International Conference on Scalable Quantum Computing with Light and Atoms

Final Conference of the FP6 Integrated Project

SCALA

SCAlable Quantum Computing with Light and Atoms

February 15-22, 2009

Cortina D'Ampezzo, Italy

Timetable

Time	Sunday 15	Monday 16	Tuesday 17	Wednesday 18	Thursday 19	Friday 20	Saturday 21	Sunday 22
7:45-8:15		*Breakfast*	*Breakfast*	*Breakfast*	*Breakfast*	*Breakfast*	*Breakfast*	*Breakfast*
8:30-9:05		Porto	Blatt	Schleich	Raimond	Bellini	Steering Committee	
9:05-9:40		Bloch	Schmidt-Kaler	Zeilinger	Walraff	Gisin	Steering Committee	Departure
9:40-10:10		*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	
10:10-10:45		Dalibard	Monroe	Kimble	Imamoglu	Rempe	General Assembly	
10:45-11:20		Moritz	Schaetz	De Martini	Vandersypen	Eschner	General Assembly	
11:20-11:55		Inguscio	Steane	Mecozzi	Browaeys	Acin	General Assembly	
12:00-16:30		Lunch Free	Lunch Free	Lunch Free	Lunch Free	Lunch Free	Lunch Free	
16:30-17:05	Arrival - Registration	Schmiedmayer	Milburn	Manko	Kurizki	Laflamme	Free	
17:05-17:35	Arrival - Registration	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	*Coffee break*	
17:35-18:10	Arrival - Registration	Lukin	Sanpera	Bonifacio	Cirac	Werner	Free	
18:10-18:45	Arrival - Registration	Macchiavello	Pachos	De Pasquale	Daley	Kampermann	Free	
18:45-19:20	Arrival - Registration	Moelmer	Martin-Delgado	Vitali	Scheel	Horodecki	Free	
19:30-21:00	*Dinner*	*Dinner*	*Dinner*	*Conf. Dinner*	*Dinner*	*Dinner*	*Dinner*	
21:00-23:00		Poster session	Poster session		Poster session	Poster session		

Monday 16^{th} February

8:30 Trey Porto - *Field sensitive addressing of field insensitive qubits*

9:05 Immanuel Bloch - *New light on strongly correlated quantum phase of bosons, fermions and bose-fermi mixtures in optical lattices*

10:10 Jean Dalibard - *Gauge potentials for cold atoms: from rotations to geometric phases*

10:45 Henning Moritz - *Strongly correlated fermionic atoms in optical lattices*

11:20 Massimo Inguscio - *Anderson localization of a non-interacting Bose-Einstein condensate*

16:30 Joerg Schmiedmayer - *Using interference to probe (de) coherence and quantum noise in many body systems*

17:35 Mikhail Lukin - *Quantum optics with tightly confined photons and atoms*

17:35 Chiara Macchiavello - *Transition behavior in communication over noisy quantum channels with correlations*

18:45 Klaus Mølmer - *Collective qubits*

Tuesday 17^{th} February

8:30 Rainer Blatt - *Quantum Information Science with Trapped Ca+ Ions*

9:05 Ferdinand Schmidt-Kaler - *Modern segmented ion traps and their application for non-equilibrium thermodynamics*

10:10 Christopher Monroe - *Ion Trap Photonic Quantum Networks*

10:45 Tobias Schaetz - *Simulating quantum systems in ion traps*

11:20 Andrew Steane - *Adaptive qubit measurement and ion trap developments*

16:30 Gerard Milburn - *Quantum optics in circuit QED.*

17:35 Anna Sanpera - *Entanglement scaling characterization*

18:10 Jiannis Pachos - *Topological Quantum Computation*

18:45 Miguel A. Martin-Delgado - *Quantum 2-Body Hamiltonian for Topological Color Codes*

Wednesday 18^{th} February

Day in honor of Paolo Tombesi's 70th birthday

8:30 Wolfgang P. Schleich - *Factorization of numbers, Schrödinger cats and the Riemann hypothesis*

9:05 Anton Zeilinger - *Fundamental Tests of Quantum Physics: From Neutrons to Entangled Photons*

10:10 H.Jeff Kimble - *Quantum Networks*

10:45 Francesco De Martini - *Entanglement and nonlocality of a microscopic-macroscopic system*

11:20 Antonio Mecozzi - *Decoherence in fiber-based cryptographic systems for quantum key distribution: the effect of the geomagnetic field*

16:30 Vladimir Manḱo - *Symplectic tomography and probability representation of quantum states*

17:35 Rodolfo Bonifacio - *Quantum theory of collective recoil lasing in relativistic e-beam and cold atoms*

18:10 Ferdinando de Pasquale - *Quantum to classical transition in system of finite size with a spontaneously broken symmetry: a mean field approach.*

18:45 David Vitali - *Experimental inhibition of decoherence on flying qubits via bang-bang control*

Thursday 19^{th} February

8:30 Jean-Michel Raimond - *Quantum state measurements in cavity QED*

9:05 Andreas Wallraff - *Generating and Probing Entanglement in Circuit Quantum Electrodynamics (QED)*

10:10 Atac Imamoglu - *Optical manipulation of quantum dot spins*

10:45 Lieven Vandersypen - *Control of electron and nuclear spins in quantum dots*

11:20 Antoine Browaeys - *Observation of collective excitation of two individual atoms in the Rydberg blockade regime*

16:30 Gershon Kurizki - *How Fast Can We Cool Down Quantum Bits?*

17:35 Juan Ignacio Cirac - *Quantum computation, state engineering and phase transitions driven by dissipation*

18:10 Andrew Daley - *Atomic three-body loss as a dynamical three-body interaction*

18:45 Stefan Scheel - *Process reconstruction using Kalman filtering -a diagnostic tool for quantum engineering*

Friday 20^{th} February

8:30 Marco Bellini - *Experimental single-photon creation and annihilation for fundamental tests of physics and quantum state engineering*

9:05 Nicolas Gisin - *Towards Quantum Repeaters*

10:10 Gerhard Rempe - *Cavity QED with individually trapped atoms*

10:45 Jürgen Eschner - *Single atom - single photon interaction*

11:20 Antonio Acin - *Random Numbers from Bell's Theorem*

16:30 Raymond Laflamme - *Noise characterization and benchmarking for quantum devices*

17:35 Reinhard F Werner - *Index Theory of QCAs: the next dimensions*

18:10 Pawel Horodecki - *Superadditivity of data transfer via quantum channels*

18:10 Hermann Kampermann - *Creation of pseudo bound entanglement in NMR quantum computing*

Monday 16^{th} February

Field sensitive addressing of field insensitive qubits

J.V. Porto, N. Lundblad, J.M. Obrecht, I.B. Spielman

Joint Quantum Institute National Institutute of Standards and Technology and the University of Maryland

Quantum computational platforms are frequently driven by competing needs: the isolation of the quantum system from the environment to prevent decoherence, and the ability to control the system with external fields. Neutral-atoms in optical-lattices can provide environmental isolation through the use of “clock” states that are robust against changing external fields, yet those same external fields are inherently useful for qubit addressing using magnetic resonance imaging-like techniques. Here we demonstrate a technique to address a spatially dense, field-insensitive qubit register using field-sensitive transitions. A subwavelength-scale effective magnetic-field gradient permits the addressing of selected elements of the qubit register, leaving unmarked qubits unaffected, with little crosstalk or leakage. We demonstrate this technique with rubidium atoms in a double-well optical lattice, and show that we can robustly perform single-qubit rotations on qubits located on a selected sub-lattice.

New light on strongly correlated quantum phase of bosons, fermions and bose-fermi mixtures in optical lattices

Immanuel Bloch

University of Mainz

Ultracold quantum gases in optical lattices allow one to explore the fundamental behaviour of strongly correlated many-body quantum systems with different quantum statistics. We show that by using novel probes, one can measure static and dynamical properties of these systems. For example the compressibility of a fermionic quantum gas mixture with repulsive interactions can be measured by probing the size of the system as an external confinement is increased. Thereby metallic and insulating phases can be distinguished from each other in a direct way. Our results are compared to ab-initio calculations of the Hubbard model using Dynamical Mean Field Theory (DMFT) and provide a first ab-initio test of DMFT. For attractive interactions between the fermions in the lattice, we find a peculiar anomalous expansion of the Fermi gas with increasing attractive interaction strength. This is attributed to the crossover of the gas from weakly bound pairs to hardcore bosons and a coinciding loss of the spin degrees of freedom of the system. Furthermore we show, how quantum phase diffusion can be used to precisely determine the renormalized interaction and tunneling parameters of interacting Bose-Fermi mixtures in optical lattices. This has allowed us to identify in parts the mechanism underlying the strong shift of the superfluid to Mott insulator transition when fermions with attractive interactions are added to a bosonic superfluid. Finally we show how spin-spin superexchange interactions can be controlled in optical superlattices and used for the efficient and massively parallel creation of entangled Bell pairs in the lattice.

