vicinity of Feshbach resonances enables to easily observe the ultranarrow photoassociation resonances. These resonances will also provide the way to tune the scattering length between the ground states by means of optical Feshbach resonances with greatly suppressed atom loss.

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Isotopic analysis of Na-K Feshbach resonances and molecules

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We study theoretically magnetically induced Feshbach resonances and near-threshold bound states in isotopic Na-K pairs. Our calculations accurately reproduce Feshbach data on Na-K(40) and explain the origin of unusual observed multiplets in the p-wave [1]. We apply the model to predict scattering and threshold bound state properties of the boson-boson Na-K(39) and Na-K(41) systems. We find that the Na-K(39) isotopic pair presents favorable properties for producing non-reactive ground state polar molecules by stimulated photoassociation schemes.

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Ultracold molecules: far-from-equilibrium quantum magnetism

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Recent experiments with ultracold molecules in optical lattices have realized strongly interacting spin-1/2 models and probed their non-equilibrium dynamics. I will discuss theoretical methods that we have developed to understand this dynamics, the comparison with experiment, and theoretical predictions. In some cases, these new techniques offer a dramatic increase in accuracy with respect to previously available methods.

COOLING AND TRAPPING OF ATOMS AND IONS

A dual species magneto-optical trap of Cs and Yb

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The potentials of ultracold polar molecules have been discussed in many areas, including quantum computation and cold quantum chemistry. This experiment aims to produce an optical lattice of ground state Caesium-Ytterbium molecules. Compared to bi-alkali molecules, CsYb should have an additional magnetic dipole moment, which enables spin dependent interactions on a lattice [1,2]. Using methods such as magnetic-association over a Feshbach reonance [3] and Stimulated Raman Adiabatic Passage (STIRAP) [4], we aim to associate ultracold clouds of Yb and Cs to ground state molecules. We present a dual species magneto-optical trap of Caesium and Ytterbium loaded with a single Zeeman slower, as well as some theoretical background to the project.

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THURSDAY

Two-Stage Magneto-Optical Trapping of ^{6}Li Using D2 Line and Narrow-Line Cooling to High Phase-Space Density

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Recently, laser cooling techniques applied to alkali atoms have been revisited. Improved cooling is of particular interest for the isotopes of lithium and potassium, where standard D2 line laser cooling does typically not result in temperatures below the Doppler limit. Sub-Doppler temperatures have been achieved by the method of gray molasses for ^{39}K, ^{40}K, and ^{7}Li [1-3] and by employing far-detuned light for ^{7}Li [4]. Low temperatures have also been achieved by laser cooling employing narrow transitions to higher optically excited states for ^{40}K, ^{41}K, and ^{6}Li [5,6]. We report on results where we load ^{6}Li atoms into a magneto-optical trap (MOT) on the D2 transition before transfer into a narrow-line MOT at 323nm. We present our cooling and compression scheme that results in a temperature of 33μK and a comparatively high phase-space density of 3×10^{-4}, which is an ideal starting point for further evaporative cooling in an optical trap.

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Grey-molasses cooling of an optically trapped Fermi gas

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Robust sub-Doppler cooling has recently been demonstrated at the D1 ($nS_{1/2}$ to $nP_{1/2}$) transition of potassium [1-3] and lithium [4], atoms that are challenging to cool on the D2 cycling transition. Two mechanisms are at work: first, Sisyphus cooling in the standing-wave dipole potential, at least partially due to polarization gradients [1]; second, velocity-selective coherent population trapping (VSCPT) in a superposition of the two hyperfine ground states [2-4]. We extend this technique to the cooling of dense clouds in optical traps. Since the VSCPT dark state relies only on ground-state coherences, it is insensitive to optical shifts from far-detuned optical traps. We also observe that the molasses has sufficient cooling power to withstand light scattering on the 4S-5P transition. Together these observations indicate that D1 cooling is a promising approach to fluorescence imaging of single fermions in an optical lattice.

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Dual isotope magneto-optical trap with only one laser beam

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Magneto-optical traps (MOTs) are the starting point for many experiments in atomic physics. Alkali atom (in our case Rb) MOTs are quite common, and they require the use of two lasers, i.e., the trap and the repumper lasers. Here we demonstrate a dual isotope magneto-optical trap using a single diode laser [1]. We generate all the optical frequencies needed for trapping both species using a fiber intensity modulator. All the optical frequencies are amplified simultaneously using a tapered amplifier. The independent control of each frequency is on the RF rather than on the optical side. This introduces an enormous simplification for laser-cooling applications that often require at least one acousto-optic modulator for each laser beam. Additional isotopes can be simply added by including extra RF frequencies to the modulator and beams for other uses can be produced the same way.

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Magneto-optical traps for Yb, Tm, Er, and Ho loaded from a buffer-gas beam source

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We report the first magneto-optical trap (MOT) loaded from a buffer-gas beam source [1, 2]. We demonstrate the unique flexibility of our source by loading MOTs for Yb, Tm, Er, and Ho, without any additional slowing stages. Residual helium background gas results in a maximum trap lifetime of 80 ms (with Yb). The addition of a single frequency slowing laser achieves an unprecedentedly high loading rate of 2.0(1.0)*10^10 Yb atoms/s and 1.3(0.7)*10^8 Yb atoms in the MOT. Our approach could be useful for species that preclude the use of a Zeeman slower, e.g. molecules, or for experiments where high atom number or throughput are critical. We plan to use this buffer-gas beam source to load a MOT with CaF using laser cooling and slowing similar to that used with YO and SrF [3, 4].

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Neutral Gas Sympathetic Cooling of an Ion in a Paul Trap

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A single ion immersed in a neutral buffer gas is studied. An analytical model is developed that gives a complete description of the dynamics and steady-state properties of the ions. An extension of this model, using techniques borrowed from the mathematics of finance, is used to explain the recent observation of non-Maxwellian statistics for these systems. Taken together, these results offer an explanation of the longstanding issues associated with sympathetic cooling of an ion by a neutral buffer gas.

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Quantum interactions in a hybrid atom-ion trap

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Using a hybrid trap, interactions between laser-cooled atoms and ions and sympathetically-cooled molecular ions are studied. Our hybrid trap consists of ^{40}Ca magneto-optical trap localized within a linear quadrupole trap used to create Coulomb crystals of various ionic species such as Yb^+, Ba^+, and $BaCl^+$. Ultracold collisions in this hybrid trap allow the characterization of novel interactions important to quantum and astro- chemistry. Additionally these collisions serve as a robust and general method to create samples of ground state molecular ions with large dipole moments, which serves as a significant milestone towards using molecular ions in quantum information studies as well as potential qubits in future quantum computation architecture. Here we discuss our current efforts to quantify certain charge-exchange reactions; observe and simulate the complex dynamics of trapped ions in an ultracold buffer gas; and demonstrate the ro-vibrational quenching of the non-vertical molecular ion $BaCl^+$ using a highly-polarizable, ultracold buffer-gas of calcium atoms.

Advancing surface-electrode ion trap capabilities: demonstrations of ball grid arrays, active in-vacuum control electronics, and integrated diffractive optics

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We report on three IARPA seedling projects that address issues in scaling of microfabricated ion traps to large numbers of qubits. In the first project (*SMIT-BGA*), Honeywell International has fabricating gold surface-electrode ion traps with back-side ball-grid-array connections to eliminate wirebonds and to reduce the physical die size. We demonstrate ion loading and transport and provide characterizations of the trap operation. The second project (*IEMIT*), also in collaboration with Honeywell International, is a successful demonstration [1] of a compact, in-vacuum 80 channel DAC system controlling a surface-electrode ion trap. This system reduces the number of through vacuum connections by a factor of ten. The third project (*IDM*), in collaboration with Griffith University, takes multiple diffractive optical elements and etches them into the surface of a surface-electrode ion trap. We demonstrate reflective optical elements for both collimation and refocusing of light from $^{171}Yb^{+}$.

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THURSDAY

Nano-friction between crystals of light and ions with atomic resolution and control from one- to many-body physics

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Friction is a ubiquitous phenomenon poorly understood at the nano-scale, where large forces dominate across atomically smooth interfaces. We study stick-slip friction – the catastrophic energy release mechanism dominant in this regime – with previously unattainable atomic resolution and control in a synthetic nano-friction interface between a Coulomb crystal of cold trapped ions and a crystal of light, an optical lattice. We tune stick-slip friction from maximal to zero, the sought after regime of superlubricity, via lattice mismatch of the two crystals by controlling the ion arrangement. We also vary the size of the Coulomb crystal from one to many ions, elucidating the connection between the single-particle and many-particle minimalistic models of nano-friction. Interestingly, we observe the transition to superlubricity, a many-particle interaction effect, with only 3 ions. The possibility of correlated quantum tunneling makes this a promising system for studying novel quantum many-body phases and dynamics of nano-friction.

'Alligator' photonic crystal waveguides for single-atom trapping and strong light-matter interactions

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Recent advances in nanophotonics provide new possibilities for optical physics [1-2]. The integration of free-space atoms with nanophotonic devices has progressed on several fronts, including nano-scale cavities [3] and dielectric waveguides [4]. Significant technical challenges exist for developing such hybrid atom-photonic systems, arising from the following requirements: (1) The fabrication is sufficiently precise to match waveguide photonic properties to atomic spectral lines; (2) atoms are stably trapped in the presence of substantial Casimir-Polder forces yet achieve strong atom-field interaction; (3) coupling to and from guided modes of nanophotonic elements is efficient; (4) sufficient optical access exits for external laser cooling and trapping; and (5) sufficient optical power handling capability to support trap depths ~ 1mK. We describe a novel 'alligator' photonic crystal waveguide that meets these stringent requirements for integration of nanophotonics with ultracold atom experiments [5]. We also discuss progress toward dynamic capacitive tuning of the PCW band structure.

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Injection of angular momentum in a polariton superfluid

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We report the formation of a ring-shaped array of vortices after injection of angular momentum in a polariton superfluid. A L=8 Laguerre-Gauss mode is generated using an holographic technique on a spatial light modulator, and the angular momentum is transferred to the fluid via quasi-resonant excitation.

We can distinguish two interesting regimes. For low power excitation (low density of polaritons) we observe a spiral pattern containing phase defects, signature of optical interferences.On the other hand, in the high density regime the interaction between polaritons become relevant and the interference disappears while vortices nucleate as a consequence of the angular momentum quantization. The radial position of the vortices evolves freely as a function of the density. Hydrodynamic instabilities resulting in the spontaneous nucleation of vortex-antivortex pairs when the system size is sufficiently large confirm that the vortices are not constrained when nonlinearities dominate the system.

Observation of Grand-canonical Number Statistics in a Photon Bose-Einstein condensate

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Large statistical number fluctuations are a fundamental property known from the thermal behavior of bosons. At low temperatures, when a macroscopic fraction of bosonic particles undergoes Bose-Einstein condensation, large fluctuations of the condensate population conflict with particle number conservation. Correspondingly, condensation is accompanied by a damping of fluctuations and the emergence of second-order coherence. Here, we report measurements of particle number correlations and fluctuations of a photon Bose-Einstein condensate in a dye microcavity. The photon gas is coupled to a reservoir of molecular excitations, which serve as both heat bath and particle reservoir to realize grand-canonical conditions. For large reservoirs, we observe strong number fluctuations of the order of the total particle number extending deep into the condensed phase. Our results demonstrate that condensation under grand-canonical ensemble conditions does not imply second-order coherence. We find a regime where Bose-Einstein condensation and statistical fluctuations as large as the particle number coexist.

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Light-Wave Mixing and Scattering with Quantum Gases

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We show that optical processes originating from elementary excitations with dominant collective atomic recoil motion in a quantum gas can profoundly change many nonlinear optical processes routinely observed in a normal gas. Not only multi-photon wave mixing processes all become stimulated Raman or hyper-Raman in nature but the usual forward wave-mixing process, which is the most efficient process in normal gases, is strongly reduced by the condensate structure factor. On the other hand, in the backward direction the Bogoliubov dispersion automatically compensates the optical-wave phase mismatch, resulting in efficient backward light field generation that usually is not supported in normal gases.

