INVITED SPEAKER ABSTRACTS

Quantum control of trapped ions at NIST

David Wineland

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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

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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

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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

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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

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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

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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

Joint Quantum Institute, NIST and the University of Maryland, College Park, MD, USA

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.

This work has been supported by an AFOSR MURI.

References

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

Bryce Gadway

JILA, NIST and University of Colorado, Boulder, Colorado 80309, USA

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

Shuai Chen

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Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China,

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.

References

[1] J.–Y. Zhang, et al., Phys. Rev. Lett. 109, 115301 (2012)
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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.

References

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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.

Fundamental Atomic Tests Invited Speaker Tuesday: 2:15pm - 4:00pm

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

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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 Atoms Invited Speaker Wednesday: 10:45am - 12:30pm

Rydberg quantum optics in dense ultracold gases

Sebastian Hofferberth

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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.

References

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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.

References

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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].

References

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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 $1x10^{-18}$.

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 $^{229}Th^{+}$.

References

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An Aharonov-Bohm interferometer for determining Bloch band topology

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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

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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].

References

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Hot Topics I Invited Speaker Thursday: 2:15pm - 4:20pm

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

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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.

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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.

References

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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

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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.

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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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Quantum Simulation/Ions/Molecules Invited Speaker Friday: 10:45am - 12:30pm

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

Michael Köhl

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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

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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

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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

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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

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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

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

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.