Gauge potentials for cold atoms: from rotations to geometric phases

Jean Dalibard

Laboratoire Kastler Brossel and CNRS

In this talk I will discuss the possible ways to apply a gauge field to an assembly of cold neutral atoms, in order to simulate the orbital magnetism of a system of charged particles in a magnetic field. A first possibility is to rotate the system, which is known to lead to the nucleation of vortices. Other schemes (not yet fully demonstrated experimentally) rely on the use of geometric phases such as Berry's phase, which arises an atom moves slowly in a light field. I will present a semi-classical interpretation of the geometric scalar and vector potentials that arise in such schemes, and I will relate the geometric forces to the radiation pressure and dipole forces known from quantum optics. I will also discuss a novel scheme to generate such Abelian gauge fields, that operates even for a large detuning with respect to the atomic resonance, making it applicable to alkali atoms without significant heating due to spontaneous emission.

[1] M. Cheneau, S. P. Rath, T. Yefsah, K. J. Günter, G. Juzeliunas, and J. Dalibard, Europhysics Letters 83, 60001 (2008): Geometric potentials in quantum optics: A semi-classical interpretation

[2] Kenneth J. Günter, Marc Cheneau, Tarik Yefsah, Steffen Patrick Rath, and Jean Dalibard, to appear in Phys. Rev. A, Rapid Comm. (2009): A practical scheme for a light-induced gauge field in an atomic Bose gas

Strongly correlated fermionic atoms in optical lattices

Henning Moritz, Robert Jördens, Niels Strohmaier, Daniel Greif, Leticia Tarruell, Tilman Esslinger

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

In a solid material strong interactions between the electrons can lead to surprising properties. A prime example is the Mott insulator, where the suppression of conductivity is a result of interactions and not the consequence of a filled Bloch band. The proximity to the Mott insulating phase in fermionic systems is the origin for many intriguing phenomena in condensed matter physics, most notably high-temperature superconductivity. Compared to real materials, a fermionic quantum gas trapped in an optical lattice offers a very pure realisation of the Hubbard model, giving a new approach to understand the physics of strongly correlated systems.

We report on the formation of a Mott insulator of a repulsively interacting two-component Fermi gas in an optical lattice. It is signalled by three features: a drastic suppression of doubly occupied lattice sites, a strong reduction of the compressibility inferred from the response of double occupancy to atom number increase, and the appearance of a gapped mode in the excitation spectrum.

Anderson localization of a non-interacting Bose-Einstein condensate

G. Roati, B. Deissler, C. D'Errico, L. Fallani, M. Fattori, C. Fort, M. Zaccanti, G. Modugno, M. Modugno and M. Inguscio

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Dipartimento di Matematica Applicata, Universita' di Firenze, 50139 Firenze, Italy.
BEC-INFM Center, Universita' di Trento, 38050 Povo, Italy.

We use a non-interacting Bose–Einstein condensate to experimentally study Anderson localization in a one-dimensional quasi-periodic lattice, i.e., a system that features a crossover between extended and exponentially localized states. Localization is probed through the transport properties and the spatial and momentum distributions. We characterize the crossover, finding that the critical disorder strength scales with the tunnelling energy of the atoms in the lattice. Our controllable BEC will be used to investigate the interplay of disorder and interaction.

Using interference to probe (de) coherence and quantum noise in many body systems

Jörg Schmiedmayer

Atominstitut der Östereichischen Universitäten, TU-Wien

Quantum coherence and Quantum noise, together with the probabilistic character of the measurement process is one of the most puzzling and fascinating aspects of quantum mechanics. Coherence can be observed in interference experiments, but the full characterization of the noise, which in many-body systems quantum can reveal the non-local correlations and entanglement of underlying many-body states remained elusive.

In the talk I will present experiments interfering two 1-dimensional quantum gases [1], which reveal how the coherence slowly dies under the influence of quantum and thermal noise [2]. To reveal the nature of the fluctuations we generalize the standard homodyne measurement of quantum optics to the analysis of interference of two fluctuating quantum systems. The full distribution function of the shot to shot variation of the interference patterns contains information about the higher order correlation functions and reveals the nature of the noise. In our experiments we clearly distinguish between contributions of fundamental quantum noise and thermal noise [3].

In an outlook we will discuss how experiments can be extended and combined with high efficient atom counting to further characterize the quantum states of mesoscopic many body systems. A as complete as possible characterization of quantum physics in these systems will be the prerequisite for efficient quantum control in these fascinating many body systems

This work was supported by the European Union MC network AtomChips, integrated project SCALA, the DIP the FWF and the Wittgenstein Prize.

[1] T. Schumm et al. Nature Physics, 1,57 (2005); S. Hofferberth et al. Nature Physics 2, 489 (2008);
[2] S. Hofferberth et al. Nature 449, 324 (2007);
[3] S. Hofferberth et al. Nature Physics 4, 489 (2008).

Quantum optics with tightly confined photons and atoms

Mikhail Lukin

Physics Department, Harvard University

We will discuss our recent work on quantum optics and quantum control using novel micro- and nano-photonic systems. This work combines the localization of light and atoms near or bellow
the optical wavelength scale. Novel applications of these ideas to problems such as single photon nonlinear optics and nanoscale sensing will be discussed.

Transition behavior in communication over noisy quantum channels with correlations

Chiara Macchiavello

University of Pavia

We analyse the performance of two-qubit quantum communication channels in the presence of correlated noise. We show that the optimal channel performance and the onset of a transition in the optimal input entanglement depend on the specific form of the correlation introduced in the noise process.

Collective qubits

Klaus Mølmer

University of Aarhus

In the conventional lay-out of a register for quantum computing, all qubits are associated with individual two-level quantum systems. Individual addressing and interaction with these systems permit one-bit gates, while an interaction between systems is needed to accomplish two-bit gates. We have recently proposed the implementation of a different encoding of quantum information in collective excitation degrees of freedom in ensembles of identical quantum systems. In this proposal one does not need to address individual particles, but one does need an interaction between all particles in the system. Such interactions are induced in small atomic clouds, excited to high lying Rydberg states, and in large atomic, molecular or spin-ensembles coupled to a suitable joint databus, such as a quantized radiation field or a motional vibration. The use of large ensembles with many more particles than qubits makes it possible to couple the qubit register information superradiantly to photons. We will review the main ideas of ensemble encoding and we will present proposals and analyses of quantum computing and quantum repeater technologies based on flying qubits between mesoscopic atomic ensembles.

Tuesday 17th February

Quantum Information Science with Trapped Ca+ Ions

Rainer Blatt

Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria, and Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria.

Trapped strings of cold ions provide an ideal system for quantum information processing. The quantum information can be stored in individual ions and these qubits can be individually prepared; the corresponding quantum states can be manipulated and measured with nearly 100% detection efficiency. With a small ion-trap quantum computer based on up to eight trapped Ca+ ions as qubits we have generated genuine quantum states in a pre-programmed way. In particular, we have generated GHZ and W states in a fast and scalable way and we have demonstrated for the first time a Toffoli gate with trapped ions which is analyzed via state and process tomography. Entanglement swapping was demonstrated on demand and high fidelity CNOT-gate operations are investigated towards fault-tolerant quantum computing. All protocols require either avoiding decoherence using appropriate experimental conditions or tailoring decoherence free subspaces. As an application to quantum metrology, with Bell states as a resource, entangled states are used for the precision measurement of optical clock shifts.
This work is supported by the Austrian Science Fund (FWF), by the European Commission (CONQUEST, SCALA) and in parts by IARPA and ARO.

Modern segmented ion traps and their application for non-equilibrium thermodynamics

Ferdinand Schmidt-Kaler

Abteilung Quanten-Informationsverarbeitung Universität Ulm

We decribe a micro chip trap for ions, where a single 40Ca+ ion has been prepared by resolved sideband cooling in the ground state of vibration [1]. Coherent manipulation of the spin qubit levels, with multiple Rabi oscillations, is possible via optical pulses on a Raman transition.The multisegmented ion trap allows for fast and precise operations on the external degree of freedom, the ions position and speed. With non-adiabatic changes of the trap control voltages, we may investigate non-equilibrium quantum states, important as a test bed for quantum-thermodnamics [2].

[1] Schulz et al, New Journal of Physics 10 (2008) 045007;
[2] Huber et al, PRL 101, 070403 (2008).

Ion Trap Photonic Quantum Networks

C. Monroe

JQI and University of Maryland

The local manipulation and entanglement of nearby atomic ion qubits through their Coulomb interaction is now established as one of the most reliable ways to build entangled states. Trapped ions can also be coupled through a photonic channel, allowing for various remote probabilistic ion-ion entanglement protocols. Recent experiments have shown entanglement, a Bell inequality violation, teleportation, and operation of a two-qubit quantum gate between two ions separated by 1 meter. Despite the probabilistic nature of this ion/photon network, it can be efficiently scaled to much larger numbers of ions for distributed large-scale quantum computing and long-distance quantum communication, especially when accompanied by local Coulomb-mediated deterministic quantum gates. Future work will couple photons emitted from trapped ions into optical cavities, and perhaps interface trapped ion qubits with other optically-active qubits such as quantum dots.