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Sympathetic cooling of a membrane oscillator in a hybrid mechanical-atomic system

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Sympathetic cooling with ultracold atoms and atomic ions enables ultralow temperatures in systems where direct laser or evaporative cooling is not possible. So far, it has only been used to cool other microscopic particles such as atoms of a different species or molecular ions up to the size of proteins [1].

Here we use ultracold atoms to sympathetically cool the vibrations of a Si_3N_4 membrane, a microfabricated structure which is currently used in many optomechanics experiments [2]. The atoms and the membrane vibrations are coupled via laser light over a macroscopic distance [3]. An optical cavity around the membrane enhances the interactions [4], allowing us to efficiently cool the membrane vibrations from room temperature to 650 ± 330 mK [5].

Our hybrid optomechanical system [6] operates in a regime of large atom-membrane cooperativity and enables a number of exciting experiments on quantum control of mechanical motion.

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Optical Frequency Combs and Temporal Solitons in Optical Microresonators

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The field of frequency metrology was revolutionized by the invention of the optical frequency comb (OFC) [1]. Later in 2007 it was discovered that OFCs can also be generated in optical microresonators [2,3], which typically have a large spacing between comb lines (10GHz to 1THz), large power per frequency comb line, and spectra in the near-infrared or the mid-infrared. However, until recently the noise often present in these OFCs made them unsuitable for frequency meteorology applications. We demonstrate that low noise OFCs can be achieved via soliton formation in Magnesium Fluoride and Silicon Nitride optical microresonators [4]. This also has been shown in Magnesium Flouride optical microresonators to provide pulses which can be used to externally broaden OFCs to sufficient bandwidths for self-referencing.

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Self-organized optomechanical structures

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We demonstrate the spontaneous emergence of hexagonal structures in a laser beam traversing a cloud of cold Rb atoms and being retro-reflected by a single plane mirror. The pump axis is the only distinguished axis and spontaneous breaking of the rotational as well as translational symmetry in the plane orthogonal to this axis is demonstrated. Light patterns and atomic density patterns are complementary: Hexagonally coordinated light peaks expel atoms due to dipole forces leading to the formation of a matching honeycomb structure in the atomic density. The scattering of the pump light at the resulting density grating sustains in turn the modulation of the light field. The length scale is given by the Talbot effect. The experiment opens novel options for the manipulation and control of matter as well as studying symmetry breaking and dynamical phase transitions in a well controlled system which can be potentially transferred to quantum matter.

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Feedback cooling using a near-Heisenberg-limited position measurement

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Near-field cavity-optomechanical coupling [1,2] is used to continuously monitor the position of a 4.3 MHz nanomechanical oscillator with an imprecision ~ 30 dB below that at the standard quantum limit. Employing this measurement as a feedback signal, radiation pressure is used to cold damp [3] the oscillator from a cryogenic bath temperature of 15 K to an effective temperature of ~ 2 mK, corresponding to a mean phonon occupation of $n \sim 10$. The inferred product of the measurement imprecision and the force noise experienced by the oscillator is ~ 20 times above the limit set by the Heisenberg uncertainty principle [4]. These results underscore the potential of cavity optomechanics as a toolbox for quantum feedback control.

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Optomechanics with ultra cold Rydberg gases

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Ultra cold gases in which atoms are coupled to highly excited Rydberg states are emerging as versatile platform for interdisciplinary research, realizing single photon sources [1], extremely non-linear Kerr media [2], quantum gates [3] or aggregate systems to study conical intersections [4] and energy transport [5]. We investigate the exploitation of such features interface a Rydberg gas with a micro mechanical oscillator. In our model system, a vibrating mirror is coupled to a medium with electromagnetically induced transparency (EIT) via the probe and coupling laser beams. Dramatic effects of Rydberg excitations on the EIT medium [1,2] allow intricate interplay between Rydberg physics and mirror mechanics.

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THURSDAY

Cavity Opto-Mechanics with Cold Atoms: Force Sensing near the Standard Quantum Limit and Coupled Oscillators

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Cavity Opto-Mechanics with cold atoms provides a system with unique properties for studying quantum physics: Highly tunable and controllable oscillators, close to their thermal groundstate, with excellent isolation from the environment and quantum-limited optical detection.

The limit of sensitivity of a force measurement dictated by quantum mechanics, the Standard Quantum Limit, is reached when measurement imprecision from photon shot-noise is balanced against disturbance from measurement back-action. To observe this quantum limit, we apply a known external force to the center-of-mass motion of an ultracold atom cloud in a high-finesse optical cavity. We achieve a sensitivity that is consistent with theoretical predictions and is a factor of 4 above the absolute Standard Quantum Limit.

The flexibility of our approach furthermore allows us to study cavity-optomechanics with multiple, coupled oscillators. To this end, we prepare two oscillators at distinct frequencies; off-resonance pumping of the cavity allows us to couple the oscillators and applying a force is employed to separately and coherently drive each oscillator. We observe the dynamics of this system both in the frequency and the time domain.

From membrane-in-the-middle to mirror-in-the-middle with a high-reflectivity sub-wavelength grating

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We fabricate highly reflective sub-wavelength grating membranes using silicon nitride. We achieve a grating reflectivity of 99.8% with a membrane mechanical frequency of ~1 MHz. We integrate the grating-membrane into a Fabry-Perot cavity and investigate its opto-mechanical properties.

A scanning cavity microscope

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We present a novel method for highly sensitive and spatially resolved absorption spectroscopy of nanoscale objects. To boost sensitivity, we harness multiple interactions of probe light with an object by placing the sample inside a high-Finesse scanning optical microcavity. The cavity is built from a laser-machined and mirror-coated end facet of a single mode fiber and a macroscopic plane mirror forming a fully tunable open access Fabry-Perot cavity [1, 2].

We present measurements with gold nanoparticles and carbon nanotubes which demonstrate a sensitivity for absorption cross sections down to ~ 1nm². We furthermore present a scheme harnessing the Purcell effect for cavity-enhanced Raman spectro-imaging. First results with individual single-wall carbon nanotubes are shown.

Our results open the perspective to use scanning cavity microscopy as a versatile tool for spectroscopy on weakly absorbing nanoparticles, for bio-sensing, and single-molecule studies.

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Thermodynamic corrections to mechanical oscillations

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Optomechanics has been successfully applied to systems involving wide range of scales from as small as 10^{-21} g for atomic level objects like cold atoms to as large as 10^3 g for macroscopic scale systems like LIGO project. As the size of the mechanical object gets larger, more degrees of freedom come in and the quantum harmonic oscillator treatment of optomechanics may become questionable. We examine models of a mechanical oscillator coupled to fermionic and bosonic degrees of freedom respectively, and find that spring-like classical oscillations can occur even if there is no underlying quantum mechanical oscillator. Methods for distinguishing between quantum harmonic oscillations and other oscillatory behavior are considered. Our model can be realized through potential implementations by using atoms as the spins and the optical cavity mode as the harmonic oscillator.

A Useful Entanglement Resource; 10 dB Spin Squeezing with Cavity QND Measurements

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Entanglement can be used to increase measurement precision beyond the fundamental limit for an unentangled state, the so-called standard quantum limit. We present the direct observation of phase sensitivity 10.2(6) dB (factor of 10.5(1.5) in variance) below the standard quantum limit with no background subtractions applied. These results are achieved using quantum non-demolition measurements of a large atomic ensemble ($5*10^5$ Rb atoms). By collectively probing the ensemble on an optical cycling transition, previously limiting sources of measurement back-action due to Raman transitions are greatly mitigated. The scheme demonstrated here is well-suited for use in optical lattice clocks, scales well with atom number, and avoids potential systematic errors due to atomic collisions.

Quantum metrology frontiers with highly squeezed quantum states of atomic ensembles

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Production of spin-squeezed atomic ensembles could greatly enhance the performance of existing atom-based sensors by overcoming the atomic shot-noise that limits these sensors. At the time of writing, our preliminary results with an ensemble of 25×10^3 ^{87}Rb atoms (prepared in magnetically insensitive states) suggest a noise reduction that is 17dB below shot-noise with 90% coherence indicating a metrologically relevant squeezing parameter of 16.5dB. With our currently known experimental inefficiencies the theoretical maximum we expect to observe lies around 23dB for 100×10^3 atoms.

We employ a measurement based squeezing method inside of a high-finesse ($>10^5$) dual-wavelength cavity, resonant at both 780 nm (probe) and 1560 nm (trap). The commensurate wavelength relationship allows identical coupling of the probe light to all atoms, generating symmetric squeezed states, opening up the future possibility of releasing the generated states into free-space for fluorescence detection, compatible with atomic fountain based sensors.

Quantum Zeno dynamics of a Rydberg atom

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The back-action of a quantum measurement can modify the evolution of a quantum system. The most famous example is the quantum Zeno effect, where the repeated measurements completely freeze the evolution. The behavior is different, however, if the eigenvalue corresponding to the result of the measurement is degenerated. In this case, the evolution of system is no longer freezed, but the dynamics is confined inside the corresponding eigenspace. This is the Quantum Zeno Dynamics (QZD).

We have experimentally implemented QZD in the Stark manifold of a Rydberg atom. Under the effect of a purely s+ polarized radio-frequency field, our atom initially in the circular state behaves as a J=25 spin, which rotates between the north and south poles of a generalized Bloch sphere. By repeatedly asking the system “have you crossed a given latitude?”, we can induce a very non classical evolution of the spin.

Generation of multiparticle entangled states using quantum Zeno dynamics

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Quantum states are usually generated by unitary operations exclusively, while interaction with the environment serves only for final measurement of the state, destroying its interesting properties. Powerful new forms of quantum dynamics have been proposed where this dichotomy is abandoned and environment coupling is used as part of the state generation. One incarnation of this general idea is quantum Zeno dynamics (QZD), where the system is coherently driven while simultaneously confining it to a subspace of its Hilbert space by a projective measurement. Using atom chips and fiber-optical cavities, we have applied QZD to create multiparticle entangled states in an ensemble of qubit atoms in a cavity. We perform quantum tomography of the resulting state and demonstrate that, in the presence of sufficiently strong measurement, the system attains a multiparticle entangled state instead of the separable state reached without the measurement.

Quantum Information Th-071

Many-particle entangled states of two-component Bose-Einstein condensates

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Many-particle entanglement is a fascinating concept that poses intellectual challenges and is at the heart of quantum computing, quantum simulation, and quantum metrology. Using controlled collisions on an atom chip [1], we prepare different many-particle entangled states of two-component Bose-Einstein condensates, perform a tomography of their quantum state [2], and explore their use in quantum metrology with an atom interferometer [3]. In recent experiments, we have created over-squeezed states, a class of non-Gaussian entangled states that are not spin-squeezed but still useful for atom interferometry beyond the standard quantum limit. Besides entanglement in a single Bose-Einstein condensate, our system could allow the generation of Einstein-Podolsky-Rosen entanglement of two spatially separated and individually addressable condensates [4].

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Quantum Information Th-072

Atomic twin Fock states in momentum space

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We report on our current work to establish a new source of atomic twin Fock state where the two modes consist of real-space momentum states instead of spin states. Since the entangled atoms fly apart of each other, such a source would enable the direct observation of non-locality with massive particles (instead of photons). Here, the two modes are the output channels of elastic collisions occurring in a Bose–Einstein condensate loaded in a moving optical lattice. Using metastable helium atoms and a microchannel plate detector, we are able to fully reconstruct the 3-dimensional momentum distribution of the output state with single atom resolution. Combined with the possibility to rotate the state on the Bloch sphere using Bragg pulses, this opens the route to a tomography of this highly non-classical state with excellent precision.

Quantum networking and sensing efforts at the Army Research Laboratory

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The Quantum Sciences group at the Army Research Laboratory presents two ongoing efforts, an atom chip for ultra-cold atoms and a MOT-based quantum memory with PPLN frequency conversion for quantum networking.

