Joint ITAMP and B2 Institute

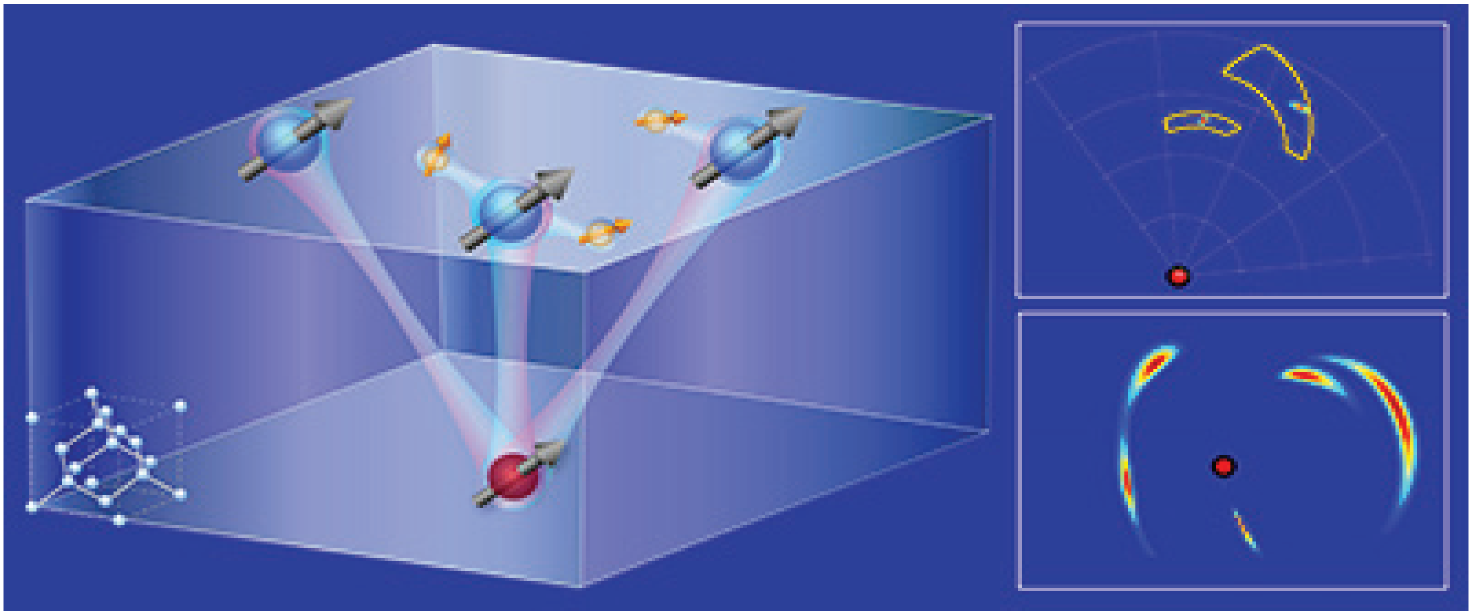
Workshop on

HYBRID QUANTUM SYSTEMS

February 16-18, 2015

Organizers:

Pierre Meystre, *The University of Arizona*
Hossein Sadeghpour, *ITAMP, Harvard-Smithsonian CFA*



Magnetic Resonance Detection of Individual Proton Spins Using Quantum Reporters, Phys. Rev. Lett. 113, 197601, 2014
A. O. Sushkov, I. Lovchinsky, N. Chisholm, R. L. Walsworth, H. Park, and M. D. Lukin

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Abstract Booklet and Schedule

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Hybrid Quantum

PROGRAM

Monday, February 16, 2015

7:30 AM	8:30 AM	*Breakfast*
8:30 AM	9:10 AM	**Andreas Wallraff** **"**Exploring Hybrid Quantum Systems with Circuit Quantum Electrodynamics: Semiconductor Quantum Dots, Rydberg Atoms and Superconducting Qubits"
9:20 AM	10:00 AM	**Liang Jiang** "Quantum Control of Superconducting Circuits"
10:10 AM	10:40 AM	*Break*
10:40 AM	11:20AM	**Jürgen Lisenfeld** "Exploring Coherent Microscopic Material Defects With A Superconducting Quantum Bit"
11:30 AM	12:10 PM	**Seigne Seidelin** "Strain-Coupled Hybrid Quantum Systems: From Quantum Dots To Rare-Earth Doped Crystals"
12:30 PM	1:30 PM	*Lunch*

Free Afternoon

6:00 PM	7:00 PM	*Dinner*
7:00 PM	7:40 PM	**Michael Köhl** "Hybrid Quantum System of A Trapped Ion And A Semiconductor Quantum Dot"
7:50 PM	8:30 PM	**Grahame Vittorini** "Modular Entanglement In A Hybrid Ion-Photon System"