Simulating quantum systems in ion traps

H.Schmitz, A.Friedenauer, Ch.Schneider, R.Matjeschk, M.Enderlein, T.Huber, J.Glueckert, D.Porras, and T.Schaetz

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str.1, D-85748 Garching, Germany

We study the building blocks for quantum simulations based on trapped ions. In the first part of the talk we focus on quantum spin-Hamiltonians simulated according to a protocol of Porras and Cirac (PRL 2004). Here, we experimentally simulated the adiabatic evolution of the smallest non-trivial spin system from para- into ferromagnetic order with a quantum magnetisation for two spins of 98%. We proved that the transition was not driven by thermal-fluctuations but of quantum mechanical origin, the source of quantum-fluctuations in quantum phase transitions. We observed a final superposition state of the two degenerate spin configurations for the ferromagnetic order corresponding to deterministic entanglement achieved with 88% fidelity. To calibrate the amplitudes of the simulated interactions, we performed a two-qubit phase-gate based on both axial motional modes with an entangling fidelity exceeding 95%. Currently, we explore the limits of quantum simulations in conventional traps, extending the operations to the radial degree of freedom, with a preliminary fidelity of the two-qubit phase-gate exceeding 92% and recently five ions cooled close to the motional ground state. In parallel we work on the realization of a surface-trap array that might allow for a 2D-lattice of ions (first of 2x2 – in principle scalable to >10x10 ions/spins). In a second part of the talk we want to present our experimental results of a (quantum) random walk of an ion – our protocol being close to the proposal of Travaglione and Milburn (PRA 2002).

Adaptive qubit measurement and ion trap developments

D. T. C. Allcock, M. J. Curtis, G. Imreh, A. H. Myerson, J. A. Sherman, D. J. Szwer, S. C. Webster, D. N. Stacey, A. M. Steane and D. M. Lucas

Oxford University

The experimental implementation of quantum information physics has two main requirements: greater precision and greater flexibility. Work of the Oxford ion trap quantum computing group towards both goals will be presented. We have studied theoretically and implemented experimentally schemes to make the best possible use of finite information in order to measure qubits rapidly with high fidelity. For example, in an experiment with low photon collection efficiency, we attain 99.99% measurement fidelity in 145μs for qubits stored in electronic states in Ca^+. Towards the second goal, several multi-trap architectures, at various stages of completion, will be discussed.

Quantum optics in circuit QED.

G J Milburn[1], C. Meaney[1], T Duty[1], J. Twamley[2], S Rebic[2].

1. The University of Queensland, Brisbane, Australia.
2. Macquarie University, Sydney, Australia

Abstract: Both quantum nanomechanics and superconducting circuit quantum electrodynamics (circuit QED) represent a new approach to the study of quantum dynamics in artificially engineered structures. A key feature of both research programs is an effective quantum description in terms of collective degrees of freedom that factor out of the microscopic dynamics, which latter are only retained as sources of noise and dissipation. In the case of circuit QED, a microwave field in a superconducting coplanar resonator can be coupled to one or more super conducting tunnel junctions so strongly as to enable a new regime of quantum optics. In this talk I will discuss a number of schemes based on this strong coupling. One such scheme is an effective Jahn-Teller model which exhibits the creation of entanglement between the field and the junction through a dynamical bifurcation. Another scheme uses an effective four level model, based on two strongly interacting

Entanglement scaling characterization

A. Sanpera

ICREA and Universitat Autònoma Barcelona (Spain)

The study of entanglement is providing a novel insight into the complexity of magnetic ordering in a large variety of systems. Within this context we investigate how the scaling of entanglement might help to characterize complex systems and how this scaling could be unveiled.

Topological Quantum Computation

Jiannis K. Pachos and James Wootton

University of Leeds

Topological quantum computation promises to drastically resolve the problem of decoherence in quantum computation in the hardware level. Here we present such a model that is a hybrid between one way quantum computation and adiabatic quantum computation. At the same time it enjoys the error-free characteristic of topological systems due to an energy gap that is present at all times, protecting the encoding space from decoherence. We shall present how one can perform the state preparation, the control manipulations and the measuring procedure. The physical realization of this model with quantum optics and Josephson junctions will be entertained.

Quantum 2-Body Hamiltonian for Topological Color Codes

H. Bombin[1], M. Kargarian[2], M.A. Martin-Delgado[1]

1 Departamento de Fisica Teorica I, Universidad Complutense, 28040 Madrid, Spain
2 Physics Department, Sharif University of Technology, Tehran 11155-9161, Iran

We introduce a two-body quantum Hamiltonian model of spin-1/2 on a 2D spatial lattice with exact topological degeneracy in all coupling regimes. There exists a gapped phase in which the low-energy sector reproduces an effective color code model. High energy excitations fall into three families of anyonic fermions that turn out to be strongly interacting. The model exhibits a $Z_2 \times Z_2$ gauge group symmetry and string-net integrals of motion, which are related to the existence of topological charges that are invisible to moving high-energy fermions.

Wednesday 18^{th} February

Day in honor of Paolo Tombesi's 70th birthday

Factorization of numbers, Schrödinger cats and the Riemann hypothesis

Wolfgang P. Schleich,

Institut für Quantenphysik, Universität Ulm

In this talk we connect the three different topics of factorization of numbers, Schrödinger cats and the Riemann hypothesis. The bridge between these areas is the concept of a Gauss sum. Gauss sums manifest themselves in various phenomena such as the Talbot effect, wave packet dynamics or quantum carpets. Moreover, Gauss sums can be used to efficiently factor numbers. In the meantime five experiments have used such an approach. They rely on NMR techniques, the physics of cold atoms and femtosecond pulses. At the moment the largest number that was factored using a Gauss sum algorithm is a 17 digit number. The talk summarizes these activities. Moreover, we propose an elementary quantum system which provides us with the Riemann Zeta function. We show that its zeroes are a consequence of the interference of two quantum systems with opposite phases. However, the preparation of such a superposition state (Schrödinger cat) is impossible unless one takes advantage of entangled quantum systems. In this sense analytic continuation familiar from complex analysis finds entanglement as its analogue in quantum mechanics.

Fundamental Tests of Quantum Physics: From Neutrons to Entangled Photons

Anton Zeilinger

University of Vienna & Austrian Academy of Sciences

Experiments on the Foundations of Quantum Mechanics have led to the field of quantum information. I will review some of the early and some of the most recent experiments. These start with demonstrations of the spinor symmetry of neutrons, tests of the linearity of quantum mechanics with cold neutrons, and finally include tests of nonlocal realistic variants of hidden variable theories.
This paper is dedicated to Paolo Tombesi at the occasion of his 70th birthday.

Quantum Networks

H.Jeff Kimble

California Institution of Technology

Quantum networks offer a unifying set of opportunities and challenges across exciting intellectual and technical frontiers, including for quantum computation, communication, and metrology [1]. The realization of quantum networks composed of many nodes and channels requires new scientific capabilities for the generation and characterization of quantum coherence and entanglement. Fundamental to this endeavor are quantum interconnects that convert quantum states from one physical system to those of another in a reversible fashion. Such quantum connectivity for networks can be achieved by optical interactions of single photons and atoms, thereby enabling quantum state transfer and teleportation between nodes. Within this setting, I will describe ongoing research in the Caltech Quantum Optics Group related to cavity QED with single atoms strongly coupled to the fields of high-quality optical resonators and collective interactions of atomic ensembles with single photons and entangled states of light.

1. "The Quantum Internet," H. J. Kimble, Nature 453, 1053 (2008).

Entanglement and nonlocality of a microscopic-macroscopic system

F.De Martini, F.Sciarrino , C.Vitelli

Università di Roma "La Sapienza" Accademia dei Lincei

The nonlocal properties of a complex microscopic- macroscopixc system involving about 1 million photons will be demonstrated experimentally. The Decoherence, Einselection and Classicality of such novel Schroedinger Cat will also be discussed.

Decoherence in fiber-based cryptographic systems for quantum key distribution: the effect of the geomagnetic field

Antonio Mecozzi [1], Cristian Antonelli [1], Misha Brodsky [2], Andrei Sirenko [3], Alexei Trifonov [4]

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(2) AT&T Labs Research, Middletown, NJ 07748,
(3) Department of Physics, NJIT, Newark, NJ 07102,
(4) MagiQ Technologies, Inc., Somerville, MA 02143

The weak geomagnetic field, with the unsuspected complicity of modern fiber technology, could potentially impair quantum key distribution in commercially available, fiber-based, plug-and-play systems. This surprising limitation arises in systems employing polarization modulation and a round-trip architecture, where the fiber is terminated at one end by a Faraday mirror that compensates for the polarization fluctuations induced by the random birefringence of the fiber. In those systems the geomagnetic field, due to the Faraday effect, behaves like a source of additional birefringence, non-reciprocal hence uncompensated by the Faraday mirror. The overall birefringence yields random polarization fluctuations and, in consequence, a possible increase of the quantum bit error rate (QBER). Fiber technology is found to play a crucial role in the depicted scenario: old fibers outperform new-generation spun fibers, designed so as to minimize polarization mode dispersion in long-haul optical communication systems. In this talk we report on the experimental demonstration of the QBER degradation caused by the Faraday effect due to a weak axial magnetic field, providing at once a theoretical framework for the understanding and the mitigation of this potential impairment.