The atom chip experiment explores the capabilities of ultra-cold/degenerate ensembles in a compact physics package. We use microwave and RF fields for coherent spin control of ^{87}Rb atoms. The atom chip enables tailoring magnetic trapping potentials, for studies of atom interferometery, novel quantum phases and quantum enhanced measurements

Our quantum memory utilizes off-axis, spontaneously emitted single photons, generated by the interaction of a 795 nm write laser beam with cold ^{87}Rb atoms. To minimize optical fiber transmission losses, the single photons are frequency-converted to the telecomm band by difference frequency generation in a PPLN crystal. Quantum memories and single photon transport are key ingredients for a scalable quantum network that could enable high fidelity distribution of entanglement over long distances.

Towards the Detection of Momentum Entangled Atom Pairs

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We present our work towards the creation and detection of momentum entangled states of metastable helium (He*) atoms.

Starting from a Bose-Einstein condensate (BEC) of metastable helium, stimulated Raman transitions transfer momentum onto the atoms. Subsequent collisions between two counterpropagating matter waves lead to atom pairs that are entangled in their momentum degree of freedom. This state represents a three-dimensional version of the one discussed in the Einstein-Podolsky-Rosen gedankenexperiment.

By using a position resolved micro-channel plate (MCP) detector the high internal energy of the He* atoms of almost 20 eV per atom allows for efficient detection of individual atoms with a high spatial and temporal resolution.

We show that a double double-slit as well as a ghost interference scheme can be used to show the entanglement and that those schemes are feasible with experimental restrictions in our setup. We discuss the main challenges in the experimental realization and present the present status of the experiment.

Control of Quantum Dynamics on an Atom-Chip

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The minimization of the effect of external perturbations and, more importantly, the control of coherent dynamics within a conveniently defined quantum space is crucial to many applications such as atom interferometry and quantum information processing. We exploited the back action of quantum measurements and strong couplings to tailor and protect the coherent evolution of a quantum system, a phenomenon known as Quantum Zeno Dynamics. Furthermore we apply a recently developed optimal control tool to drive the quantum dynamics from initial state toward a chosen target. This tool allows to reach any point in the Hilbert space of interest, in a time much faster than allowed by non-optimized continuous coherent evolution. Our control and protection protocols are realized on a compact, easy to use, Atom-Chip device, using a ^{87}Rb BEC, a system which simplifies the approach to future developments.

High-fidelity cluster state generation of ultracold atoms in an optical lattice

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We propose a method for generating high-fidelity multipartite spin entanglement of ultracold atoms in an optical lattice in a short operation time with a scalable manner, which is suitable for measurement-based quantum computation. To perform the desired operations based on the perturbative spin-spin interactions, we propose to actively utilize the extra degrees of freedom (DOFs) usually neglected in the perturbative treatment but included in the Hubbard Hamiltonian of atoms, such as, (pseudo-)charge and orbital DOFs. Our method simultaneously achieves high fidelity, short operation time, and scalability by overcoming the following fundamental problem: enhancing the interaction strength for shortening the operation time breaks the perturbative condition of the interaction and inevitably induces unwanted correlations among the spin and extra DOFs.

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Coherent optical memory with 94% efficiency

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We report our experiment on the high-efficiency coherent optical memory based on electromagnetically induced transparency (EIT) scheme using optically dense cold cesium atoms. The optical depth for the EIT transition at the D_1 line is up to 650. Operation of the EIT at the D_1 line in addition with preparation of population in the single Zeeman state |F=3,m=3> eliminates the additional photon and atomic coherence losses due to the off-resonant coupling of the EIT control field to the unwanted excited states. This is crucial to obtain a high memory efficiency which requires to operate the EIT at high optical depths and strong control fields. At very high optical depth, the off-resonant coupling of the control field on the probe transition induces a four-wave mixing process which may result in the probe gain and introduce additional quantum noises. We discuss the effect of the four-wave mixing in our current experiment and in another related experiment, as well as the way to reduce the four-wave mixing.

RYDBERG ATOMS

Towards Single-Photon Nonlinear Optics via Pattern Formation in Spatially Bunched Atoms

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There is a great interest in enhancing light-atom interaction strengths to the point where injecting a single photon triggers a nonlinear optical response. Single-photon nonlinear effects are predicted to occur in a homogeneous gas of two-level atoms, but this has not been observed experimentally. We show theoretically that the nonlinearity that arises due to atomic bunching gives rise to more than two orders of magnitude enhancement in the third-order nonlinear optical susceptibility over the case of a homogeneous gas. With this enhanced material response, we predict that single-photon nonlinearities are attainable in sub-Doppler-cooled two-level atoms. We find that these results agree with our experimental observation of multimode, transverse optical pattern formation in sub-Doppler-cooled atoms, wherein we observe the intensity threshold to be two orders of magnitude lower than that reported for a homogeneous gas. With this ultra-low threshold, our system has the potential to realize a single-photon optical switch.

Optical properties of a strongly correlated array of induced dipoles

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We calculate the transmission of near resonant light through a monolayer of induced dipoles. Using classical-electrodynamics simulations we show that for a regular lattice, dipole-dipole interactions lead to departures from the Beer-Lambert law. In contrast to a quasi-2D ultracold random gas as modeled by authors in [1], the regular lattice displays strong correlation effects including ferro- and anti-ferroelectric phases which relate to super- and sub-radiant modes respectively. Such features could be observed using experimental cold atoms in optical lattices or metamaterials. We also highlight the significance of inhomogeneous broadening which destroys the correlations [2].

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Photonic Controlled-Phase Gate Based on Rydberg Interactions

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Photons are ideal carriers of information in quantum communication. Since they do not interact, the implementation of deterministic photonic quantum computation depends on the creation of a non-permanent strong interaction between single photons. The implementation of neutral Rydberg atom gates [1] inspired the development of photonic gates, using the coherent reversible mapping of the quantum states of photons onto highly interacting Rydberg atoms [2-5]. Here we propose an interaction-based two-qubit gate between photons stored in Rydberg levels of an atomic ensemble. We perform a detailed study of errors due to the many-body interaction between Rydberg spin-waves, and we propose a compensation scheme for these errors. Furthermore we completely separate interaction and propagation by eliminating the Rydberg level from the storage process. Our proposed controlled-phase gate can achieve 99% fidelity with current technology.

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Single-Photon Switch and Transistor Based on Rydberg Blockade

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All-optical switching is a technique in which a gate light pulse changes the transmission of a target light pulse without the detour via electronic signal processing. We take this to the quantum regime, where the incoming gate light pulse contains only one photon on average [1]. The gate pulse is stored as a Rydberg excitation in an ultracold gas using electromagnetically induced transparency. Rydberg blockade suppresses the transmission of the subsequent target pulse. Finally, the stored gate photon can be retrieved. A retrieved photon heralds successful storage. The corresponding postselected subensemble shows an extinction of 0.05. Using a Forster resonance, we achieve a gain of 20 for one incoming photon, thus demonstrating a single-photon transistor. The gain quantifies the change of the transmitted target photon number per incoming gate photon. The detected target photons reveal in a single shot with fidelity above 0.86 whether a Rydberg excitation was created during the gate pulse [2].

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THURSDAY

Strongly Interacting Photons in a Rydberg Polariton Gas: Few Photon Spectroscopy and Coulomb Bound States

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Free space photons can be made to strongly interact by converting them into dark state polaritons dressed with Rydberg atoms. Recently a two-photon bound state was experimentally observed in such systems [1]. Here we dsicuss the zoology of two-photon bound states and scattering states that emerge in this system. We show how to efficiently measure the full two-photon scattering matrix using a series of pulsed experiments. We use this method to characterize the fidelity of two-photon gates in this system. We then consider a special class of bound states that emerge when the Rydberg interaction brings the two polaritons into Raman resonance. We show that these exotic bound states have the spectrum of a 1D Coulomb bound particle. Furthermore, these "Coulomb" states travel with negative group velocity, which allows a simple preparation and detection scheme. We demonstrate the backward propagation, preparation, and detection of Coulomb states with full numerical simulations.

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THURSDAY

Generating topological spin textures in spinor Bose-Einstein condensates by a stimulated Raman interaction

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Here we present the generation of spin monopoles, non-Abelian vortices, skyrmions, fractional vortices, coreless vortices, and singular vortices in an 87-Rb Bose-Einstein condensate. A coherent Raman process allows us to engineer the internal and external momenta, superfluid velocities, and spatial spin distribution of the condensate as well as control the complex relative phases of the magnetic spin components. Using techniques from singular optics we can generate complex laser beams and therefore a great diversity of spin textures and topological excitations in the BEC. This optical imprinting also permits, for example, multiple monopoles to exist in a single BEC, enabling the study of monopole-anti-monopole dynamics. Studying the behavior of these spin textures provides insight into other fields, furthers understanding of fundamental spin-dependent symmetries and light-matter interactions, and extends applications of ultracold atomic physics to metrology and information.

Stability of a Floquet Bose-Einstein condensate in a one-dimensional optical lattice

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Motivated by recent experimental observations (C.V. Parker et al., Nature Physics, 9, 769 (2013)), we analyze the stability of a Bose-Einstein condensate (BEC) in a one-dimensional lattice subjected to periodic shaking. In such a system there is no thermodynamic ground state, but there may be a long-lived steady-state, described as an eigenstate of a "Floquet Hamiltonian". We calculate how scattering processes lead to a decay of the Floquet state. We map out the phase diagram of the system and find regions where the BEC is stable and regions where the BEC is unstable against atomic collisions. We show that Parker et al. perform their experiment in the stable region, which accounts for the long life-time of the condensate (~ 1 second). We also estimate the scattering rate of the bosons in the region where the BEC is unstable.

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Sayan Choudhury and Erich J Mueller, arXiv preprint , arXiv: 1405.1398 (2014)

Topological phases in spin-orbit coupled dipolar bosons in a one-dimensional lattice

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We study the spin-orbit coupled dipolar bosons in a one-dimensional optical lattice. In the Mott-insulating regime, this system can be described by the quantum XYZ spin model in a transverse field. The magnetic dipolar interactions between atoms give rise to the inter-site interactions. We focus on investigating the effect of dipolar interactions on the topological phase. The topological phase can be shown when spin-orbit coupling incorporates with the repulsive dipolar interaction. We find that the dipolar interactions can broaden the range of parameters of SO coupling and transverse field for exhibiting the topological phase. We investigate the spin correlations between the two nearest neighbour atoms for indicating the topological phase. This may be useful for detecting topological phases in experiments.

Fractionalized Majorana fermions (parafermions) with ultracold atoms

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Parafermions are topologically protected modes which can be thought of as fractionalized Majorana fermions. They commute up to a nontrivial phase factor in contrast to the minus sign for fermions. It has been suggested that these exotic modes exist at the interface of a fractional quantum Hall system and a superconductor. In the light of recent advances towards the realization of fractional quantum Hall states with bosonic ultracold atoms, we propose a realization of parafermions in a system consisting of a Bose-Einstein-condensate trench within a bosonic fractional quantum Hall state. We show that parafermionic zero modes emerge at the endpoints of the trench and give rise to a topologically protected degeneracy. We also discuss methods for preparing and detecting these modes.

p-wave pair amplitude and *s*-wave superfluid phase transition in the BCS-BEC crossover regime of an ultracold Fermi gas with a spin-orbit interaction

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We theoretically investigate pairing properties of an ultracold Fermi gas with an *s*-wave pairing interaction and asymmetric spin-orbit coupling. In the *s*-wave superfluid state at T=0, we determine the parameter region where the broken spatial inversion symmetry due to the asymmetric spin-orbit interaction induces a large amount of *p*-wave pair amplitude. In this regime, a *p*-wave superfluid state is expected, when one suddenly changes the *s*-wave pairing interaction into the *p*-wave one using a Feshbach resonance. We also show that the region satisfying this regime has high phase transition temperature T_c, within the framework of the strong-coupling Gaussian fluctuation theory. Since the realization of a *p*-wave superfluid Fermi gas is an exciting challenge in cold Fermi gas physics, our results would be useful for realization of this unconventional pairing state using the recent artificial gauge field technique.