Tuesday, February 17, 2015

7:30 AM	8:30 AM	*Breakfast*
8:30 AM	9:10 AM	**Philipp Treutlein** "Hybrid Atom-Membrane Optomechanics"
9:20 AM	10:00 AM	**Dan Stamper-Kurn "**Optically Measuring And Coupling Quantum Systems in A Cavity"
10:010 AM	10:40 AM	*Break*
10:40 AM	11:20AM	**James Shaffer** "Using Rubidium Rydberg Atoms To Probe Atom-Surface Interactions"

11:30 AM	12:10 PM	**Tilman Pfau** "A Single Charge In A Bose-Einstein Condensate: From Two To Few To Many-Body Physics"
12:30 PM	1:30 PM	*Lunch*

Free Afternoon

6:30 PM	7:30 PM	*Dinner*
7:30 PM	8:10 PM	**Cindy Regal** "Towards A Quantum Interface Between Electricity And Light"
8:20 PM	10:00 PM	**Richerd Schmidt** "Decoherence and absorption spectra of impurities in ultracold quantum gases" **Berit Vogell "**Long Distance Coupling of a Quantum Mechanical Oscillator to the Internal States of an Atomic Ensemble"

Wednesday, February 18, 2015

7:30 AM	8:30 AM	*Breakfast*
8:30 AM	9:10 AM	**Konrad Lehnert** "Arbitrary Temporal And Spectral Mode Conversion Of Microwave Signals With A Mechanical Oscillator"
9:20 AM	10:00 AM	**Peter Rabl** "Implementation of The Dicke Lattice Model in Hybrid Quantum System Arrays"
10:10 AM	10:40 AM	*Break*
10:40 AM	11:20 AM	**Tom Purdy** "Near Ground State Cooling And Thermometry At Optomechanical Equilibrium"
11:30 AM	12:10 PM	**Misha Lukin** "New Interface Between Quantum Optics and Nano Science"
12:30 PM	1:30 PM	***Lunch***

Free Afternoon

6:00 PM	7:00 PM	***Dinner***
7:00 PM	7:40 PM	**Mukund Vengalattore** "Spin-Mediated Optomechanics"
7:50 PM	8:30 PM	**Joerg Wratchtrup** "Hybrid Spin Systems"
8:45 PM	***Closing of the Workshop***	

Quantum Control of Superconducting Circuits

Liang Jiang

Yale University

We develop an efficient scheme that allows for arbitrary operations on a cavity mode using a strongly dispersive qubit-cavity interaction and time-dependent drives. The scheme can readily be implemented using circuit QED systems. Moreover, the scheme can be extended for quantum error correction to protect information encoded in photonic cat states.

Hybrid Quantum System Of A Trapped Ion And A Semiconductor Quantum Dot

Michael Köhl

University of Bonn, Institute of Physics

Wegelerstrasse 8, 53115 Bonn, Germany

Coupling individual quantum systems lies at the heart of building scalable quantum networks. Here, we report the first direct photonic coupling between a semiconductor quantum dot and a trapped ion and we demonstrate that single photons generated by a quantum dot controllably change the internal state of an Yb^+ ion. We ameliorate the effect of the sixty-fold mismatch of the radiative line widths with coherent photon generation and a high-finesse fiber-based optical cavity enhancing the coupling between the single photon and the ion. The transfer of information presented here via the classical correlations between the s_z projection of the quantum-dot spin and the internal state of the ion provides a promising step towards quantum state-transfer in a hybrid photonic network.

Arbitrary Temporal And Spectral Mode Conversion Of Microwave Signals With A Mechanical Oscillator

Konrad Lehnert
Jila

Electromagnetic waves provide a powerful way to link distant objects. They travel fast, interact weakly, and can be efficiently routed between locations using cables or fibers. These qualities make them ideal candidates for transmitting information in a quantum network. Yet linking quantum enabled devices with cables has proved difficult because most cavity quantum electrodynamics (cQED) systems used in quantum information processing can only absorb and emit signals with a specific frequency and temporal envelope. In this talk, I will describe a new type of tunable electromechanical device that overcomes both of these mismatches for microwave signals. In particular, I will show that it can alter the temporal and spectral content of microwave signals with noise sufficiently low to preserve quantum information. This device offers a way to build quantum microwave networks using separate and otherwise incompatible components.

Exploring Coherent Microscopic Material Defects With A Superconducting Quantum Bit

Jürgen Lisenfeld, Georg Weiss, and Alexey Ustinov

Physikalisches Institut, Karlsruhe Institute for Technology
D-76131 Karlsruhe, Germany

Advances in nanotechnology lay the ground for a thriving variety of novel devices suitable to explore new realms of quantum phenomena on the mesoscopic scale. Superconducting quantum bits, as an example, have reached very long coherence times by designs that avoid or weaken their undesired coupling to environmental degrees of freedom. One particular problem are parasitic Two-level systems (TLS) which originate in material defects. TLS were reported to cause noise and decoherence in single-photon detectors, SETs, SQUIDs, and microwave- as well as nano-mechanical resonators, although their physical origin remains unclear. Mutual coupling between TLS has been conjectured to explain various anomalies of glasses, and was recently suggested as the origin of low-frequency noise in superconducting devices.