Symplectic tomography and probability representation of quantum states

Vladimir I. Man'ko

Lebedev Physical Institute Moscow, Russia

The tomographic approach where the quantum states are described by a family of probability distributions instead of the wave function or density matrix is reviewed. The evolution equation for the tomographic probability distribution which is obtained by means of Radon transform of the Moyal evolution equation for the Wigner function is presented. The energy levels of a quantum system are expressed in terms of the equation for the tomographic probability distribution which is obtained using Radon transform of the corresponding Moyal equation for the Wigner function of stationary quantum states. The Heisenberg and Schroedinger-Robertson uncertainty relations are presented in the form of inequalities containing only measurable optical tomograms which were the experimental results of the homodyne detection of photon quantum states. The photon-number tomography and spin tomography are discussed. The entanglement problem as well as Bell's inequalities are formulated in terms of the properties of the joint probability distribution function (tomogram) of multipartite quantum system. The approach reviewed is presented in [1-3].

[1] S. Mancini, V.I. Man'ko and P. Tombesi,"Wigner function and probability distribution for shifted and squeezed quadratures," Quantum Semiclass. Opt., vol. 7, pp. 615-623 (1995).

[2] S. Mancini, V.I. Man'ko and P. Tombesi,"Symplectic tomography as classical approach to quantum systems," Phys. Lett. A, vol. 213, pp. 1-12 (1996).

[3] S. Mancini, V.I. Man'ko and P. Tombesi, "Classical-like description of quantum dynamics by means of symplectic tomography," Found. Phys., vol. 27, pp. 801-824 (1997).

Quantum theory of collective recoil lasing in relativistic e-beam and cold atoms

Rodolfo Bonifacio

INFN Sezione di Milano

Very different physical systems such as relativistic e-beam in a FEL and cold atoms in a BEC, driven by a LASER pump, exhibits similar behavior which can be described by the same model equations: a Schrodinger-like equation for a macroscopic wave function coupled self-consistently with the equation for the back-scattered field amplitude. By a Madelung transformation we show that the particles behave as a quantum fluid in the classical plus a quantum potential. The classical limit is recovered when the one-photon momentum recoil is smaller than the particle momentum spread. We demonstrate spontaneous symmetry breaking (self-bunching), discrete momentum distribution and Superradiant back-scattering. We describe recent experiments at MIT and LENS in a BEC and the conceptual design of a table-top FEL in the Angstrom region.

Quantum to classical transition in system of finite size with a spontaneously broken symmetry: a mean field approach.

Ferdinando de Pasquale[1], Gian Luca Giorgi[2], and Marco Zannetti[3]

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A spontaneously broken symmetry implies the existence of different ground states related each by symmetry transformations. It is known that in the thermodynamic limit, because of superselection rules, interference between macroscopic states cannot exist. We studied the disappearance of state interference and entanglement as the macroscopic limit is approached for models belonging to different classes of symmetry: the Ising and anysotropic XY model in the presence of a factorizing transverse field, belonging to a discrete symmetry case, and the BCS and Heisenberg spin model,where the symmetry is continuous. The approach to the thermodynamic limit is studied by means of the exact solution in the case of the factorized XY chain and the Heisenberg model, while a mean field theory is introduced as far as the Ising and the BCS models are considered. The transition from quantum to classical behaviour is found to occurs exponentially or algebraically with the increasing of the size system N respectively in the case of a discrete or continuous symmetry breaking.

Experimental inhibition of decoherence on flying qubits via bang-bang control

David Vitali, Sajeev Damodarakurup, Giovanni di Giuseppe, Marco Lucamarini, Paolo Tombesi

Dipartimento di Fisica, Università di Camerino, Camerino, Italy

Decoherence may significantly affect the polarization state of single-photon pulses during the propagation within dispersive media because of the unavoidable presence of more than a single frequency in the envelope of the photon pulse. Here we report on the suppression of polarization decoherence in a ring cavity obtained by properly retooling for the photon qubit the "bang-bang" protection technique already employed for nuclear spins and nuclear-quadrupole qubits. Our results show that bang-bang control can be profitably extended to all quantum information processes involving flying polarization qubits.

Thursday 19th February

Quantum state measurements in cavity QED

Jean-Michel Raimond

Laboratoire Kastler Brossel Département de physique de l'Ecole Normale Supérieure 24 rue Lhomond, 75005 Paris

Using long-lived circular Rydberg atoms as sensitive probes of a quantum field trapped in a high-quality superconducting cavity, we perform a Quantum non Demolition measurement of the cavity field photon number. We observe quantum jumps of light whose analysis provides a detailed insight into field relaxation mechanisms. Quantum Zeno effect occurs when repeated QND measurements compete with the injection of a coherent field in the cavity by a classical source.
Combining QND measurements with controlled displacements, we reconstruct the cavity field quantum state for coherent states and non-classical Fock and 'Schrödinger cat' states. The latter exhibit Wigner functions with non-gaussian features and negative values. We observe in real time the decoherence of a Schrödinger cat. This quantum state reconstruction opens fascinating perspectives for detailed non-classical state studies and investigations of decoherence processes.

Generating and Probing Entanglement in Circuit Quantum Electrodynamics (QED)

Andreas Wallraff

Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland

In our lab, we control the interaction of photons and qubits on the level of individual quanta [1] to perform novel quantum optics [2] and quantum information processing experiments [3] using superconducting electronic circuits. In this talk, I will discuss an experimental approach to generate entanglement between any pair of remote qubits in a multi-qubit circuit QED system using side-band transitions through a joint quantum bus [4]. With this scheme, similar of the one used in ion traps, we have generated all 4 Bell states and tomographically measured their density matrix using a joint dispersive read-out [5] that does not require single-shot measurement of individual qubits. We have also explored the generation of multi-qubit entangled states using global interactions of three qubits resonantly coupled to a single cavity mode [6].

[1] A. Wallraff et al., Nature (London) 431, 162 (2004)
[2] J. Fink et al., Nature (London) 454, 315 (2008)
[3] P. Leek et al., Science 318, 1889 (2007)
[4] P. J. Leek et al., arXiv:0812.2678 (2008)
[5] S. Filipp et al., arXiv:0812.2485 (2008)
[6] J. M. Fink et al., arXiv:0812.2651 (2008)

Optical manipulation of quantum dot spins

Atac Imamoglu

ETH Zurich

I will describe all-optical measurements that reveal rich spin dynamics in single self-assembled InAs/GaAs quantum dots (QD). To study single electron spin physics, we use resonant optical pumping: the degree of steady-state electron spin cooling reveals the relative strength of various spin relaxation processes. To study the dynamics of quantum dot nuclear spins, we carry out pump-probe measurements where we first polarize nuclear spins and monitor the degree of polarization as a function of external parameters.

Control of electron and nuclear spins in quantum dots

Lieven Vandersypen

Kavli Institute of Nanoscience TU Delft

We will report on two recent unpublished results that are relevant for quantum information processing with electron spins in quantum dots. First, under fixed-frequency continuous wave irradiation with microwave magnetic fields, we observe that the electron spin remains locked into spin resonance when we sweep the magnetic field away from the resonance condition. This surprising effect originates from a build-up of nuclear spin polarization, which acts to exactly compensate for the resonance offset in the external magnetic field. Within a general picture, this resonance locking is accompanied by a reduced distribution of nuclear fields, hence extended electron spin dephasing times. Second, we perform continuous-wave spectroscopy of two-electron states in a double quantum dot. We can excite pure interdot charge transitions, as well as (weaker) transitions involving spin flips. These transitions could potentially offer new approaches to realizing two-qubit gates

Observation of collective excitation of two individual atoms in the Rydberg blockade regime

Antoine Browaeys

Institut d'Optique

The dipole blockade between Rydberg atoms has been proposed as a basic tool in quantum information processing with neutral atoms. In this presentation, I will detail our recent experimental demonstration of the Rydberg blockade of two individual atoms separated by 4 μm. Moreover, I will show that, in this regime, the single atom excitation is enhanced by a collective two-atom behavior associated with the excitation of an entangled state. This observation is an important step towards the deterministic manipulation of entanglement of two or more atoms using the Rydberg dipole interaction. I will finally report the status of the experiment.

How Fast Can We Cool Down Quantum Bits?