Implementation, phase structure and real time dynamics in atomic quantum simulators of lattice Gauge-Higgs theory

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We propose how to implement a quantum simulator of the U(1) gauge-Higgs model with asymmetric nearest-neighbor Higgs coupling by using a system of cold atoms in an optical lattice [1]. The gauge-Higgs coupling in the imaginary time direction naturally arises from the violation of the U(1) local gauge invariance of the simulator caused by the deviation from the fine-tuned system parameters. A general method to supply the Higgs coupling in all space-time directions may be realized by coupling atoms in an optical lattice to another particle reservoir filled with the Bose-condensed atoms via laser transitions. Clarification of the dynamics of the gauge-Higgs model sheds some lights upon various unsolved problems including the inflation process of the early universe. We study the phase structure of this model by Monte Carlo simulations, and also discuss the real time dynamics of each phase through the analysis of the Gross-Pitaevskii model.

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THURSDAY

Collective mode analysis of a Bose-Einstein condensate in a density-dependent gauge potential

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Synthetic gauge potentials created with Ultracold atomic gases have become the focus of intense interest both experimentally [1] and theoretically [2]. Most schemes are static in the sense that there is no feedback between the matter field and the method used to prescribe them. Here, we study the collective modes of a Bose-Einstein condensate subject to an optically induced density-dependent (interacting) gauge potential [3]. The excitation frequencies of the trapped one-dimensional condensate are obtained by solving the Bogoliubov-de Gennes equations as a function of the strength of the gauge field. It is found that at critical values of the gauge field strength the condensate exhibits dynamical instabilities. By studying the full nonlinear dynamics of this model, signatures of the instabilities can also be seen; including the departure of the dipole mode frequency from the trap frequency.

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Synthetic Spin-Orbit Coupling Without Light

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Recent experimental successes in Raman-induced spin-orbit coupling in ultracold atomic systems opened the door to the study of a novel class of many-body Hamiltonians. However, these techniques have been limited thus far to Abelian spin-orbit couplings. In this talk I will present a new technique for producing two- and three-dimensional non-Abelian (Rashba-like) spin-orbit couplings for ultracold atoms without involving light. Instead, a sequence of pulsed inhomogeneous magnetic fields imprint suitable phase gradients on the atoms. These techniques can be easily implemented on an atom chip. I will then consider the implementation of this spin-orbit coupling on a lattice. Exploiting the geometry of the atom-chip, both staggered and non-staggered non-Abelian fluxes can be induced. Finally, I demonstrate how combining the pulsed spin-orbit coupling with lattice shaking techniques can be used to produce Chern bands with C=2. Using exact diagonalization, we explore the novel Fractional Chern Insulating states that emerge in these models.

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Self-organized Rice-Mele model in ultracold atoms

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One of the signatures of nontrivial topology in one-dimensional (1D) systems are solitons that exist on domain walls between topologically distinct phases. In the field of ultracold atoms it is, however, difficult to realize defects such as domain walls due to a perfect structure of optical trapping potentials. We show a 1D system of cold atoms in which a structure with nontrivial topological properties may emerge due to self organization. In this process of self organization defects that support solitons may be created. Our system consists of interacting two species fermions trapped in periodically driven lattice potential. Together, interaction and lattice shaking lead to the creation of density-wave structure of one species while the other species may be described with Rice-Mele model. We calculate configuration dependent Zak phase certifying the non-trivial topology and show existence of localized modes. We complement theoretical deriviatons discussing experimental methods that may be used in order to probe topological phenomena.

Optical-lattice Floquet systems

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Ideas to engineer the Floquet Hamiltonian of periodically driven many-body systems have recently been successfully applied to optical-lattice systems. Examples include the dynamical control of the bosonic Mott transition in Arimondo's group and the realization of strong artificial gauge fields in the groups of Bloch, Esslinger, Ketterle, and Sengstock. I will discuss the dynamical realization of topological insulators in driven optical lattices and compare high-frequency approaches (like our proposal [1]) with Floquet-topological-insulator schemes requiring intermediate frequencies (like the proposal [2]). In this context also a method for the tomography of (topological) band insulators will be proposed [3]. Moreover, I will present a careful study of how to selectively couple the lowest Bloch band of an optical lattice to a more dispersive excited band using resonant driving. Such orbital coupling is shown to allow for the coherent melting a bosonic ground-band Mott insulator into a (low-entropy) excited-band superfluid.

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Measuring geometric phases in Bloch bands: The topology of a Dirac cone

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In addition to the dispersion relation, electronic bands are characterized by their topological properties, which give rise to intriguing phenomena such as the integer Quantum Hall effect or topological insulators. Using ultracold bosonic atoms in a graphene-type honeycomb lattice, we experimentally studied the local topological structure of individual Dirac points. By combining Bloch oscillations with Ramsey interferometry, we measured Berry phases for various closed loops in quasi-momentum space. When enclosing a single Dirac point, we observed a Berry phase of pi, while enclosing zero or two Dirac points resulted in a vanishing Berry phase. By imbalancing the lattice beams, we moved and subsequently merged the Dirac points in the Brillouin zone and characterized the resulting change in topological structure. Furthermore, we present preliminary measurements of interband topological properties using Stückelberg interferometry. These approaches can be applied to arbitrary lattices and can provide complete topological maps of the band structure.

Quantum magnetism of bosons with synthetic gauge fields in one-dimensional optical lattices: a Density Matrix Renormalization Group study

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Significant effort is devoted to realize synthetic gauge fields for ultra-cold atoms in optical lattices. This permits to investigate strongly correlated Mott insulating phases, where the interplay between strong interactions and gauge fields can give rise to exotic quantum magnetism that is difficult to access in solid state physics. We provide a comprehensive study of the quantum magnetism in the Mott insulating phases of the 1D Bose-Hubbard model with Abelian or non-Abelian synthetic gauge fields, using DMRG. We focus on the interplay between the synthetic gauge field and the asymmetry of the interactions, which gives rise to a very general effective magnetic model: a XYZ model with various Dzyaloshinskii-Moriya interactions, which are strongly reminiscent of those present in strongly correlated electronic materials. The properties of the different quantum magnetic phases and phase transitions of this model are investigated.

Synthetic fields in synthetic dimensions

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The combination of ultracold atomic gases with optically-induced synthetic gauge fields promises a potent new experimental tool. In the context of lattice-type physics, large synthetic magnetic fields offer the chance to experimentally probe such fascinating systems as insulating phases with chiral edge states and nontrivial Chern numbers, and the fractal Hofstadter butterfly spectrum. To avoid the heating issues associated with large Raman-coupling rates, we treat the Zeeman quantum number of each atom as an index in an effective 1-D lattice and combine that with optical Raman coupling and a 1-D real-space optical lattice to produce the dynamics of a spinless 2-D lattice gas in a homogeneous magnetic field.

Topologically Robust Transport of Photons in a Synthetic Gauge Field

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We implement a synthetic gauge field for photons using a two-dimensional lattice of coupled micro-ring resonators, on a silicon photonics platform. We demonstrate the presence of topologically robust edge states in our system using direct imaging of the edge state wavefunction. Using transmission and delay measurements made on a number of devices, we further show that the edge states are less susceptible to fabrication induced disorder when compared to bulk states. Also, the edge state transport is diffusive whereas the bulk states are localized. Moreover, we compare the transmission along edge states to a topologically trivial one-dimensional system and unambiguously demonstrate the robustness of edge states.

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Atomic Hong-Ou-Mandel effect in tunnel-coupled optical tweezers

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We present recent work in which we demonstrate near-complete control over all the internal and external degrees of freedom of single laser-cooled ^{87}Rb atoms trapped in sub-micron optical tweezers. By dynamically introducing a tunnel-coupling between the tweezers, we implement a massive-particle analog of the Hong-Ou-Mandel effect where atom tunneling plays the role of the photon beamsplitter. The HOM effect is used to probe the influence of atomic indistinguishability on the two-atom dynamics for a variety of initial conditions. These experiments demonstrate the viability of the optical tweezer platform for bottom-up generation of low-entropy quantum systems and provide an alternative route toward direct observation of quantum dynamics in tunable finite-sized systems.

Quantum co-walking of two interacting particles in one-dimensional lattices

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We investigate continuous-time quantum walks of two indistinguishable particles (bosons, fermions or hard-core bosons) with nearest-neighbor interactions in one-dimensional lattices. The two interacting particles can undergo independent and/or co-walking dependent on both quantum statistics and the interaction strength. We find that for a strong interaction the two particles may form a bound state as a pair of co-walkers that behave like a single composite particle with quantum statistics dependent propagation speed. Such an effective single-particle picture of co-walking is analytically derived in the context of perturbation and consistent with numerical result. In addition to observing bound state, two-particle quantum walks offer a novel detect for exploring quantum statistics and spin dynamics. The two-particle quantum walks in our models can be simulated by light propagations in waveguide arrays or spin-impurity dynamics of ultracold atoms in optical lattices.

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Direct Observation of Strongly Correlated Bosonic Quantum Walks

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Quantum coherence, quantum statistics, and strong interaction between particles are the key components of strongly correlated quantum matter. With the single-site detection and addressing abilities in our quantum gas microscope, we demonstrate a bottom-up approach to engineer strongly correlated matter, and realize single particle and strongly correlated two-particle quantum walks in one dimension. We detect single particle quantum walks and position space Bloch oscillations with exceptional quantum coherence, and observe the crossover from strong bunching to anti-bunching as the bosons fermionize due to strong repulsive interactions. We create repulsively bound atom pairs and study their coherent dynamic. Our work constitutes a new level of control over few-body states in optical lattices and will enable state engineering in quantum simulation and quantum information processing applications.

In situ probing of interacting fermions in an optical lattice

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The Fermi Hubbard model, despite its formal simplicity, contains intriguing physics and poses questions regarding quantum magnetism and d-wave superconductivity which have not been answered yet. The possibility of realizing this model with ultracold fermions in optical lattices has paved the way to many fascinating experiments.

We experimentally investigate the Fermi Hubbard model by locally probing its phases. We prepare a degenerate Fermi gas of potassium-40 atoms and load it into a three-dimensional optical lattice. Our high resolution imaging system combined with a selective RF transfer allows us to independently image the in situ density profiles of the atoms in doubly or singly occupied lattice sites. Varying the on-site interaction by means of a Feshbach resonance we can explore the phases of the Fermi Hubbard model. I will report on our steps towards the local characterisation of the transition to a Mott insulator state.

Fermi Gas Microscope with Lithium-6

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We present the first site-resolved images of fermionic lithium-6 atoms in an optical lattice. Lithium's light mass and its broad Feshbach resonance provide fast and controllable many-body dynamics. The light mass also gives the atoms a large recoil energy, making it difficult to scatter many photons while keeping the atoms pinned at their lattice sites. In addition, lithium has unresolved hyperfine structure in the excited $2P_{3/2}$ state, precluding the use of the polarization gradient cooling used in rubidium single-site experiments. We solve these problems with pulsed Raman sideband cooling in a 2.5 mK deep optical lattice with ~1 MHz trap frequencies at 566 nm spacing and detect the resonantly scattered light to produce images with 520 nm resolution. Quantum gas microscopy with bosonic atoms has enabled direct observation of local correlations [1] and site-resolved manipulation [2] in optical lattices and led to new studies of quantum phase transitions and many-body dynamics. Our work opens the door to local probing and control of systems with fermionic statistics.

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Quantum gas microscope of ytterbium atoms

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Our group focuses on the development of a quantum gas microscope using ytterbium atoms[1,2]. Ytterbium atoms have zero electronic spin, and thus, provide much longer coherence time compared to that of alkali atoms, and are a good candidate for a quantum computer [3].