In our experiments, we utilize the interaction of a superconducting phase qubit with individual two-level defects that are residing in the tunnel barrier of its Josephson junction. When qubit and TLS are tuned into resonance, they form a quantum hybrid system. This allows one to use the qubit as a tool both for direct manipulation as well as readout of the TLSs' quantum states. To tune TLS properties, we apply mechanical strain to the sample using a piezoelectric transducer and perform strain-dependent defect spectroscopy to obtain new insights into how TLSs are distributed in the sample (see Figure). We will present first unambiguous proof for mutual defect interactions and discuss further experiments on TLS coherence.

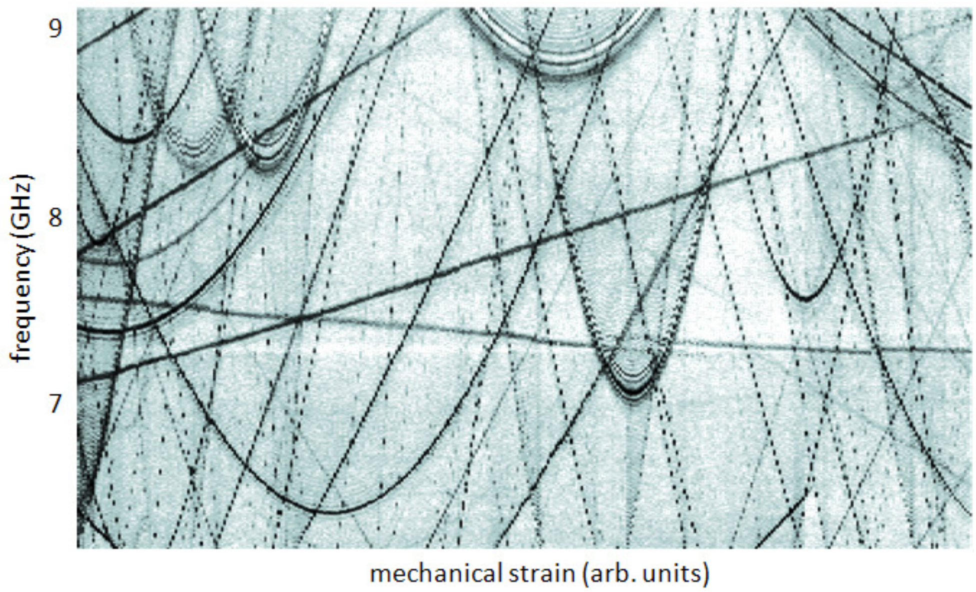

Figure: Resonances of microscopic defects appear as dark traces in strain-spectroscopy

New Interface Between Quantum Optics and Nano Science

Misha Lukin

Harvard University

We will discuss recent developments at a new scientific interface between quantum optics, nanoscience and quantum information science. Specific examples include the use of quantum optical techniques for manipulation of individual atom-like impurities at a nanoscale and for realization of hybrid systems combining ultracold atoms with nanophotonic devices. We will discuss how these techniques and systems are used for realization of quantum networks, magnetic resonance imaging with single atom resolution and NMR spectroscopy of individual molecules.

Hybrid Quantum Circuits: Superconducting Circuits Interacting With Other Quantum Systems

Franco Nori

RIKEN and the University of Michigan

An experimentally realizable hybrid quantum circuit has been proposed [1] for achieving a strong coupling between a spin ensemble and a transmission-line resonator via a superconducting flux qubit used as a data bus. The resulting coupling can be used to transfer quantum information between the spin ensemble and the resonator. In particular, in contrast to the direct coupling without a data bus, our approach should require far less spins to achieve a strong coupling between the spin ensemble and the resonator (e.g., three to four orders of magnitude less). This proposed hybrid quantum circuit could enable a long-time quantum memory when storing information in the spin ensemble, and allows the possibility to explore nonlinear effects in the ultrastrong-coupling regime.

We also proposed [2] how to realize high-fidelity quantum storage using a hybrid quantum architecture including two coupled flux qubits and a nitrogen-vacancy center ensemble (NVE). One of the flux qubits is considered as the quantum-computing processor and the NVE serves as the quantum memory. By separating the computing and memory units, the influence of the quantum-computing process on the quantum memory can be effectively eliminated, and hence the quantum storage of an arbitrary quantum state of the computing qubit could be achieved with high fidelity. Furthermore, the present proposal is robust with respect to fluctuations of the system parameters, and it is experimentally feasible with currently available technology.

We also investigated [3] photon-mediated transport processes in a hybrid circuit-QED structure consisting of two double quantum dots coupled to a common microwave cavity. Under suitable resonance conditions, electron transport in one double quantum dot is facilitated by the transport in the other dot via photon-mediated processes through the cavity. We calculate the average current in the quantum dots, the mean cavity photon occupation, and the current cross-correlations with both a full numerical simulation and a recursive perturbation scheme that allows us to include the influence of the cavity order-by-order in the couplings between the cavity and the quantum dot systems. We can then clearly identify the photon-mediated transport processes.