Goren Gordon, Guy Bensky, David Gelbwaser-Klimovsky, Durga B. Rao Dasari, Noam Erez and Gershon Kurizki

Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel

Quantum two-state systems, known as quantum bits (qubits), are the universal building blocks of the coveted quantum computers and other devices based on quantum logic. Unavoidably, qubits are in contact with their uncontrolled thermal environment, alias a macroscopic "bath". The higher the temperature of the qubits, the less useful they are for quantum logic operations. Hence the imperative need to cool down the qubits as much and as fast as possible, so as to increase their ground-state population and thus purify their state, prior to each quantum logic operation. Yet, the fundamental limit on the speed of all existing cooling scheme is the finite duration of the system equilibration with the bath. This duration is long compared to the bath memory time, over which deviations from Markovian behavior are significant. But do we really have to wait that long? We show that repeated non-demolition disturbances of the equilibrium state of the qubits by impulsive phase-shifts or measurements can lead to ultrafast cooling, well within the non-Markovian time-domain, much faster than by known methods. Alternatively, cooling to extremely low temperatures is achievable over the equilibration time. These anomalous cooling processes stem from the remarkably simple quantum dynamics of the qubit bath interaction on ultrafast time-scales. They can be used in principally novel, advantageous, cooling schemes to assist quantum logic operations.

Quantum computation, state engineering and phase transitions driven by dissipation

Ignacio Cirac [1], Frank Verstraete [2], Michael Wolf[3]

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(2) Institut für Quantenoptik und Quanteninformation, Universität Wien, Vienna, Austria.
(3) Niels-Bohr-Institute, University of Copenhagen, Copenhagen, Denmark.

The strongest adversary in quantum information science is decoherence, which arises due to the coupling of a system with its environment. The induced dissipation tends to destroy and wash out the interesting quantum effects which give rise to the power of quantum computation, cryptography, and simulation.While this is certainly true for many forms of dissipation, we show here that dissipation can also have exactly the opposite effect: it can be a full–fledged resource for universal quantum computation without any coherent dynamics needed to complement it.The coupling to the environment drives the system to a steady state where the outcome of the computation is encoded. In a similar vein, we show that dissipation can be used to engineer a large variety of strongly correlated states in steady state,including all stabilizer codes, matrix product states, and their generalization to higher dimension. We also show that it can drive quantum phase transitions. Work done in collaboration with F. Verstraete and M. Wolf

Atomic three-body loss as a dynamical three-body interaction

A. J. Daley[1], J. M. Taylor [2], S. Diehl[1], M. Baranov[1], and P. Zoller[1]

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(2) Department of Physics, Massachusetts Institute of Technology, Building 6C-411, Cambridge, MA 02139, United States of America

Cold atoms in optical lattices offer new possibilities in quantum simulation, making it possible to probe quantum many-body phenomena that are difficult to observe in solid-state systems. They offer clean realisations of many microscopic lattice models, with excellent control over the system parameters and many possibilities to measure the properties of the system. In addition, they exhibit only weak dissipative processes, resulting in long coherence times. This allows new aspects of coherent many-body physics to be probed in an experiment, such as the formation of long-lived metastable states [1] or the study of time-dependent many-body dynamics. On the other hand, addition of controlled dissipation can be useful in the preparation interesting many-particle states [2].
In this context, we study the effects of three-body loss processes on the lattice system [3]. Such losses can give rise to effective three-body interactions, which dynamically suppress the probability of three particles occupying a single lattice site. This counter-intuitively leads to a decrease in the effective rate of loss as the real collisional loss rate is increased, in a similar manner to recently observed effective two-body interactions that arise from two-body loss for molecules in a lattice [4]. The resulting effective three-body interactions have important potential applications in the engineering of many-body states (e.g., Pfaffian-like states related to the quantum Hall effect and colour superfluid states involving a three-species mixture of fermions). The loss processes can be described by a many-body master equation, which we simulate in one dimension by combining quantum trajectories methods with the time-dependent density matrix renormalisation group algorithm.

[1] A. Kantian et al., New J. Phys 9, 407 (2007).
[2] S. Diehl et al., Nature Physics 4, 878 (2008).
[3] A. J. Daley et al., Phys. Rev. Lett., in press (preprint: arxiv:0810.5153v1).
[4] N. Syassen et al., Science 320, 1329 (2008).

Process reconstruction using Kalman filtering -a diagnostic tool for quantum engineering

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(2) Department of Mathematics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom

Successful quantum engineering of light and matter relies to a large extent on one's ability to generate and coherently manipulate a desired quantum state. Quantum tomography provides a tool to assess the quality of the quantum states and processes involved. We present here a novel quantum tomographic reconstruction method based on Bayesian inference via the Kalman filter update equations [1]. This methods not only yields the optimal Bayesian reconstruction, but in addition provides error bars on any derived quantity. This is a first step towards the broader goal of devising an omnibus reconstruction method that could be adapted to any tomographic setup and that treats measurement uncertainties in a statistically well-founded way.

[1] accepted for publication in New J. Phys. (2009).

Friday 20th February

Experimental single-photon creation and annihilation for fundamental tests of physics and quantum state engineering

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We experimentally implement the basic operators creating and annihilating a single photon in a field and apply them, and their combinations, to different states of light. A complete analysis of the resulting states by means of quantum tomography has demonstrated the generation of highly nonclassical light and has allowed us to probe fundamental quantum rules. The accurate mastering of such quantum operators is a first step towards the controlled generation of arbitrarily engineered quantum states.

Towards Quantum Repeaters

Nicolas Gisin, Mikael Afzelius, Hugues de Riedmatten and Christoph Simon Björn Lauritzen, Ji í Miná , Imam Usmani

Group of Applied Physics, University of Geneva, Switzerland

The ultimate limit of direct point to point quantum key distribution is around 300-500 km. Longer distances fiber-based quantum communication will require both high-fidelity entanglement swapping and multi-mode quantum memories.
A new protocol for an efficient multimode quantum memory based on atomic ensembles has been developed and demonstrated. The atomic ensemble, Nd ions, is "frozen" in a crystal inside a cryostat. The protocol is inspired from photon echoes, but avoids any control light pulse after the single-photon(s) is (are) stored in the medium, thus avoiding any noise due to fluorescence.
First results on the new protocol for quantum memories in rare-earth doped crystals demonstrate a quantum light-matter interface. The coherence of the re-emitted photons is investigated in an interference experiment showing net visibilities above 95%.
Many hundreds of km long quantum communication is a long term objective. Many of the necessary building blocks have been demonstrated, but usually in independent experiments and with insufficient fidelities and specifications to meet the goal. Still, today's the roadmap is relatively clear and a lot of interesting physics shall be found along the journey.

Cavity QED with individually trapped atoms

Gerhard Rempe

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Single atoms dipole trapped in an optical microcavity are an ideal resource for scalable quantum computing and distributed quantum networking. Several experiments have demonstrated this potential. For example, a single-photon server emitting individual light quanta into a well defined spatial and temporal light mode has been demonstrated [1,2]. Moreover, an atom-photon quantum interface has been realized with the ability to generate entanglement between an atom and a photon as well as between photons [3,4]. With high photon production rates and long atom trapping times [1,4], optical cavity QED has now reached a state where experiments can be performed with just one atom, without the need of averaging over an ensemble of single atoms. Moreover, cavity QED experiments with strong light-matter coupling can now be performed in a novel quantum nonlinear regime where transitions between atom-cavity states are driven by two photons [5]. In this regime the photons emitted by the atom-cavity system show a strong tendency to arrive in pairs [6]. This might facilitate a two-photon light source or an interaction between two photons, all controlled by a single atom. The talk will highlight some recent experiments along these lines.

[1] M. Hijlkema et al., "A single-photon server with just one atom," Nature Phys. 3, 253 (2007).
[2] J. Bochmann et al., "Fast Excitation and Photon Emission of a Single-Atom-Cavity System," PRL 101, 223601 (2008).
[3] T. Wilk et al., "Single-atom single-photon quantum interface," Science 317, 488 (2007).
[4] B. Weber et al., "Photon-photon entanglement with a single trapped atom," PRL 102, 030501 (2009).
[5] I. Schuster et al., "Nonlinear spectroscopy of photons coupled to one atom," Nature Physics 4, 382 (2008).
[6] A. Kubanek et al., "Two-photon gateway in one-atom cavity quantum electrodynamics," PRL 101, 203602 (2008).

Single atom - single photon interaction

J. Eschner, F. Rohde, C. Schuck, M. Hennrich, M. Almendros, A. Haase, N. Piro, F. Dubin, J. Huwer

ICFO - The Institute of Photonic Sciences, Barcelona, Spain

Experiments are reported where single trapped ions interact with single photons. In one experiment, we generate single photons by a spontaneous Raman transition in a single Ca+ ion, reaching efficiencies and properties comparable to cavity-QED set-ups. In another experiment we demonstrate the absorption by a single ion of single photons from a down-conversion source which has been made narrowband, tunable, and resonant with the D-P transition in Ca^+ at 850nm. The latter experiment is a first step towards exploring schemes of photon-to-atom entanglement transfer.