To increase the numerical aperture of the system, we introduced a solid immersion lens (SIL) between the Yb atomic cloud and the objective lens. Atoms were transported to the surface of the solid immersion lens using a system comprised by three optical dipole traps and the optical accordion technique. After being transported, a pancake-shaped two-dimensional condensate was created near the surface of the SIL [4]. Later, two optical accordion beams (1080nm wavelength) were retro-reflected, trapping the atoms in a square lattice with a 540 nm period. Fluorescence images with single-site resolution of the atoms trapped in the two-dimensional optical lattice were successfully obtained.

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Experimental demonstration of more than 100 individually addressable qubits for quantum simulation and quantum computation

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Efficient quantum simulation and quantum information processing requires scalable architectures that guarantee the allocation of large-scale qubit resources. In our work, we focus on the implementation of multi-site geometries based on microfabricated optical elements. This approach allows us to develop flexible, integrable and scalable configurations of multi-site focused beam traps for the storage and manipulation of single-atom qubits and their interactions [1]. We give an overview on the investigation of ^{85}Rb atoms in two-dimensional arrays of well over 100 individually addressable dipole traps featuring trap sizes and a tunable site-separation in the single micrometer regime. Furthermore, we experimentally demonstrate single-atom quantum registers with more than 100 occupied sites, single-site resolved addressing of single atom quantum states in a reconfigurable fashion and discuss progress in introducing Rydberg based interactions in our setup.

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Qubit fidelity of a single atom transferred among the sites in a ring lattice

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Controlled transfer of atomic qubits opens a route towards quantum information storage and processing. We demonstrate transfer among single atoms trapped in sites of the ring lattice with the aid of an auxiliary moving optical tweezer [1]. Atom in one site follows the moving tweezer when it crosses the lattice and is transported to another site with high efficiency of 95%. In comparison with other schemes [2, 3], it is applied more conveniently for single atoms array. Quantum state tomography is performed to obtain qubit fidelity during the transfer. Additionally, we investigate the coherence properties and analyze in details via spin echo techniques. The reduced fidelity results from instabilities of the tweezer and heating of atoms.

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THURSDAY

Coherent dipole-dipole coupling between two single atoms at a Förster resonance

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Resonant energy transfers, the redistribution of an electronic excitation between two particles coupled by the dipole-dipole interaction, occur in a variety of chemical and biological phenomena [1], most notably photosynthesis. Here, we study, both spectroscopically and in the time domain, the coherent, dipolar induced exchange of electronic excitations between two single Rydberg atoms separated by a controlled distance, and brought in resonance by applying electric or microwave fields [2]. The coherent oscillation of the system between two degenerate pair states occurs at a frequency that scales as the inverse third power of the distance, the hallmark of dipole-dipole interactions [3]. We finally study the propagation of an excitation in a three-atom system. These results show our ability to actively tune strong, coherent interactions in quantum many-body systems.

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A 2D array of Rydberg coupled atomic qubits

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We are developing a 2D array of optically trapped single atom qubits for quantum computation experiments. We demonstrate stochastic loading of an average of 30 Cs atom qubits in a 49 site array with 3.8 µm site to site spacing. Parallel qubit rotations are performed with microwaves and site selective single qubit gates are demonstrated using focused beams of two-frequency Raman light. Single qubit gate fidelity is characterized with randomized benchmarking. Using Rydberg excitation and blockade we demonstrate entanglement of pairs of trapped atoms, and will report on progress towards running quantum algorithms in the array.

SPECTROSCOPY, ATOMIC AND MOLECULAR STRUCTURE

Spectroscopy, Atomic and Molecular Structure Th-107

The $4d^8$ - $4d^7(4f +6p)$ transitions of In VI

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The sixth spectrum of indium (In VI) has been investigated in the grazing incidence wavelength region. The spectrum was recorded on 10.7-m grazing incidence spectrographs at National Bureau of Standards Laboratory in Washington D.C. The source used was a sliding spark operated at different discharge currents. The ground configuration of In VI is $4p^6 4d^8$ and the excited configurations are of the type $4d^7 n\ell$ $(n \geq 4)$. Joshi and VanKleef [1, 2] reported $4d^8$, $4d^7 5p$ and $4d^7 5s$ configurations. In the present work, the $4d^8$ - $4d^7(4f+6p)$ transition array has been studied using Hartree-Fock calculations with relativistic corrections by Cowan's code, incorporating the other interacting configurations $4d^7(5p+5f)+4p^5(4d^9+4d^8 5s)$ for odd parity matrix. More than 75 new energy levels have been established so far based on the identification of about 230 spectral lines. Our wavelength accuracy in the 190 - 400Å region is ±0.005Å. Final interpretation will be based on the least squares fitted parametric calculations.

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Spectroscopy, Atomic and Molecular Structure Th-108

Photoionizing $^{174}Yb^+$ to $^{174}Yb^{2+}$

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We report on the photoionization of $^{174}Yb^+$ ions trapped inside a radio-frequency ion-trap. The photoionization is realized in a three-step scheme. In the second intermediate step the $4f^{14}7p_{1/2}$ level in $^{174}Yb^+$ is excited via the transition from the $4f^{14}5d_{3/2}$ levelwith a cw-laser at 245 nm. Another photon at 245 nm finally provides the energy for the ionization. A laser at 976 nm is applied continuously in order to clear the long-lived $4f^{14}5d_{5/2}$ level. The photoionization is typically achieved with intensities of 10 W/cm^2 at 245 nm. Effects from stray charges created by this laser can thereby be minimized. The $^{174}Yb^{2+}$ ions are identified using crystallized mixed-species ion-pairs: The effect of a $^{174}Yb^{2+}$ 'guest' ion onto the position of a $^{174}Yb^+$ 'host' ion as well as the motional resonance-frequencies of this two-ion crystal are detected, unambiguously indicating for the successful ionization.

THURSDAY

Precision frequency measurement of transitions between singlet states in atomic helium

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We report the precision frequency measurement of transitions between singlet states in atomic helium, including the 2^1S_0-2^1P_1 transition at 2058 nm [1] and the 2^1P_1-3^1D_2 transition at 668 nm [2]. Our measured transition frequencies can be combined with the theoretical ionization energy of 3D states and other precisely measured transitions to obtain the ionization energies of the 2^1S_0 and 2^1P_1 states. These results should provide crucial tests for atomic calculations and stimulate new theoretical developments of the singlet states in atomic helium. More importantly, our determined ionization energy of the 2^1P_1 state in ^{4}He shows a discrepancy of approximately 3.5σ with the currently most precise theoretical calculation.

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Probing near threshold double and single ionization of helium atoms

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Interactions of charged particles with atoms and molecules are of immense importance since they provide information about the collision dynamics involved in the delicate quantum mechanical process. Particularly, the reactions involving electrons are of prime importance in diverse areas, few of them may be listed as plasma physics, radiation damage in biological tissue. The pioneer work of Ehrhardt et al. [1] showed a pathway to obtain detailed information on the dynamics of an electron impact single ionization (e, 2e) process through a kinematically complete experiment. Following the work of Ehrhardt et al. [1], which provides full momentum information of both the outgoing electrons, many kinematically complete (e, 2e) studies have been done on a wide variety of geometrical and kinematic arrangements for various atomic targets. Theoretical descriptions for the electron impact single ionization of hydrogen and helium atoms have been very successful using non-perturbative approaches such as convergent close coupling [2], exterior complex scaling [3] and time dependent close coupling [4]. Problems still persist for electron impact ionization of more complex targets and even for the simple two electron target helium near the threshold regime.

We report in this communication the fully differential cross section (FDCS) results for the double ionization of helium atoms in the threshold regime at 5 eV excess energy. We calculate FDCS in the second Born approximation and also include post collision interaction (PCI) between two ejected electrons in the theoretical treatment. We compare our theoretical results with the measurements of Ren et al. [5]. The post collision interaction (PCI) has been found to be instrumental in describing the trends of FDCS.

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The dynamical properties of autoionization of rare-earth Eu atom

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The velocity-map-imaging method is employed to investigate experimentally the dynamical process of ejected electrons from Eu $4f^76p_{1/2}8s$ autoionizing states. The atom is stepwise excited from the $4f^76s6s$ $^8S_{7/2}$ ground state to the $4f^76s8s$ $^8P_{7/2}$ Rydberg state via the $4f^76s6p$ $^6P_{5/2}$ intermediate state, then excited further to the $4f^76p_{1/2}(J=3)8s$ and $4f^76p_{1/2}(J=4)8s$ autoionizing states with the three-step isolated-core excitation method.

The ejected electron from the autoionizing process can be focused and imaged by the electron lens the kinetic energy of which is resolved by the position sensitive detector. Combining velocity-map-imaging method with the mathematical transformation, the velocity of ejected electron can be determined, yielding both energy and angular distributions of it. By tuning the wavelength of the third laser across the autoionization resonance, the variation characteristics of the asymmetric parameters and branching ratio are observed. The possibility of the population inversion due to autoionization has been discussed.

Enantiomer-specific detection of chiral molecules via microwave spectroscopy

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We recently devised and demonstrated a definitive, large signal, mixture compatible spectroscopic method for the determination of the chirality of molecules. Three-wave mixing – with signals enhanced through the use of cold molecules – provides the phase sensitive enantiomeric signal [1,2]. Either buffer-gas or supersonic beam cooling can provide high molecular internal state phase space densities [3]. Here we present further developments of the technique, demonstrating sensitivity at the 1% enantiomeric excess level using the novel RABBIT geometry spectrometer. The addition of enhanced spectroscopic techniques should yield unprecedented chiral sensitivity, and progress toward this is described.

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Theoretical transition rates of forbidden lines in doubly-ionized iron group elements

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Accurate fine-structure atomic data for the Fe-peak elements (Sc, Ti, V, Cr, Mn, Fe, Co and Ni) are essential for interpreting astronomical spectra currently available. The lowly-ionized spectra of several iron group elements have been observed in nebular and stellar environments [1-2]. Yet, our present knowledge of their atomic structure is lagging behind the avalanche of high-quality spectra arising from these ions. We present our systematic approach for studying the electronic structures and radiative rates of forbidden lines of doubly-ionized iron peak elements. The magnetic dipole (M1) and electric quadrupole (E2) transition probabilities are computed using the pseudo-relativistic Hartree-Fock (HFR) code of Cowan [3] and the central Thomas-Fermi-Dirac-Amaldi potential approximation implemented in AUTOSTRUCTURE [4] using a new method of optimization for the potential scaling parameters. The extensive sets of results obtained using these two theoretical approaches are then compared to the rare experimental and theoretical data available in the literature for these ions in order to assess the advantages and shortcomings of each method and provide astrophysicists with a comprehensive set of reliable radiative data.

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Second Spectrum of Selenium

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We investigated the spectrum of singly ionized selenium (Se II) and found serious irregularities in the published results [1]. Our investigation was based on the study of $4s^24p^3$- $[4s^24p^2(4d+5d+5s+6s)+4s4p^4]$ transition array. The previously reported analysis has been revised extensively. Out of fifty-two reported levels, thirteen were rejected and new level values were found. Since the mean energies of $4s^24p^24d$ and $4s4p^4$ configurations differ only by 2000 cm^{-1} therefore, the proximity of the two configurations result in the strong mixing of levels. The earlier reported levels given without designation or configuration assignments are now well interpreted with Hartree-Fock calculations. Apart from even parity configurations, similar designations were also given for odd parity levels. Consequently, we also extended our investigation to include $4s^24p^25p$ and $4s^24p^24f$ configurations. Almost all the levels of $4p^25p$ configuration have been found but the study of $4p^24f$ is still under progress and the latest findings will be presented in the conference.