We have also studied [4] electron-spin-photon coupling in a single-spin double quantum dot embedded in a superconducting stripline cavity. With an external magnetic field, we show that either a spin-orbit interaction (for InAs) or an inhomogeneous magnetic field (for Si and GaAs) could produce a strong spin-photon coupling, with a coupling strength of the order of 1 MHz. With an isotopically purified Si double dot, which has a very long spin coherence time for the electron, it is possible to reach the strong-coupling limit between the spin and the cavity photon, as in cavity quantum electrodynamics. The coupling strength and relaxation rates are calculated based on parameters of existing devices, making this proposal experimentally feasible.

These are a few examples of our studies on hybrid quantum circuits. For a pedagogical review, see [5].

[1] Z.-L. Xiang, X.-Y. Lu, T.-F. Li, J.Q. You, F. Nori, Hybrid quantum circuit consisting of a superconducting flux qubit coupled to a spin ensemble and a transmission-line resonator, Phys. Rev. B 87, 144516 (2013). [PDF][Link][arXiv]

[2] X.-Y. Lu, Z.-L Xiang, W. Cui, J.Q. You, F. Nori, Quantum memory using a hybrid circuit with flux qubits and NV centers, Phys. Rev. A 88, 012329 (2013). [PDF][Link][arXiv]

[3] N. Lambert, C. Flindt, F. Nori, Photon-mediated electron transport in hybrid circuit-QED, EPL 103, 17005 (2013). [PDF][Link][arXiv]

[4] X. Hu, Y.X. Liu, F. Nori, Strong coupling of a spin qubit to a superconducting stripline cavity, Phys. Rev. B 86, 035314 (2012). [PDF][Link][arXiv]

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PDF files of our publications are in http://dml.riken.jp/publications.php

A Single Charge In A Bose-Einstein Condensate: From Two To Few To Many-Body Physics

Tilman Pfau

Physikalisches Institut, Universität Stuttgart, Germany.

Electrons attract polarizable atoms via a $1/r^4$ potential. For slow electrons the scattering from that potential is purely s-wave and can be described by a Fermi pseudopotential. To study this interaction Rydberg electrons are well suited as they are slow and trapped by the charged nucleus. In the environment of a high pressure discharge Amaldi and Segre, already in 1934 observed a lineshift proportional to the scattering length [1].

At ultracold temperatures and Rydberg states with medium size principle quantum numbers *n*, one or two ground state atoms can be trapped in the meanfield potential created by the Rydberg electron, leading to so called ultra-long range Rydberg molecules [2].

At higher Rydberg states the spatial extent of the Rydberg electron orbit is increasing. For principal quantum numbers *n* in the range of 100-200 and typical BEC densities, up to several ten thousand ground state atoms are located inside one Rydberg atom, We excite a single Rydberg electron in the BEC, the orbital size of which becomes comparable to the size of the BEC. We study the coupling between the electron and phonons in the BEC [3].

We also observe evidence for ultracold charge transfer processes for a single ion which is shielded by a Rydberg electron. Also reactive processes due to few-body Langevin dynamics involving a single ion can be studied.

As an outlook, the trapping of a full condensate inside a Rydberg atom of high principal quantum number and the imaging of the Rydberg electron's wave function by its impact onto the surrounding ultracold cloud seem to be within reach [4].

[1] E. Amaldi and E. Segre, Nature 133, 141 (1934)
[2] C. H. Greene, et al., PRL 85, 2458 (2000); V. Bendkowsky et al., Nature 458, 1005 (2009)
[3] J . B. Balewski, et al., Nature 502, 664 (2013)
[4] T. Karpiuk, et al., arXiv:1402.6875

Near Ground State Cooling And Thermometry At Optomechanical Equilibrium

Thomas Purdy

NIST

Quantum correlations between optical and mechanical fields lead to a variety of effects. In a system with a strong resonant probe laser driving an optical cavity coupled to a mechanical resonator, the fluctuating radiation pressure from optical shot noise (RPSN) drives random mechanical motion, a consequence of quantum measurement backaction. A detuned probe laser produces Raman sideband cooling of the mechanics, while simultaneously, the RPSN heats the mechanics. These competing processes lead to an equilibrium at a finite temperature, which is small when the mechanical frequency exceeds the optical cavity linewidth, i.e. the resolved sideband limit. Quantum correlations with the zero point motion also allow the mechanical occupation to be extracted from the asymmetry of spontaneous Stokes and anti-Stokes scattered Raman sidebands.