Random Numbers from Bell's Theorem

Antonio Acin

ICFO - The Institute of Photonic Sciences, Barcelona, Spain

We consider graph states of arbitrary number of particles undergoing generic decoherence. We present methods to obtain lower and upper bounds for the system's entanglement during the evolution in terms of that of considerably smaller subsystems. For an important class of noisy channels, namely the Pauli maps, these bounds coincide and thus provide the exact analytical expression for the entanglement. All the results apply also to some families of (mixed) graph-diagonal states, and hold true for any entanglement measure.

Noise characterization and benchmarking for quantum devices

Raymond Laflamme, Martin Laforest, Colm Ryan

Institute for Quantum Computing University of Waterloo ON Canada, N2L 3G1

Quantum error correction and its fault tolerant extension lead to the accuracy threshold theorem which says that despite some noise, at a level below the threshold, it is still possible to quantum compute efficiently. Underlying this theorem is an assumption on noise models that hopefully are physically reasonable. This talk will give a method to learn about the noise model for quantum information processing device with having in mind quantum error correction. Standard methods for measuring the noise are based on quantum process tomography and require an exponentially large number of experiments. I will describe protocols that will determine efficiently the probability of k errors independently of which qubit is affected and which type of error it is for memory based on the ideas described in Emerson et al. (Science 317, 1893, 2007). I will also characterization of errors for one and two bits gates based on the work of Knill (arXiv:0707.0963). I will also describe work on benchmarking of quantum gates that indicates whose goals is to assess the performance of quantum information processors (arXiv:0808.3973). I will give an overview of experimental implementation on these ideas using NMR in both the liquid and solid-state.

Index Theory of QCAs: the next dimensions

V. Nesme[1], RF Werner[2]

(1) LU Hannover
(2) TU Braunschweig

For cellular automata in one lattice dimension the index is a parameter, which describes the amount of quantum information moved in each dynamical step. It is a locally computable invariant, i.e., even if there is no translation invariance in the system, it can be computed from the local transition rules anywhere in the chain. At the same time the index, a positive rational, labels the connected components in the group of cellular automata. We argue in this talk that a quantity with similarly strong properties does not exist for higher dimensional systems, unless we restrict to the translation invariant case. Candidates for an index quantity are presented, together with some partial results.

Superadditivity of data transfer via quantum channels

Pawel Horodecki [1,2]

(1) Faculty of Applied Physics and Mathematics, Gdansk University of Technology, Gdansk, Poland
(2) National Quantum Information Centre of Gdansk, Sopot ul. W. Andersa 27, Poland

We shall recall the notion of superadditivity in data transfer in quantum communication called also activation effect. We shall review activation effects in quantum capacities presenting in particular construction of channels [1],[2] leading to most powerful effect of this type [3]. Then we shall present superadditivity in classical capacities of quantum multi-access channel which is a resource for quantum networks [4]. Remarkably this is the first improvement of classical data transfer without need of quantum memory. Finally we shall report its analogs in continuous variables channels and discuss some of their features [5].
Recent part of the work was done in collaboration with L. Czekaj, R. Chhaylany and J. Korbicz.
The work was supported by EC through SCALA project and by LFPPI network.
[1] K. Horodecki et al., Phys. Rev. Lett., vol. 94, 160502, (2005).
[2] K. Horodecki et al., IEEE Trans. Inf. Theory, vol. 54, 2621 (2008).
[3] G. Schmidt, J. Yard, Science, vol. 321, 1812 (2008).
[4] L. Czekaj, P. Horodecki, arXiv:0807.3977 (2008).
[5] L. Czekaj, J. Korbicz, R. Chhaylany, P. Horodecki, in preparation (2009).

Creation of pseudo bound entanglement in NMR quantum computing

Hermann Kampermann[1], Xinhua Peng[2,3], Dieter Suter[2], Dagmar Bruss[1]

(1)Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf
(2)Experimentelle Physik IIIa, Technische Universität Dortmund
(3)Hefei National Laboratory for Physical Sciences, University of Science and Technology of China

We use Nuclear Magnetic Resonance (NMR) to experimentally generate a three qubit pseudo bound entangled state, i.e. a state which is non-distillable but nevertheless entangled. We characterize the produced state via state tomography to show that the pure part has a positive partial transposition with respect to any bipartite splitting and we use the concept of witness operators to prove its entanglement.

List of posters

1 - **Dorit Aharonov** *Quantum Hamiltonian Complexity*

2 - **David Allcock** *Segmented Ion Traps for Quantum Computing*

3 - **Marc Almendros** *Single photon source for ion trap quantum networks*

4 - **Remigiusz Augusiak** *Generalized entropic inequalities: Stronger measurable criteria for separability of bipartite quantum states*

5 - **Almut Beige** *Entangling distant quantum dots using classical interference*

6 - **Joerg Bochmann** *Shaping the Phase of a Single Photon*

7 - **Lukas Brandt** *Manipulation of atoms with optical tweezers*

8 - **Sibylle Braungardt** *Fermion and spin counting in strongly correlated systems*

9 - **Jonathan Busch** *Turning two bad cavities into one good cavity*

10 - **Jianming Cai** *Entanglement in Biological Systems*

11 - **Tommaso Calarco** *Controlled atom-ion entanglement*

12 - **Jai-Min Choi** *Single Atom Interferometry via Quantum Transport*

13 - **Gabriele De Chiara** *Structural phase transitions in ion crystals*

14 - **Gemma De las Cuevas** *Unifying all classical spin models in a Lattice Gauge Theory*

15 - **Jerome Dilley** *Developing atom-photon interfaces for single-photon generation and storage*

16 - **André Eckardt** *Exploring frustrated quantum antiferromagnetism with ultracold atoms in shaken optical lattices*

17 - **Martin Enderlein** *Perspectives of simulating spin-Boson systems with trapped ions*

18 - **Jerome Esteve** *Squeezeing and entanglement in a BEC*

19 - **Charles Evellin** *Towards Entanglement of Two Individual ^{87}Rb Atoms Using the Rydberg Blockade*

20 - **Søren Gammelmark** *Quantum Learning by Measurement and Feedback*

21 - **Rene Gerritsma** *High fidelity entangling gate on trapped ions*

22 - **Otfried Guehne** *Decoherence of multipartite entanglement*

23 - **Christine Guerlin** *Cavity optomechanics with a Bose-Einstein condensate*

24 - **Birger Horstmann** *Simulation of an Acoustic Black Holes on an Ion Ring*

25 - **Gerhard Huber** *Employing Trapped Cold Ions to Verify the Quantum Jarzynski Equality*

26 - **Thomas Huber** *Demonstration of a geometric two ion/qubit phase gate on the radial modes of motion*

27 - **Tobias Kampschulte** *Quantum jumps and continuous spin measurement in a strongly coupled atom-cavity system*

28 - **Adrian Kantian** *Preparing Excited Many-Body States: The η-state as an experimental example*

29 - **Joanna Kenner** *Atoms in micro-fabricated optical cavities*

30 - **Matthias Kleinmann** *Deterministic purification of an entangled state using a single copy*

31 - **Barbara Kraus** *State preparation using dissipation and unitaries*

32 - **Jens Kruse** *Quantum Information Processing with Atoms in Arrays of Dipole Potentials*

33 - **Wolfgang Lange** *Photon-mediated entanglement of trapped ions*

34 - **Daniel Ljunggren** *Developing atom-photon interfaces for single-photon generation and storage*

35 - **Johannes Majer** *Hybrid Quantum Systems: Integrating Atomic and Solid-State Qubits*

36 - **Irene Marzoli** *Perfect state transfer and entanglement generation and distribution in FM long-range interacting spin chains*

37 - **Pietro Massignan** *p-wave superfluidity and Topological Quantum Computation in a Bose-Fermi mixture*

38 - **Markus Müller** *Mesoscopic Rydberg gate based on Electromagnetically Induced Transparency*

39 - **Dieter Meschede** *Single atom for QIP*

40 - **Francesco Minardi** *Few-body physics in an ultracold Bose-Bose mixture*

41 - **Simone Montangero** *Optimized atom transport for quantum gates in optical lattices*

42 - **Martin Muecke** *Fast Excitation and Photon Emission of a Coupled Atom-Cavity System*

43 - **Michael Murphy** *Communicating at the quantum speed limit using optimal control*

44 - **Karim Murr** *Two Photons strongly coupled to one atom in cavity quantum electrodynamics*

45 - **Alice Myerson** *High-Fidelity Readout of Trapped-Ion Qubits and Qunybbles*

46 - **Antonio Negretti** *Atomic Schroedinger cat states via optical probing*

47 - **Robert Nyman** *Cold-atom experiments with integrated optics*

48 - **Simone Paganelli** *Mesoscopic entanglement in cold gases*

49 - **Nicolas Piro** *A single ion interacting with single spontaneous parametric down-conversion photons*