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THURSDAY

High-precision nonadiabatic calculations of dynamic polarizabilities and hyperpolarizabilities for low-lying vibrational-rotational states of hydrogen molecular ions

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The static and dynamic electric multipolar polarizabilities and hyperpolarizabilities of H_2^+, D_2^+, and HD^+ ions in the ground states and first excited states are calculated nonrelativistically and nonadiabatically using explicitly correlated Hylleraas basis sets. Comparisons are made with published results. In particular, we make contact with earlier calculations in the Born-Oppenheimer calculation[1]. We find that the static hyperpolarizability for the ground state of HD^+ is seven orders of magnitude larger than the corresponding dipole polarizability. For the dipole polarizability of the first excited-state HD^+, the high precision of the present method facilitates treatment of a near cancellation between two terms. For applications to laser spectroscopy of trapped ions we find tune-out and magic wavelengths for the HD^+ ion in a laser field. In addition, we also calculate the first few leading terms for long-range interactions of a hydrogen molecular ion interacting with a ground-state H, He, and Li atoms.

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Atomic hyperpolarisabilities and the non-linear optics of atomic gases

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The properties of one and two-electron atoms are calculated numerically using configuration interaction and perturbative methods. We present calculations here for the dynamic hyperpolarizabilities of these atoms, including the excited alkali-metal states spanning up to Rydberg states, e.g. of n = 10. The emphasis here is on low-energy fields of interest in atomic clocks, and high-energy excitations that probe near Rydberg states. The properties of the ground and the excited state hyperpolarizabilities will be discussed, as well as the variance of transition energies and magic wavelengths with hyperpolarizability. A method being developed to approximate the hyperpolarizability contributions from the core electrons will also be introduced. Two forms of the susceptibilities, $\chi_3(\omega,I)$ that describe the non-linear optics of atoms in electric fields, will be presented that describe the variation of the refractive index of an atomic gas in ground or excited states, as well as third-harmonic generation.

THURSDAY

Measurement of the 5D Level Polarizability in Laser Cooled Rb Atoms

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Polarizabilities of ground and highly excited states of alkali atoms are known quite accurately. Considering intermediate states there are some difficulties both theoretically and experimentally. For example, the polarizabilities of 5S and 5P have been measured long ago with high precision while being in agreement with theory. However, 5D level is challenging. There are several theoretical predictions which differ up to 20% [1,2]. We managed to measure scalar and tensor polarizabilities with an accuracy of 1% and 10% respectively [3].

We used rubidium atoms preliminary cooled and localized in a magneto-optical trap, and formed a cloud at the center of a plane capacitor. Atoms were under the influence of a constant electric field which created the Stark shift of the levels. We measured the shift of the resonant frequency of the transition 5P->5D using the cascade excitation scheme.

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THURSDAY

Atom Interferometry Th-118

An analog of polarization in atom optics: a Raman waveplate to measure the Gouy phase in matter waves

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The field of atom optics has seen the emergence of many analogs of optical components. We extend atom optics to study the analog of optical polarization for the case of a pseudo-spin-1/2 BEC. A two-photon Raman interaction serves as a waveplate for atoms with the retardance controlled by the pulse area and the waveplate angle set by the relative phase of the Raman beams. Using this Raman waveplate in concert with Stern-Gerlach absorption imaging allows us to perform the equivalent of optical polarimetry on a BEC and to obtain the analog of the optical Stokes parameters. This technique allows for the study of atom-optic analogs of optical beams with transverse, spatially varying polarization such as vector vortex and full-Poincare beams. Stokes maps of a full-Bloch BEC can be measured utilizing this technique, and studying the evolution of these maps reveals the Gouy phase for matter waves.

Atom Interferometry Th-119

Atomic matter-wave interferometer on an external atomchip

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We construct an atomic interferometer using ^{87}Rb Bose-Einstein condensate trapped on an external atomchip. Our BEC manipulation system has compact size and high-repetition-rate with the help of anodically bonded atomchip on the vacuum cell [1]. A nearly pure condensate is split using RF-induced double well potentials [2]. The trap is turned off allowing the two BECs to interfere in free fall. For varying the RF current frequency and amplitude, we investigate behaviors of the beam-splitter from the observed fringes in the atomic density distribution. We are now working towards more precise control of the atoms.

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A programmable broadband low frequency active vibration isolation system for atom interferometry

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Vibration isolation at low frequency is important for precision measurement experiments that use atom interferometers (AI). To decrease the vibration noise in an AI, it is crucial to isolate the AI from the environmental vibration noise [1] caused by the retro-reflecting mirror [2, 3] of Raman beams. We designed and demonstrated a compact stable active low frequency vibration isolation system(VIS) for our 10-meter high AI[4], simplified the structure of the active VIS by reducing one actuator, and then built the system using only the basic elements for building a closed loop. With the help of FPGA-based control subsystem, the vibration isolation system performed flexibly and accurately. When the feedback is on, the intrinsic resonance frequency of the system will change from 0.8 Hz to about 0.015 Hz. It can suppress vertical vibrations (0.01-10 Hz) from the background by a factor of 200 with the assistance of a passive vibration isolation platform.

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Manipulation of atomic velocities with broadband light-pulse atom interferometry

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We are investigating the use of light-pulse interferometry techniques for manipulating atomic motion. Interferometer sequences where the output phase is dependent on the initial atomic velocity can be tailored to give cooling forces, and have potential for use in molecular cooling [1]. As a test system, we work on a Doppler-broadened, Zeeman-degenerate sample of Rubidium-85 atoms after release from a MOT, where stimulated Raman pulses form the interferometer beamsplitters and mirrors. These pulses are subject to large amounts of dephasing, which we counteract by adapting NMR-type spin echo and composite pulse techniques. We present a demonstration of cooling of an atomic cloud using interferometric techniques.

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A milliradian phase resolution Ca atom interferometer with transparent ITO electrodes

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Recently, the Röntogen phase (He-McKellar-Wilkens phase) was measured using a large Mach-Zehnder atom interferometer by Gillot et al. [1], where a large Stark phase shift results in reductions in visibility. We have developed an atom interferometer with milliradian phase resolution using a sub-Hz linewidth diode laser [2] and free from a large Stark phase shift using the transparent ITO electrodes with anti-reflection coating. The Ramsey-Bordé atom interferometer was composed of the $^3P_1$ and $^1S_0$ states of Ca atoms which were excited by two pairs of the copropagating parallel laser beams with equal distances. The first pair of beams were incident on the first electrode and the other pair of beams were incident on the second electrode with the same strength but opposite direction of the electric field, so that the Stark phase shifts can be cancelled out. The phase shifts under the electric field and the magnetic field are investigated.

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THURSDAY

Large Momentum Transfer and Faster Signal Scalings in Acceleration-Sensitive Atom Interferometry

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We have demonstrated an acceleration-sensitive atom interferometer configuration with 80 photon recoils of momentum separation between the two arms of the interferometer [1] (also at arXiv:1307.0268). This is the largest momentum splitting yet achieved while maintaining a measurable interferometeric signal. We construct the interferometer horizontally, through the use of a horizontal optical waveguide. This interferometer configuration is based upon a combination of multiple 10-photon-recoil Bragg splitting pulses combined with momentum-state-selective acceleration (of up to 60 photon recoils) in an optical Bloch lattice.

Using this technique we have demonstrated an increased scaling law of interferometric signal with time [2] (also at arXiv:1311.2143). A standard Ramsey-Bordé configuration has a signal proportional to the interferometer time, T; while the standard Mach-Zehnder configuration has a signal proportional to T^2. We demonstrate a configuration in which the signal scales faster than T^3, and suggest extension to even higher powers of T. This technique should allow higher sensitivity for the same interferometer time, or the same sensitivity in a shorter time, allowing measurements of more quickly changing accelerations.

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Progress towards in-beam hyperfine spectroscopy of antihydrogen

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Antihydrogen is the simplest atom consisting purely of antimatter. Its matter counterpart, hydrogen, is one of the best studied atomic systems in physics. Thus comparing the spectra of hydrogen and antihydrogen offers some of the most sensitive tests of matter-antimatter symmetry. The ASACUSA collaboration is pursuing an experiment to measure the ground-state hyperfine splitting of antihydrogen in a polarized beam [1,2], a quantity which was measured in hydrogen in a beam to a relative precision of $4x10^{-8}$ [3] and in a maser to better than 10^{-12} [5,6] .

After recently reporting the first observation of a beam of antihydrogen atoms 2.7 m downstream of the formation region in a field-free environment [4], preparations are under way to finalize the atomic resonance beam apparatus to perform a hyperfine measurement. During the shutdown of CERN, a source of cold polarized hydrogen atoms was built and experiments are under way to characterize the apparatus with a hydrogen beam of similar properties as compared to the expected antihydrogen beam. First scans of the hyperfine structure of hydrogen showing encouraging results for the achievable precision in a measurement with antihydrogen will be reported.

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ALPHA-2: an upgraded apparatus for physics with trapped antihydrogen

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Antihydrogen offers a unique way to test matter/antimatter symmetry. Antihydrogen can reproducibly be synthesised and trapped in the laboratory for extended periods of time [1, 2] offering an opportunity to study the properties of antimatter at high precision. New techniques to study antihydrogen have emerged; the ALPHA collaboration at CERN can now interrogate the bound state energy structure with resonant microwaves [3] and determine the gravitational mass to inertial mass ratio [4]. The results are not yet sensitive enough to draw conclusions on matter/antimatter symmetry but the recent progress shows that experiments with trapped antihydrogen are possible and the collaboration is firmly en-route towards precision measurements. The ALPHA-collaboration has upgraded the trapping apparatus improving access for both laser beams and microwave radiation. We present the upgraded apparatus in detail.

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Positron storage for the production of an antihydrogen beam

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Since the recent publication of the first observation of an antihydrogen beam by the ASACUSA-Cusp collaboration [1]. Work has been undertaken to improve the experimental setup to produce a more intense beam, and hence realise the physics goal of the experiment - Rabi-like beam spectroscopy of antihydrogen. Of crucial importance to these efforts is the production and storage of a dense positron plasma. During the long shutdown at CERN work has been undertaken to improve the positron accumulation apparatus. The positron trapping rate has been increased by an order of magnitude from 7e4 /s [1] to 7e5 /s. This has been achieved by improving a number of different experimental conditions, including increasing the trap magnetic field from low (0.3 T) to high (1 T). In this poster, the ASACUSA-cusp collaboration positron accumulation apparatus and present results will be discussed.

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THURSDAY

Production of a cold antihydrogen beam with a cusp trap

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Antihydrogen is the simplest atomic system to perform precision measurements on the properties of antimatter. Comparing the ground-state hyperfine transition frequencies of hydrogen and antihydrogen is one of the most sensitive direct tests of CPT symmetry. Towards this goal the ASACUSA collaboration had developed an antihydrogen beam apparatus that can be used for Rabi-like in-flight spectroscopy measurements. The production of antiatoms is performed in an anti-Helmholtz type magnetic configuration (cusp), which allows spin-dependent focusing and formation of a polarised beam. During mixing of antiprotons and positrons in the cusp field a total of 80 antihydrogen atoms have been successfully detected 2.7 meters away from the source, where residual magnetic fields are negligible. After correcting for detection efficiency the beam count rate for antiatoms with n<43 principal quantum number was 40 mHz [1]. This result opens a new window to direct tests of fundamental symmetries in the Standard Model of elementary particle physics.

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THURSDAY

Hyperfine structure and relativistic corrections to ro-vibrational energy levels of the D_2^+ ion

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Provided high-resolution laser spectroscopy is feasible for the D_2^+ ion, together with high precision calculations of relativistic and quantum electrodynamic corrections, it is possible to derive an improved value of the deuteron-electron mass ratio and extract properties of the deuteron [1]. Although hydrogen molecular ion isotopes of H_2^+ and HD^+ have been studied intensively both theoretically and experimentally [2], there is scare work on the D_2^+ ion. In this paper, we will present a systematic calculation of ro-vibrational energy levels and hyperfine structure of the D_2^+ ion, including the leading-order relativistic and QED corrections, for the state of (v, L), where v = 0-4, L = 0-4.