I will present several experiments performed at JILA with a membrane optomechanical cavity. We demonstrate Raman asymmetry thermometry on cryogenically precooled devices. We are able to extract physical device temperatures up to 50 K, as well as Raman sideband cooled mechanical occupations down to a few tenths of a quanta. For the strongest optical damping, the effective mechanical temperature reaches optomechanical equilibrium, as evidenced by the symmetry in Raman scattering spectrum of the cooling laser. These demonstrations indicate that our membrane optomechanical devices are ideally suited for a variety of hybrid systems applications including microwave-to-optical quantum frequency conversion.

I will also present progress at NIST toward the creation of a primary Raman asymmetry thermometer based on a microwave frequency mechanical resonator potentially covering the range of cryogenic to room temperature.

Implementation of The Dicke Lattice Model in Hybrid Quantum System Arrays

Peter Rabl
TU-Vienna

Generalized Dicke models can be implemented in hybrid quantum systems built from ensembles of nitrogen-vacancy (NV) centers in diamond coupled to superconducting microwave cavities. By engineering cavity assisted Raman transitions between two spin states of the NV defect, a fully tunable model for collective light-matter interactions in the ultra-strong coupling limit can be obtained. Our analysis of the resulting non-equilibrium phases for a single cavity and for coupled cavity arrays shows that different superradiant phase transitions can be observed using existing experimental technologies, even in the presence of large inhomogeneous broadening of the spin ensemble. The phase diagram of the Dicke lattice model displays distinct features induced by dissipation, which can serve as a genuine experimental signature for phase transitions in driven open quantum systems.

Towards A Quantum Interface Between Electricity And Light

C. A. Regal[1], K. W. Lehnert[1,2,] R. W. Simmonds[2], R. W. Andrews[1], R. W. Peterson[1], T. P. Purdy[1], K. Cicak[2]

[1]JILA: University of Colorado and NIST, Boulder, Colorado
[2]NIST, Boulder, Colorado

A communication network capable of sharing quantum information among its nodes would have information security guaranteed by physical laws of nature. Such a quantum network remains an as yet unrealized ambition of quantum science and technology. In contrast to the technically remote quantum computer, most of the elements of a quantum network operate with sufficient fidelity today. Quantum information can be stored and manipulated when encoded in the state of a superconducting electrical circuit. Likewise the information can be transferred over kilometer distances and at ambient temperature when encoded as a light field in an optical fiber. The major challenge in realizing a quantum network is the physical incompatibility of the quantum technologies that operate in the electrical versus optical domain.

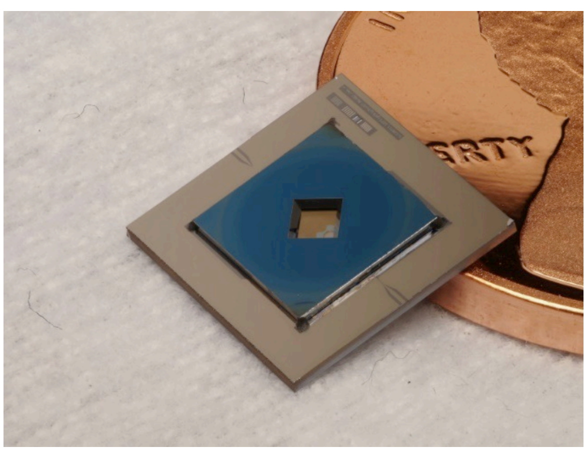

Figure 1: An image of the micromechanical oscillator. The oscillator is a SiN membrane suspended across 1 mm^2 square hole (diamond region) in a silicon chip.

In this talk, I will describe our progress towards building a transducer capable of converting quantum information between the electrical and optical domains. In particular, we are developing a device that uses a micromechanical oscillator to transfer information noiselessly between these domains. Although they appear humble and classical (Fig. 1), micromechanical oscillators can exhibit quantum behavior when their vibrations are strongly coupled either to optical light or to microwave electricity. In our scheme, we build oscillators with a single vibrational mode that is simultaneously coupled to a microwave resonant circuit and high-finesse optical cavity. We have tested the classical behavior of this device in a cryogenic environment (4 K), showing that its conversion efficiency is about 10% and that it is bidirectional converting light into electricity as well as it converts electricity into light [1]. This bidirectional property is an important prerequisite for preserving a quantum state in the transducer as it is consistent with a unitary conversion process. Reaching the quantum regime will require that we operate the device at an even lower temperature (100 mK). To that end, we have begun tests of the performance inside of dilution refrigerator cryostat with optical access between the ambient and cryogenic environments.

[1] Bidirectional and efficient conversion between microwave and optical light, R. W. Andrews, R. W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal and K. W. Lehnert, Nature Phys. 10 , 321–326 (2014).