50 - **Ulrich Poschinger** *A Spin Qubit in a Segmented Micro-Ion Trap*

51 - **Uffe Vestergaard Poulsen** *Small atomic ensembles interacting with light*

52 - **Guido Pupillo** *Quantum phases of strongly interacting polar molecules*

53 - **Jakob Reichel** *Single atom preparation on atom chips*

54 - **Stephan Ritter** *Entanglement distribution between a trapped atom and two photons*

55 - **Matteo Rizzi** *Quantum-Hall States in Cold Atomic Rotating Traps with Strong Dissipation*

56 - **Carles Rodó** *Operational Quantification of Continuous-Variable Correlations*

57 - **Marco Roncaglia** *Rapidly-converging methods for the location of quantum critical points*

58 - **Roman Schmied** *Optimal Surface-Electrode Trap Lattices for Quantum Simulation with Trapped Ions*

59 - **Hector Schmitz** *A Quantum Random Walk in a Paul Trap*

60 - **Christian Schneider** *Towards a two-dimensional lattice of spins*

61 - **Volkher Scholz** *Complexity of lattice time evolutions*

62 - **Heike Schwager** *A quantum interface between light and nuclear spins in quantum dots*

63 - **Danny Segal** *Ion shuttling and quantum jump statistics for Ca+ ions in a miniature Penning trap array*

64 - **Zahra Shadman** *On superdense coding with noisy channels*

65 - **Yvan R.P. Sortais** *Investigation of the Energy Distribution and Cooling of a Single Atom in an Optical Tweezer*

66 - **Giovanni Vacanti** *Cooling atoms into entangled states*

67 - **James Wootton** *Universal quantum computation with the $D(S_3)$ anyon model*

68 - **Shengjun Wu** *Entropic uncertainty and information complementarity*

69 - **Susanne Yelin** *Optical quantum computing using ultracold polar molecules*

70 - **Bruno Zimmermann** *Microscopy of a molecular 6Li-BEC*

71 - **Stefano Zippilli** *Photonic interfaces based on single trapped atoms*

Poster session

1 - Quantum Hamiltonian Complexity

Dorit Aharonov

The Hebrew University of Jerusalem

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2 - Segmented Ion Traps for Quantum Computing

D. T. C Allcock, A. H. Myerson, M. J. Curtis, D. J. Szwer, N. M. Linke, G. Imreh, J. A. Sherman, S. C. Webster, D. J. Stacey, D. M. Lucas, A. M. Steane

Centre for Quantum Computation, Clarendon Laboratory, University of Oxford, UK

We report the successful loading of $^{40}Ca^{+}$ ions in two segmented radio frequency traps. Ion traps have been used to demonstrate coherent manipulation of the quantum states of a small number of ion qubits. Segmented electrodes incorporated into the structure of these traps are designed to allow for the creation of multiple trapping regions and ion transport along the axis of the trap. The development of these techniques should open the possibility of greatly expanding the number of ion qubits under simultaneous coherent control.
The first trap was built on a sub-millimetre scale by the University of Liverpool. This is intended to be an intermediate step in adapting techniques of ion transport to micro-scale traps without the attendant high heating rates and low trap depths. We will report on trapping and initial experiments in this trap.
The Second trap is a micro-scale, planar, chip-top trap fabricated by Sandia National Laboratories. Scaling down the trap size presents new challenges including increased heating rates and reduced trap depth. This trap forms part of a broader investigation into microfabricated planar traps at Oxford. This project also incorporates gold-on-quartztraps that have been fabricated in-house and the next generation of traps from Sandia that are currently in development. Progress on these traps will be reported on also.

3 - Single photon source for ion trap quantum networks

M. Almendros, F. Rohde, C. Schuck, J. Huwer, N. Piro, M. Hennrich, F. Dubin and J. Eschner

ICFO - The Institute of Photonic Sciences Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

We report on an experiment where a single calcium ion is converted into a bright source of single photons with adjustable bandwidth. The experimental setup consists of two linear Paul traps mounted in vacuum vessels separated by approximately one meter. Both traps are surrounded by two high numerical aperture HALO-lenses covering 8% of the total solid angle. As for ions embedded in an optical cavity, such HALO-lenses allow us to achieve a large photon scattering rate into the optical mode which we analyze. We trigger the emission of single photons on the $P_{1/2}$ - $S_{1/2}$ electronic transition via spontaneous Raman scattering. Control of the infrared pulse allows us to engineer the coherence of the emitted photons. While spontaneous emission in principle sets the linewidth to 20 MHz, the use of spontaneous Raman scattering largely overcomes this limitation. Indeed, the time distribution of emitted photons can be varied from the nanosecond to the microsecond timescales. In the latter case, the coherence of heralded photons is comparable to atomic devices based on high finesse cavities. Furthermore, we reach a detection rate in a single-mode which is also comparable to atom-cavity systems.

4 - Generalized entropic inequalities: Stronger measurable criteria for separability of bipartite quantum states

Remigiusz Augusiak[1], Julia Stasinska[2]

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Recently it was shown that if a given state fulfills the reduction criterion, it must also satisfy the known entropic inequalities. The natural question arises as to whether it is possible to derive some scalar inequalities stronger than the entropic ones, assuming that stronger criteria based on positive but not completely positive maps are satisfied. A positive answer to this question is given. Using arbitrary positive maps we present various methods leading to new entropic or entropic-like inequalities. Interestingly, the new inequalities, unlike the standard ones, can detect bound entanglement efficiently. Moreover, as in the case of the standard entropic inequalities they can be written in the form of a mean value of a multicopy entanglement witnesses. This gives possibilities of future experimental realization. The inequalities are investigated on some particular class of states.

5 - Entangling distant quantum dots using classical interference

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We show that it is possible to employ reservoir engineering to turn two distant and relatively bad cavities into one good cavity with a tunable spontaneous decay rate [1]. As a result, quantum computing schemes, that would otherwise require the shuttling of atomic qubits in and out of an optical resonator, can now be applied to distant quantum dots. To illustrate this we transform a recent proposal to entangle two qubits via the observation of macroscopic fluorescence signals [2] to the electron-spin states of two semiconductor quantum dots. Our scheme requires neither the coherent control of qubit-qubit interactions nor the detection of single photons. Moreover, the scheme is relatively robust against spin-bath couplings, parameter fluctuations, and the spontaneous emission of photons.
[1] J. Busch et al., Phys. Rev. A 78, 040301(R) (2008).
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6 - Shaping the Phase of a Single Photon

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We report on the controlled phase shaping of a light pulse containing a single photon. The single photon is sent through a fiber electro-optical modulator, and the applied phase change is confirmed via interference with a second unmodulated reference photon. According to Hong et al. [1], coalescence is expected for indistinguishable photons. This effect is insensitive to shot-to-shot phase changes but depends on phase changes that occur during the evolution of the light pulse [2]. For instance, the application of a sudden pi-phase change in the middle of the photon wave packet results in maximally distinguishable photons and, hence, a disappearance of the interference effect. However, a time-resolved measurement proves that this is caused by averaging over two subgroups that show clear photon coalescence and anticoalescence, respectively. Moreover, our scheme allows for arbitrary phase shapes. For example, a linear phase ramp represents a change in the frequency of the photon, and results in characteristic oscillations in the time-resolved two-photon interference [2].

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7 - Manipulation of atoms with optical tweezers

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The controlling and positioning of single atoms [1,2] has been the dream for the past decades. This is of interest for quantum engineering and quantum computation. The ultimate goal is to position single atoms with nanometric precision, for example for positioning single atoms into optical cavities [3]. Furthermore arbitrary potential landscapes can be created, so the dynamics of individual atoms can be controlled and observed. By realising controlled collision collisions or cavity-mediated atom-atom interaction, entangled cluster states can be realised as a resource for one-way quantum computing [4].

We present a new scheme which allows to arbitrarily and independently manipulate the positions and motional properties of single trapped atoms. Cold atoms are loaded from a magneto optical surface trap [5] into an array of dipole-force traps, which act like optical tweezers. This array of dipole-force traps is generated by imaging the intensity distribution of a spatial light modulator with an isoplanatic optical system [6] into the vacuum chamber and is thus forming the optical tweezers.

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8 - Fermion and spin counting in strongly correlated systems

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We apply the atom counting theory to strongly correlated Fermi systems and spin models, which can be realized with ultracold atoms. The counting distributions are typically sub-Poissonian and remain smooth at quantum phase transitions, but their moments exhibit critical behavior, and characterize quantum statistical properties of the system. Moreover, more detailed characterizations are obtained with experimentally feasible spatially resolved counting distributions.