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µTest of the change of m_p/m_e using laser cooled and optically trapped ^{40}CaH

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We propose to test the variatino in the proton-to-electron mass ratio via the precise measurement of the ^{40}CaH $X^2\Sigma(v,N,F,M)$ = (0,0,1,+/-1) - (1,0,1,+/-1) transition frequency (37.8 THz) with the uncertainly of the order of 10^{-17}. ^{40}CaH molecules are produced by laswer ablation on $^{40}CaH_2$ crystal and buffer-gas cooled. Doyle group succeeded to get a ^{40}CaH molecular beam with the kinetic energy of 4 K with 10^8 molecules/pulse [1]. The kinetic energy can be reduced by laser-cooling (Doppler cooling + Polarizatino gradient cooling) [2,3]. Molecules with kinetic energy lower than 10 µK are trapped in a 3D optical lattice. The trap laser frequency is tuned to frequency, where the Stark shift in the transition frequency is eliminated (magic frequency). The magic frequensies are estimated to be 378.43 THz and 465.14 THz, where the Stark shift with the intensity yielding the potential depth of 10 µK is less than 10^{-16} when the trap laser frequency is detuned from the magic frequencies by 1 MHz.

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THURSDAY

Test of m_p/m_e variation via measurement of N_2^+ vibrational transition frequencies

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We propose to test the variation in the proton-to-electron mass ratio by measuring the $X^2\Sigma_g(v,N,F,M)$ = (0,0,1/2,+/-1/2) - (1,0,1/2,+/-1/2) transition frequencies of N_2^+ (I = 0) molecular ion [1]. N_2^+ molecular ions are trapped in a linear electrode after the state selective resonance-enhanced multiphoton ionization of N_2 molecules, and sympathetically cooled with laser cooled ions [2]. As there is no E1 transition between different vibrational-rotational states in the $X^2\Sigma$g state, the thermalization by blackbody radiation is inhibited. With this transition, the Zeeman and electric quadrupole shifts are zero. The Stark shift induced by the trap electric field is less than $10^{-19}/(\mathrm{V/cm})^2$, therefore, the measurement can be performed also with a Coulomb crystal with a broadening of 10 μm in the radial direction. This transition is observed by Raman trasition eliminating the Stark shift by employing lasers with "magic" wavelength. Therefore, measurement with the uncertainty of the order of 10^{-17} is possible using a simple experimental setup (enployment of cryogenic chamer and formation of a string crystal are not necessary).

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Test of Einstein Equivalence Principle with bosonic and fermionic quantum matter: Search for spin-gravity coupling effects

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We report on a conceptually new test of the equivalence principle performed by measuring the acceleration in Earth's gravity field of two isotopes of strontium atoms, the bosonic ^{88}Sr isotope which has no spin vs the fermionic ^{87}Sr isotope which has a half-integer spin. The effect of gravity upon the two atomic species has been probed by means of a precision differential measurement of the Bloch frequency for the two atomic matter waves in a vertical optical lattice, improving the short-term sensitivity of the atomic gravimeter of a factor 16. Both the scalar and spin-gravity universality of free-fall were tested with a relative precision of 10^{-7}.

THURSDAY

Species-Selective Lattice Launch for High-Precision Atom Interferometry

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We propose a new technique [1] to be applied in atomic fountains to test the Einstein's Equivalence Principle (EEP) with dual species in the condensed phase [2-5]. So far, these fountains do not allow for a selective acceleration of two different species of atoms thus limiting the performances of an EEP test [6].

With our method we propose to use two laser wavelengths, each beam interacting with only one atom species. By this way, we achieve a selective control of the velocity of each isotope, leading to unprecedented precision of a quantum EEP test.

At this point and having the physical recipe and numerical tools in hand, we are summing up this method for the realistic case of Rb/K mixtures with state-of-the-art technology lasers.

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Testing General Relativity in a terrestrial lab through laser gyroscopes

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GINGER (Gyroscopes IN GEneral Relativity) is an INFN project[1] for measuring in a ground-based observatory the Lense-Thirring effect (the inertial frame dragging, foreseen by General Relativity, induced by the proper rotation of a massive source). It will consist in a structure of three laser gyroscopes mutually orthogonal with about 6m of side, located in a deep underground location, possibly the GranSasso INFN laboratory. The triaxial structure will provide full determination of the laboratory frame angular velocity to be compared with the Earth rotation rate in the fixed stars frame given by IERS through VLBI.

Large-size gyrolasers have already reach very high sensitivity, allowing relevant geodetic measurements[2]. The accuracy required for LT effect measurement is better than 10^{-14} rad/s: Earth angular velocity must be measured at 10^{-9}accuracy, with one order of magnitude improvement on actual level. We will present the main issues and the chosen strategy for achieving this goal.

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Atomic Clocks Th-134

Magic wavelengths measurement via observation of light shift on $^{40}Ca^+$ optical frequency standard

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The ratio of the oscillator strengths is one of the most important indexes in atomic transitions, which can be calculated via the measurement of the magic wavelengths, which have been predicted theoretically and measured experimentally in neutral atomic systems. Magic wavelengths also exist in ion systems. A scheme of measuring the magic wavelengths is introduced via observation of light shift in $^{40}Ca^+$ optical frequency standard; it is the first time realized in ion system. By this method, two magic wavelengths are measured with high precision, and the values are $\lambda_{|m|=1/2}$=395.7992(7) nm and $\lambda_{|m|=3/2}$=395.7990(7) nm, which is agree with the theory within a fractional uncertainty of $<4\times10^{-6}$. Based on the two magic wavelengths measured, the ratio of the oscillator strengths on $4S_{1/2}$-$4P_{1/2}$ and $4S_{1/2}$-$4P_{3/2}$ transitions is calculated to be 2.009(4), with a fractional uncertainty of $\sim2.0\times10^{-3}$.

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Atomic Clocks Th-135

Determination of the magic wavelength for the $^1S_0$ – $^3P_0$ transition in magnesium 24

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We report on the experimental determination of the magic wavelength for the spin-forbidden clock transition in magnesium 24. The knowledge of this particular wavelength, where the differential AC Stark shift of the involved clock states vanish, is mandatory for clock operation with a high accuracy.

A continuous loading scheme transfers atoms into a dipole trap opening a loss channel to the $^3P_0$ state, where the coldest atoms get trapped. This is necessary due to ionization of the 3D states by the magic light and the lack of sud-Doppler cooling techniques. 10^4 atoms are further transferred to the optical lattice.

Evaluating the differential light shift of the carrier transition, we could determine the magic wavelength to 468.38±0.35 nm. Further investigations will minimize this uncertainty.

Improving the stability of an atomic clock

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The stability of an atomic clock sets the timing precision it can achieve, and further influences the pursuit of higher accuracy. Here we discuss efforts and strategies towards the goal of reaching 1×10^{-18} instability in <1000 seconds averaging-time. An important stability limit, the Dick effect, stems from the sequential nature of the measurement procedure in which the interrogation-time is only a fraction of the total cycle-time. Synchronous interrogation of two atomic systems permits common-mode rejection of the Dick effect in comparative measurements, and we demonstrated measurement improvements from this technique. By employing an interleaved, anti-synchronized interrogation of two atomic systems, we can achieve zero-dead-time operation, which highly suppresses the aliasing problem at the heart of the Dick effect. Furthermore, efforts to improve the frequency stability of the cavity-stabilized probe laser beyond the state-of-the-art are described, as well as operation with large atom number for reducing the quantum projection noise.

Reducing the Uncertainty of Blackbody Radiation Shift in a Strontium Optical Clock

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Optical clocks have demonstrated remarkable performance in terms of stability and accuracy and therefore have a large range of applications in fundamental physics and metrology. We are operating an optical clock based on strontium atoms trapped in an optical lattice [1]. The uncertainty of our ^{87}Sr strontium lattice clock is 3×10^{-17}, where the dominating contribution is due to the uncertainty of the blackbody radiation (BBR), The BBR field needs to be known more accurately to reduce this uncertainty contribution: Currently we are working on the way to interrogate ^{87}Sr atoms in an environment with well controlled temperature, since a well controlled temperature produces a well characterized BBR field that allows together with an accurately known atomic reaction to the BBR field [2] for a high accuracy correction of the BBR shift. We expect an uncertainty contribution from the BBR shift of about 5×10^{-18}.

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Precise characterization of the blackbody radiation environment in an optical lattice clock

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The Stark shift caused by blackbody radiation (BBR) is a key factor limiting the performance of many atomic frequency standards, due in part to the difficulty in precisely characterizing the BBR environment bathing the atoms. Here we describe the implementation of an in-vacuum radiation shield that furnishes a uniform, well-characterized BBR environment for the atoms in an optical lattice clock. Under normal (room-temperature) operation, this shield enables specification of the BBR shift to better than 1 ppt for our Yb lattice clock, corresponding to an uncertainty contribution of 1×10^{-18} in fractional frequency units. Further operation of the shield over a range of elevated temperatures demonstrates consistency between our evaluated BBR environment and the expected atomic response.

The SOC2 transportable ^{171}Yb lattice clock

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THURSDAY

Optical lattice clocks based on elements with two valence electrons like Sr, Hg, Mg and Yb are strong competitors in the quest for next generation time and frequency standards. Recently, a stability and accuracy in the 10^{-18} range has been reported for lattice clocks using Yb [1] and Sr [2] for stationary setups.

In the framework of the SOC2 project [3], we are developing a transportable Yb lattice clock demonstrator, since the development of transportable optical lattice clocks is desirable for both performance evaluation and applications, e.g. in a microgravity environment. To ensure transportability, our setup is based entirely on diode and fiber lasers and features an intra-vacuum enhancement resonator to allow the formation of a large volume lattice using moderate laser power. We present a characterization of our clock setup, as well as our plans for a transport of the apparatus from the University of Duesseldorf to INRIM in Torino.

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 263500.

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An ultra-low frequency-noise laser based on a 48 cm long ULE cavity for a Sr lattice clock

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Ultra-stable lasers are essential instruments to interrogate narrow atomic transitions, e.g. in optical atomic clocks. The stability of ultra-stable lasers is obtained from the length stability of an external reference cavity, which is fundamentally limited by the Brownian thermal noise of the material, especially of the mirrors.

We have designed a 48 cm long cavity made of ultra low expansion (ULE) glass. In order not to be limited through length fluctuations induced by vibration acceleration a special balanced mount was implemented. Using three heat shields and precision temperature controls we have obtained a thermal time constant of about 10 days and a temperature variation measured close to the cavity of 2 µK in 1000 s. From a comparison with the Sr lattice clock [1] we have observed a laser instability of 7×10^{-17} at 300 s averaging time. With this laser the clock instability was reduced to 4×10^{-16} $(\tau/s)^{-1/2}$.

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THURSDAY

Dual species intercombination MOT of ^{171}Yb and ^{87}Sr: Toward a dual optical lattice clock

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An optical lattice clock is one of the promising candidates for the redefinition of the second. Frequency comparisons of same optical lattice clocks have been carried out and their reproducibilities have been confirmed at the 10^{-17} level [1,2]. Recently, a comparison of optical lattice clocks with different species has been performed to determine the frequency ratio of the clock transitions [3]. In these experiments, the uncertainty of the temperature of the environment dominates the uncertainty of the measurement results.

Our aim is to demonstrate two optical lattice clocks of ^{171}Yb and ^{87}Sr in the same chamber (dual optical lattice clock). Since the trapped atoms are surrounded by the same blackbody radiation (BBR), the frequency shift due to the BBR would be partially cancelled, resulting in a smaller uncertainty in the frequency ratio measurement. The recent demonstration of dual species intercombination MOT of ^{171}Yb and ^{87}Sr will be presented.

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THURSDAY

Measurement of the clock-transition spectrum of the ultracold ytterbium atoms

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We have done the experiments on developing the ytterbium optical clock. By two-stage laser cooling, the ^{171}Yb atoms are cooled down to 10 μK. Then they are loaded into an optical lattice with the wavelength of 759 nm. Furthermore the lifetime and temperature of atoms in the optical lattice are measured. We have observed the $^1S_0$-$^3P_0$ clock-transition spectra of the ultracold ^{171}Yb atoms in the optical lattice by using the ultranarrow-linewidth 578-nm laser. First we find the resonant frequency of the clock-transition $^1S_0$-$^3P_0$ by measuring the ground-state population as a function of the frequency of the 578-nm laser; then we precisely measure the clock-transition spectra by using the normalization method with help of the pumping lasers, the 649-nm laser for the transition $^3P_0$-$^3S_1$ and the 770-nm laser for the transition $^3P_2$-$^3S_1$. At present the linewidth of the clock-transition spectrum of the ^{171}Yb atoms is about 16 Hz for the 60-ms interrogating time.