Decoherence And Absorption Spectra Of Impurities In Ultracold Quantum Gases

Richard Schmidt

ITAMP, Harvard-Smithsonian

We study the decoherence of an impurity subject to the interaction with a bath of ultracold atoms and the corresponding spectral signatures. Our emphasize is on the question whether and under which conditions a heavy impurity immersed in a Fermi liquid is subject to the orthogonality catastrophe with its resulting edge singularities and complete loss of coherence [1]. For infinite mass the quasi-particle weight of the impurity vanishes in all dimensions. While in one spatial dimension this result also holds for an impurity of finite mass, theoretical predictions in d=2 are not conclusive [2]. We study the finite-mass corrections to the non-equilibrium dynamics of an impurity in a gas of lattice fermions after an interaction quench and calculate the time-dependent Ramsey interference signal using a novel hybrid approach which combines path integral and functional determinant methods [3]. We find that a finite quasi-particle peak persists in $d \geq 2$ in agreement with previous work [4,5] and explore the influence of finite temperature and system size.

Using our microscopic approach we study furthermore the time evolution of a Bose-Einstein-Condensate after the excitation of a Rydberg atom and the formation of a sequence of giant molecular bound states [6]. Our calculation reveals the emergence of a novel type of orthogonality catastrophe present in coupled BEC-Rydberg systems. We determine the absorption spectra of the system and we predict the non-equilibrium time evolution of various experimentally measurable observable following the sudden excitation of the Rydberg state and discuss possible experimental implementations [7].

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[2] A. Rosch, Adv. Phys. 48, 295 (1999).

[3] R. Schmidt, D. Benjamin, E. Demler, in preparation (2015).

[4] F. Sols, F. Guinea, Phys. Rev. B 36, 7775 (1987).

[5] A. Rosch, T. Kopp, Phys. Rev. Lett. 75, 1988 (1995).

[6] A. Gaj et al., Nature Comm. 5, 4546 (2014).

[7] R. Schmidt, E. Demler, H. Sadeghpour, in preparation (2015).

Strain-Coupled Hybrid Quantum Systems: From Quantum Dots To Rare-Earth Doped Crystals

Signe Seidelin

CNRS

An exciting challenge of modern physics is to investigate the behavior of a material object - for instance a mechanical oscillator - placed in a non-classical state. So far only few quantum physics experiments based on material objects have been performed due to the difficulty of such endeavour. One approach consists in exploiting a hybrid quantum system based on a mechanical oscillator coupled to an atom-like object. Diverse coupling mechanisms between these two radically different degrees of freedom have been demonstrated by the community in recent years [1], such as magnetic, capacitive, opto-mechanical, or via surface potentials, etc. A particularly appealing coupling mechanism is based on material strain. Here, the oscillator is a bulk object containing an embedded artificial atom (dopant, quantum dot,...) which is sensitive to mechanical strain of the surrounding material. Vibrations of the oscillator result in a time-varying strain field that modulates the energy levels of the embedded structure. Such strain coupling naturally circumvents instabilities arising from drifts in physical distance between resonator and atom, or drifts with respect to any external structure providing the coupling (magnetic structure etc.): as the atom-like system is an intrinsic part of the bulk materiel, the relative position remain fixed and the coupling strenght is perfectly stable. In the first part of my talk, I will discuss a recent proof-of-principle experiment in which we demonstrated a coupling, based on material strain, between a photonic nanowire and a semi-conductor quantum dot [2]. However, due to the relatively large spectral linewidth of quantum dots in general, other systems might prove more suitable for reaching the so-called resolved-sideband regime. This regime - a pre-requisite for some active cooling schemes for mechanical oscillators - requires a linewidth of the emitter well below the mechanical oscillation frequency. A recent experiment from the group of P. Maletinsky successfully reached this regime by using a bulk diamond resonator containing Nitrogen Vacancy centers [3]. In the second part of my talk, I will discuss a system based on rare-earth doped crystals, which holds promise to reach even deeper into this regime. More concretely, we are currently studying an yttrium orthosilicate (Y_2SiO_5) crystal containing a triply charged europium ion (Eu^{3+}), which is optically active. The reason behind this choice stems from the extraordinary coherence properties of this dopant, combined with its strain-sensitivity: the Eu^{3+} in an Y_2SiO_5 matrix has an optical transition with the narrowest linewidth known for a solid-state emitter [4], and the transition is directly sensitive to strain [5].

[1] M. Aspelmeyer, P. Meystre, and K. Schwab, Quantum optomechanics, Physics Today 65, 29 (2012)

[2] I. Yeo et al., Strain-mediated coupling in a quantum dot–mechanical oscillator hybrid system, Nature Nanotechnology 9, 106 (2014)

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[4] R. Yano, M. Mitsunaga, and N. Uesugi, Ultralong optical dephasing time in Eu3+:Y2SiO5, Optics Letters, 16, 1884 (1991)

[5] M. J. Thorpe et al., Frequency stabilization to 6 x10-16 via spectral-hole burning, Nature Photonics, 5, 688 (2011)

Using Rubidium Rydberg Atoms To Probe Atom-Surface Interactions

J. P. Shaffer

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440 West Brooks Street, Norman, Oklahoma 73019, USA

Atom-surface interactions are important to understand because of the many ground breaking areas of engineering where such systems appear, e.g. atoms in cavities, atoms near microwave striplines, etc. Casimir-Polder forces and atom-surface phonon polariton coupling, for example, are interesting particularly for research directions aimed at developing quantum devices. To fully utilize atoms near surfaces for applications such as these, electric fields arising from atoms adsorbed on the surface need to be understood and if possible minimized. In this talk, I describe experiments where Rubidium Rydberg atoms in a magnetic trap are excited near a single crystal quartz surface. Using Rydberg electromagnetically induced transparency (EIT) the electric fields at the quartz surface are measured. Heating the substrate reduces the effect of the adsorbates. We also present results that show that slow electrons can be captured by the surface dipoles further reducing the surface electric fields. This system shows promising results for coupling Rydberg atoms to surface phonon-polaritons on a dielectric surface and using the electrons captured by the surface to study 2-D electron gases.

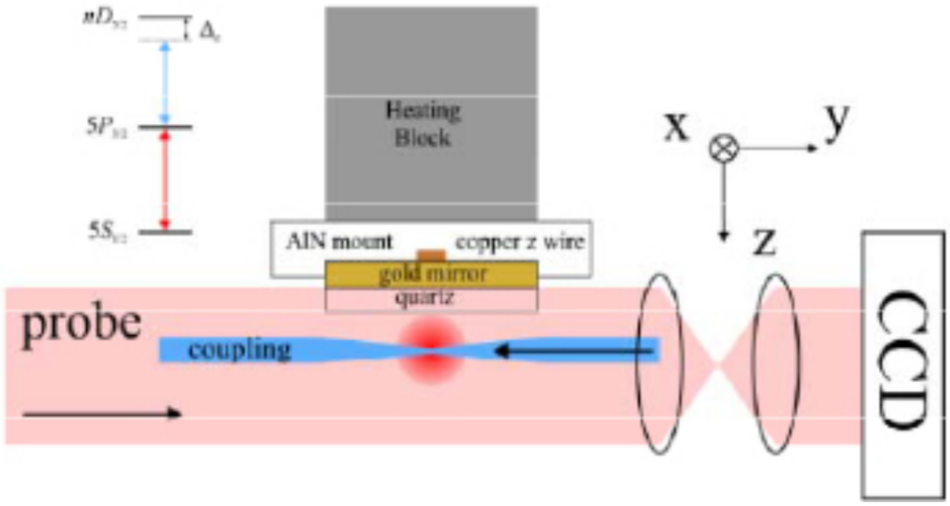

Figure 1: This figure is a conceptual drawing of the experiment. The sensitivity of Rydberg atoms to electric fields is used to measure the electric fields on a surface. The electric fields can be generated by phenomena such as surface waves or adsorbates. The inset shows the atomic level diagram used for the measurements.

Optically Measuring And Coupling Quantum Systems in A Cavity

Dan Stamper Kurn
UC Berkeley

Cavity quantum electrodynamics generally lets one direct the interactions between polarizable objects and light, increasing the relevance of a single optical mode. As such, optical cavities improve our ability to extract information about a quantum object through its interaction with light, and also our ability to cause quantum objects to interact with one another remotely by exchanging photons. I will discuss studies of cavity optomechanics using gases of ultracold atoms trapped within a high finesse Fabry-Perot resonator. Cavity-based measurement allows us to detect forces as the standard quantum limit, a long-time goal for optomechanical systems. We also demonstrate coherent coupling between distinct mechanical objects, mediated by cavity photons, and also characterize the simultaneous influence of measurement on this interaction.

Hybrid Atom-Membrane Optomechanics

Philipp Treutlein

University of Basel

We have realized a hybrid mechanical system in which ultracold atoms and a micromechanical membrane are coupled by radiation pressure forces. The atoms are trapped in an optical lattice, formed by retro-reflection of a laser beam from an optical cavity that contains the membrane as mechanical element. When we laser cool the atoms, we observe that the membrane is sympathetically cooled from ambient to millikelvin temperatures through its interaction with the atoms. Sympathetic cooling with ultracold atoms or ions has previously been used to cool other microscopic systems such as atoms of a different species or molecular ions up to the size of proteins. Here we use it to efficiently cool the fundamental vibrational mode of a macroscopic solid-state system, whose mass exceeds that of the atomic ensemble by ten orders of magnitude. Our hybrid system operates in a regime of large atom-membrane cooperativity. With technical improvements such as cryogenic pre-cooling of the membrane, it enables ground-state cooling and quantum control of low-frequency oscillators in a regime where purely optomechanical techniques cannot reach the ground state.

A. Jöckel, A. Faber, T. Kampschulte, M. Korppi, M. T. Rakher, and P. Treutlein,
"Sympathetic cooling of a membrane oscillator in a hybrid mechanical-atomic system",
Nature Nanotechnology, advance online publication (2014).