Comparison between a strontium optical lattice clock with primary and secondary frequency standards

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The LNE-SYRTE atomic clock ensemble allows high accuracy frequency comparisons between the microwave (Cs, Rb) and the optical (Sr, Hg) frequency domains with an overall uncertainty of a few 10^{-16} [1]. In order to highlight the Sr optical clock potential to realize a future "optical second", we have compared the Sr clock with Cs and Rb frequency standards in several measurement campaigns that will also contribute to further constraint an hypothetical drift of the fundamental constants. The result of these measurements will be presented. In parallel, we will report on the efforts to improve the LNE-SYRTE Sr optical lattice clocks performances, by reducing the uncertainty budget due to blackbody radiation frequency shift, by reaching better stability with cavity based nondestructive detection [2], and by actively stabilising the phase dissemination of the ultra stable "clock" laser.

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THURSDAY

Non-destructive imaging and feedback stabilized production of cold atomic clouds

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Reliable production of cold atomic clouds with well-defined properties is a notoriously difficult task. Variations in the final atom number and temperature arise mainly due to unpredictable fluctuations in the experimental sequence. Non-destructive measurements of the ensemble properties within the sequence allow for an adjustment of the cooling procedure to obtain the desired outcome. Our scheme utilizes an imaging technique based on Faraday rotation combined with on-line digital image evaluation and feedback to the evaporation sequence. We demonstrate sub-percent run to run stability of the final atom number obtained by a single point feedback and discuss the limitations of this approach. A weak-gain multiple point feedback can be applied to counteract repeated external disturbances. In addition, it is investigated if the formation of a Bose-Einstein condensate can be stabilized by this feedback mechanism.

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Dispersive probing as a tool for monitoring dynamical processes in ultracold gases

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We report on heterodyne detection for tracking the evolution of the density and quantum state populations of ultracold atomic samples via dispersive light-matter interactions. As an example, the process of forced evaporative cooling was followed non-destructively in real time. Using the information gained from such dispersive interrogations the number fluctuations in the resultant sample can be conditionally reduced [1]. Extending on our scheme, we have monitored the coherent spin dynamics in a prolate sample evolving in magnetic filed gradient under the action of a near-resonant Rabi-drive [2]. From the recorded heterodyne signal, gradiometry with a bandwidth in the kilohertz domain was performed in a single-shot measurement. We present our ongoing work on a novel separate-paths multi-heterodyne dispersive probing scheme aimed at non-destructive tracking of atom-molecule coherence near Feshbach resonances [3], and simultaneously probing multiple quantum states.

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Compact semiconductor laser modules for precision quantum optical experiments in space

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We present a novel technology for assembling ultra-stable, space qualified semiconductor laser systems. Electronic and optical components of our laser modules are micro-integrated on an aluminium nitride (AlN) ceramic plate with a footprint of 30x80mm² only. To meet the requirements for operation in space the laser is hermetically sealed in a robust metal housing.

The AlN body can be equipped with two arbitrary laser chips, a chip-based phase modulator, an optical grating, and two optical fiber ports. This allows for realization of diverse hybrid compact laser systems like for instance a high power, narrow linewidth Extended Cavity Diode Laser (ECDL) followed by a Power Amplifier (PA). This combination is suitable for experiments in quantum optics including laser cooling, optical trapping and atom interferometry.

Moreover, we show that our technology platform is capable of housing ultra-narrow-linewidth lasers enhanced by an optical cavity, frequency doubled lasers as well as compact spectroscopy units.

Subwavelength alteration of one-dimensional optical lattices using radiofrequency-induced adiabatic potentials

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Traditional optical lattices are limited in length scale to approximately half a wavelength of the lattice laser; the ability to tailor a lattice's periodicity, band structure, and Wannier functions would be a significant aid in using optical lattices to explore analogous solid-state physics. One pathway to lattice modification is the use of radiofrequency dressing to create adiabatic potentials of novel geometry from ``bare'' spin-dependent lattices of traditional geometry. We present measurements made on a one-dimensional radiofrequency-dressed optical lattice in the new regime where the dressed lattice is both deeper than previously achieved and longer-lived. Momentum distributions, loss rates, and dressed-state spin populations are explored. The bare lattices are sufficiently deep and the rf coupling sufficiently strong such that the adiabatic potentials could potentially be useful for experiments exploring novel optical lattice geometries.

Scalable 2D array of dipole traps formed by pinhole diffraction for neutral atom quantum computing

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To build a scalable neutral atom quantum computer, we propose trapping atoms in the dipole traps formed by diffraction at a two-dimensional array of pinholes. We have computed the properties of traps formed by diffraction of laser light at a pinhole for realistic laser parameters [1]. Using two circularly polarized laser beams incident at an angle, atoms can be brought together and apart controllably by exploiting the light polarization dependence of the traps [2]. The diffraction pattern can be projected into a vacuum chamber by a single lens, resulting in different trap sizes and aspect ratios depending on the lens placement [3]. We are exploring changes to the diffraction pattern for large incident laser angles that limit the range of motion of our traps. We will present comparisons of our computational results with direct intensity measurements, and our progress towards building an experimental setup to load atoms into these traps.

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Design of optical Talbot focal point array for neutral atom quantum computing

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As a new platform for quantum computation and quantum simulation, we consider atoms regularly arranged in space via optical Talbot effect. We design an atom array, formed as a periodic self-image of light transmitted through a periodic structure, to satisfy both the individual qubit control and entanglement conditions (i.e., $\lambda_{Laser}<d<10\lambda_{Laser}$). For this, we have fabricated a two-dimensional grating with a 50x50 micro-hole array on a chromium sputtered glass substrate, and tested its performance by quantum-dot sheet fluorescence tomography. The resulting Talbot carpet image in three dimension exhibits that the period of five-micrometer and lateral focal point size of less than 1 micrometer (i.e., $\Delta x \sim \lambda_{Laser}$) are achieved. We plan to capture cold rubidium single atoms in an off-resonant dipole trap array of triangular lattice structure.

Bose-Einstein Condensation in a Periodic Magnetic Lattice

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We report the realization of a periodic array of Bose-Einstein condensates of ^{87}Rb F=1 atoms trapped in a 1D 10 μm-period magnetic lattice created by a patterned magnetic film on an atom chip [1]. Clear signatures for the onset of BEC in multiple sites of the magnetic lattice is provided by in-situ site-resolved radiofrequency spectroscopy, in which the spectra reveal pronounced bimodal distributions consisting of a narrow component characteristic of a BEC together with a broad thermal cloud component. The realization of a periodic array of BECs in a magnetic lattice represents a significant step toward the implementation of magnetic lattices for quantum simulation of many-body condensed matter phenomena in lattices of complex geometry such as triangular, honeycomb, Kagome and super-lattices.

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Generalized Thermodynamic Properties

Jesus Morales, Jose Juan Peña

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In a previous work [1], we have proposed a Schrödinger-like thermodynamic equation where the role played by the quantum wavefunctions and Witten superpotential are carried out by the statistical partition functions *Z(T)* and internal energy *U(T)*, respectively. In this work, we propose a non linear differential equation, of Riccati type, where the variable is the standard *Z(T)* that is used as particular solution to obtain its generalized $Z_g(T)$; from there, any other thermodynamic property is straightforwardly improved. As an useful application of $Z_g(T)$, the study of the generalized thermodynamic properties $U_g(T)$, heat capacity $C_g(T)$ and entropy $S_g(T)$, associated to the model of ideal monatomic gas in one, two and three dimensions, is shown. Beyond this example, due that the proposal is general this can be used to generalize other thermodynamic statistical models as well as to obtain new partition functions that can be used advantageously in modeling thermodynamic applications.

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Supersymmetry, shape invariance and the hypergeometric equation

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In quantum mechanics, supersymmetry relates a pair of Hamiltonians which are almost isospectral. Shape invariance arises in a supersymmetric system with special forms of the potential which remain form invariant as one goes from one Hamiltonian to its supersymmetric partner. We have shown that the solubility of the hypergeometric equation can be understood as an underlying supersymmetry and shape invariance of the differential equation. The study of the hypergeometric equation is important because the hypergeometric function contains all of the orthogonal polynomials for special values of the three parameters that it depends on. Since each of the orthogonal polynomials defines a complete basis in which the wave function of any quantum mechanical system can be expanded, the understanding of their solubility is quite important in any algebraic study of a quantum mechanical system. The analysis has been carried out with generalized raising and lowering operators for the hypergeometric equation.

On the Geometric Implications of Maxwell's Equations

Felix T. Smith

A new examination of the structure of Maxwell's equations shows that their self-consistency implies a constraint on the geometry of the medium in which electromagnetic processes take place that is not compatible with the four-dimensional space-time proposed by Minkowski. Instead the underlying geometry is best described as a 3-dimensional position space that is not quite Euclidean, having a homogeneous 3-space curvature that is negative and time dependent. Its radius of curvature is then imaginary, and increases in absolute magnitude linearly with time at a rate measured by *ic*. This provides direct, independent, quantitative evidence confirming the geometry of the Hubble expansion through entirely local effects observed at the present time in the measurable phenomena of electricity, magnetism and light. Important consequences follow directly for special relativity and its applications in atomic processes through the Dirac equation.

THURSDAY

	Monday 4 August	Tuesday 5 August	Wednesday 6 August	Thursday 7 August	Friday 8 August
8:30 AM	**Welcome and Nobel Prize Session**	**Molecules**	**Ultrafast Science**	**Quantum Calculation**	**Bose Gases**
	Welcome remarks (15)	P. Julienne (45)	U. Keller (45)	Jake Taylor (45)	J. Dalibard (45)
	D. Wineland (45)	B. Gadway (30)	N. Dudovich (30)	A. Aspuru-Guzik (30)	Y. Shin (30)
	S. Haroche (45)	M. Zeppenfeld (30)	C. Geddes (30)	A. White (30)	S. Stringari (30)
10:15 AM	**Coffee Break**	**Coffee Break**	**Coffee Break**	**Coffee Break**	**Coffee Break**
10:45 AM	**Quantum Gases I**	**Quantum Gases II**	**Rydberg Atoms**	**Precision Measurements**	**Quantum Simulation/ Ions/Molecules**
	T. Esslinger (45)	C. Chin (45)	T. Pohl (45)	K. Eikema (45)	P. Zoller (45)
	R. Grimm (30)	Y. Takahashi (30)	S. Hofferberth (30)	A. Ludlow (30)	E. Hudson (30)
	Z. Hadzibabic (30)	S. Chen (30)	A. Browaeys (30)	E. Peik (30)	M. Köhl (30)
12:30 PM	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Lunch**
2:00 PM					**Hybrid Quantum Systems (2:00 pm)**
2:15 PM	**Artificial Atoms**	**Fundamental Atomic Tests**	**Free**	**Hot Topics I**	A. Rauschenbeutel (45)
	J. Wrachtrup (45)	D. DeMille (45)		U. Schneider (25)	C. Regal (30)
	E. Waks (30)	K. Blaum (30)		L. Fallani (25)	O. Painter (30)
	M. Hafezi (30)	M. Kasevich (30)		F. Ferlaino (25)	15-minute break
4:00 PM	**Poster I**	**Poster II**		P. Cappellaro (25)	**Hot Topics II (4:00 pm)**
				J. Doyle (25)	J. Reichel (25)
4:20 PM				**Poster III (4:20 pm)**	M. Oberthaler (25)
					P. Richerme (25)
					D. Hall (25)
					V. Vuletic (25)
6:00 PM					
6:20 PM					
7:00 PM				**Banquet**	