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Spin-Mediated Optomechanics

Mukund Vengalattore
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I will describe our realization of a hybrid quantum system where a macroscopic mechanical resonator is coupled to the collective spin of an ultracold gas through a remote optical interface. Through this interface, the spin ensemble is capable of sympathetic cooling, sub-SQL detection and control of the mechanical resonator. As such, this hybrid quantum system represents a powerful scheme to combine the robustness of the mesoscopic resonator with the sensitivity and coherence of the spin ensemble. I will describe our ongoing studies of this hybrid quantum system in relation to quantum metrology and the out-of-equilibrium dynamics of open quantum systems.

Modular Entanglement In A Hybrid Ion-Photon System

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Trapped atomic ions are qubit standards for the production of entangled states in quantum information science and metrology applications. Trapped ions can exhibit very long coherence times, while external fields can drive strong local interactions via phonons, and remote qubits can be entangled via photons. However, transferring quantum information across spatially separated ion trap modules for a scalable quantum network architecture relies on the juxtaposition of both phononic and photonic buses. We report the successful combination of these protocols within and between two ion trap modules on a unit structure of this architecture [1]. Importantly, trapped ions are the only experimental system to date where the remote entanglement generation rate exceeds the experimentally measured decoherence rate of the entangled state, paving the way for a scalable system with a non-forbidding overhead in resources. We also report the experimental implementation of a technique to maintain phase coherence between spatially and temporally distributed quantum gate operations in such a system, a crucial prerequisite for scalability [2], and demonstrate a time-resolved photon detection technique to entangle frequency-distinguishable qubits and improve network robustness [3].

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Long Distance Coupling of a Quantum Mechanical Oscillator to the Internal States of an Atomic Ensemble

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Combining atomic, molecular and optical (AMO) physical systems with newly developed solid state devices into so-called *hybrid quantum systems* is motivated by the idea to combine the advantages of both, AMO and solid state systems, while compensate their disadvantages.

We propose and investigate a hybrid optomechanical system consisting of a micro-mechanical oscillator coupled to the internal states of a distant ensemble of atoms [1]. The interaction between the systems is mediated by a light field which allows to couple the two systems in a modular way over long distances. Coupling to internal degrees of freedom of atoms opens up the possibility to employ high-frequency mechanical resonators in the MHz to GHz regime, such as optomechanical crystal structures, and to benefit from the rich toolbox of quantum control over internal atomic states. Previous schemes involving atomic motional states [2,3,4] are rather limited in both of these aspects. We derive a full quantum model for the effective coupling including the main sources of decoherence. As an application we show that sympathetic ground-state cooling and strong coupling between the two systems is possible.

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Exploring Hybrid Quantum Systems with Circuit Quantum Electrodynamics: Semiconductor Quantum Dots, Rydberg Atoms and Superconducting Qubits

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Semiconductor quantum dots, Rydberg atoms and superconducting qubits all possess excitations in the microwave frequency domain. For this domain we have developed a wide range of novel approaches to create, store, manipulate and detect individual photons using micro-fabricated superconducting quantum electronic circuits. A key ingredient of this approach are coplanar wave guide resonators in which the field energy of an excitation is distributed over a mode volume much smaller than that of a mirror based resonator. This feature creates sizable electromagnetic fields at the level of individual microwave photons mediating strong electromagnetic interactions with a variety of different quantum systems. In an approach known as circuit quantum electrodynamics (QED) we have learned how to probe fundamental quantum optical effects and to demonstrate basic features of quantum information processing with superconducting quantum bits [1,2]. In this presentation, I will discuss two projects in which we explore the physics of semiconductor quantum dots and Rydberg atoms in the context of circuit QED. In the first project we investigate the coherent dipole coupling of semiconductor double quantum dots to microwave photons [3,4] and detect radiation emitted from the dots in inelastic electron tunneling processes. In a complementary project we perform steady-state microwave spectroscopic and time-resolved coherent dynamics measurements of Rydberg atoms in the vicinity of surfaces [5,6]. We detect the state of the Rydberg atoms using field

ionization and develop novel schemes based on dispersive interaction with a resonator field. Our Rydberg atom experiments are performed in a cryostat between room temperature and 3 K [2] which are to be extended down to the millikelvin range. Ultimately, we plan to trap Rydberg atoms on-chip to investigate the single atom and single photon limit of cavity QED at the interface with superconducting circuits. This may allow us to explore quantum coherent interfaces between atomic and solid state qubits in the context of quantum science and technology.

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Hybrid Spin Systems

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Nuclear spins are exceptional quantum bits owing to their long coherence time and high fidelity quantum state control. Yet, as their coupling to the environment is low reading out quantum states is challenging. One natural choice is to use hyperfine coupling to electron spins which can be read much simpler. However, this typically causes excess noise and hence shortens nuclear spin relaxation time. Ideally, electron spins are present only for nuclear spin initialization and readout and are removed otherwise. We demonstrate this principle and enhance nuclear spin memory times by two orders of magnitude. We apply extended memory times for efficient photon storage in nuclear spins, repetitive error correction and entanglement purification.