9 - Turning two bad cavities into one good cavity

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Over the last years, several groups have succeeded in building optical cavities which operate in the strong coupling regime. However, the decay rates of these cavities are still too large for many quantum technological applications. To overcome this problem, we discuss the possibility to realise an optical cavity mode with a tunable spontaneous decay rate by interfering the light from two distant cavities [1]. System reservoir engineering results in the creation of two independently decaying common cavity field modes. One of them can be removed effectively from the evolution of the system via overdamping. The life time of the remaining mode is only limited by absorption in the outcoupling mirrors of the resonators.
[1] J. Busch et al., Phys. Rev. A 78, 040301(R) (2008)

10 - Entanglement in Biological Systems

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We demonstrate that entanglement can persistently recur in an oscillating two-spin molecule that is coupled to a hot and noisy environment, in which no static entanglement can survive. The system represents a non-equilibrium quantum system which, driven through the oscillatory motion, is prevented from reaching its (separable) thermal equilibrium state. Environmental noise, together with the driven motion, plays a constructive role by periodically resetting the system, even though it will destroy entanglement as usual. As a building block, the present simple mechanism supports the perspective that entanglement can exist also in systems which are exposed to a hot environment and to high levels of de-coherence, which we expect e.g. for biological systems. Our results furthermore suggest that entanglement plays a role in the heat exchange between molecular machines and environment. Experimental simulation of our model with trapped ions is within reach of the current state-of-the-art quantum technologies.

11 - Controlled atom-ion entanglement

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We propose to unite atoms and ions in one setup to combine their advantages for scalable quantum information processing. A possible setup consists of a register of atom-qubits stored in an optical lattice with a movable ion carrying information and creating long distance entanglement between the atoms. The basic ingredient for this scheme is the ability to perform controlled atom-ion interaction in traps. We investigate the controlled collisions between a single trapped atom and a single trapped ion.
We model the atom-ion interaction by the long-range $1/r^4$ polarization potential combined with a quantum-defect parameter as a boundary condition at the origin. The quantum-defect parameter represents the phase accumulated by the wavefunction at small distances. The essential parameters for the quantum-defect theory are the singlet and triplet scattering lengths. These quantities are not yet known but can be measured in upcoming experiments. In general a Multichannel Quantum-Defect Theory (MQDT) is needed for describing the system. For specific scattering lengths we formulate an effective single channel model.
The goal of this work is to realize a two-qubit phase gate and therefore provide the basic ingredient of quantum computation for the system under consideration. For one realistic combination of singlet and triplet scattering length an adiabatic quantum gate process is calculated numerically. This process is optimized and accelerated with the help of optimal control techniques.

12 - Single Atom Interferometry via Quantum Transport

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For the realization of experimental testbed for quantum computation[1] we have developed a one dimensional optical lattice system with state selective transportability[2] of single neutral atoms, which will enable us to generate entanglement between atoms[2] and cluster states[3]. Besides the prospect of quantum state engineering, state selective transport allows to study intriguing single particle phenomena such as a quantum walk [4] or a single trapped atom interferometer, emerging from the wave-like properties of single atoms Recently we have realized the detection of atom pair separations down to nearest neighbors in our optical lattice(λ /2 = 433 nm)[5] and we observed state dependent transport with 96 % fidelity per one potential transport. With this ability the spatial distribution of a single atomic wavefunction can be precisely studied after sequential coherent splitting and recombining. Furthermore, we have developed a novel method of microwave sideband cooling of single atoms into the axial vibrational ground state of the optical lattice, allowing for controlled coherent motional dynamics of single neutral atoms. We will present experimental demonstration of state selective quantum transport and single atom interferometry.

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13 - Structural phase transitions in ion crystals

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A chain of singly-charged particles, confined by a harmonic potential, exhibits a sudden transition to a zigzag configuration when the radial potential reaches a critical value, depending on the particle number. Here we show that this structural change is a phase transition of second order, whose order parameter is the crystal displacement from the chain axis. We study analytically the transition using Landau theory and find full agreement with numerical predictions. Our theory [1] allows us to determine analytically the system's behaviour at the transition point. In addition, we show that the statistical properties of a Coulomb crystal can be measured by means of a Ramsey interferometry procedure performed on the spin of one ion in the chain [2]. The ion spin, constituted by two internal levels of the ion, couples to the crystal modes via spatial displacement induced by photon absorption. The loss of contrast in the interferometric signal allows one to measure the autocorrelation function of the crystal observables. Close to the critical point, where the chain undergoes a second-order phase transition to a zigzag structure, the signal gives the behaviour of the correlation function at the critical point.

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14 - Unifying all classical spin models in a Lattice Gauge Theory

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We show that the partition function of all classical spin models, including all discrete Standard Statistical Models and all abelian discrete Lattice Gauge Theories (LGTs), can be expressed as a special instance of the partition function of the 4D Z_2 LGT. In this way, all classical spin models with apparently very different features are unified in a single complete model, and a physical relation between all models is established. As applications of this result, we present a new method to do mean field theory for abelian discrete LGTs with d > 3, and we show that the computation of the partition function of the 4D Z_2 LGT is a computationally hard (#P-hard) problem. We also extend our results to abelian continuous models, where we show the approximate completeness of the 4D Z_2 LGT. All results are proven using quantum information techniques.

15 - Developing atom-photon interfaces for single-photon generation and storage

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University of Oxford

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16 - Exploring frustrated quantum antiferromagnetism with ultracold atoms in shaken optical lattices

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Strong time-periodic potential modulations can be a robust and powerful tool for the manipulation of many-body systems as they are realized experimentally with ultracold atoms. Such control schemes are reminiscent of manipulating internal atomic or molecular degrees of freedom by means of coherent radiation, and we describe them theoretically by an approach similar to the dressed atom picture. A striking example is given by a recent experiment: For bosonic atoms in an optical lattice it has been observed that the quantum phase transition from a superfluid to a Mott-insulator (and back) can be induced by smoothly switching on (and off again) the amplitude of a time-periodic acceleration of the whole lattice potential [Zenesini et al., arXiv:0809.0768]. This phenomenon relies on a complex dynamics being a combination of both diabatic and adiabatic following of many-body Floquet states [PRL 95, 260404 (2005) & PRL 101, 245302 (2008)]. In this contribution we propose a further application, namely the realization of a system of repulsively interacting bosons in a triangular lattice potential with the tight-binding hopping matrix elements being effectively positive in response to suitable time-periodic forcing. Our scheme allows to study quantum frustration in the motional degrees of freedom of many bosonic atoms, with currently available experimental setups. By controlling an anisotropy in the hopping matrix elements, it should be possible to switch between different ordered and quantum disordered ground states (cf. [Schmied et al., NJP 10, 045017 (2008)]).

17 - Perspectives of simulating spin-Boson systems with trapped ions

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Under certain conditions, the Hamiltonian describing the electronic structure as well as the Coulomb interaction of trapped ions resembles the spin-Boson Hamiltonian which, e.g., describes quantum dissipation in solid-state physics. We aim for a quantum simulation where the spin is represented by two laser-coupled electronic levels of one ion and the phonons in a crystalline chain of ions play the role of the Bosonic bath [1]. Since trapped atomic ions provide a very clean system with a wide range of tunable parameters, this might also allow the experimental access to the strong coupling regime of the spin-Boson model (SBM), inaccessable in typical solid-state systems.
Here we would like to discuss interesting features of the SBM and the perspectives of simulating them in our setup [2]. Since we recently achieved the initialisation of five ions in the radial motional ground state, we hope to observe behaviour characteristic for the SBM in a feasibility study.

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18 - Squeezeing and entanglement in a BEC

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Entanglement is a resource that allows the improvement of precision measurements beyond the conventional bound reachable by classical means. In an atomic interferometer, the standard quantum limit can be overcome by feeding the two input ports with quantum-entangled states, in particular spin squeezed states. Bose-Einstein condensates of ultracold atoms are considered good candidates to provide such states involving a large number of particles. In this poster, we demonstrate their experimental realization by splitting a condensate in a few parts using a lattice potential. Site resolved detection of the atoms allows the measurement of the conjugated variables atom number difference and relative phase. The observed fluctuations imply entanglement between the particles, a resource that would allow a precision gain of 3.8 dB over the standard quantum limit for interferometric measurements.

19 - Towards Entanglement of Two Individual ^{87}Rb Atoms Using the Rydberg Blockade

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Our experiment is designed to trap individual ^{87}Rb atoms in optical tweezers, manipulate the qubit that is encoded in the hyperfine levels of their ground states, and move them around without losing their conference[1]. Together with a deterministic scheme that entangles two atoms, all the necessary tools for quantum computing will be completed. In order to achieve this goal we use the Rydberg blockade which is one of the most promissing ways to deterministically entangle two or more atoms and to drive fast quantum gates[2][3]. A microscope objective with a high numerical aperture allows us to focus two dipole trap beams to waists of less than μm, which guarantees the trapping of only one atom per trap[4]. We can chose the distance between the two atoms, ranging from $4\mu m$ to $20\mu m$. We picked the Rydberg state $|r\rangle = |58d_{3/2}, F = 3, m_F = 3\rangle$. Due to a large dipole-dipole interaction, the doubly excited state $|rr\rangle$ is shifted of about 50 MHz when the atoms are $4\mu m$ apart. Therefore, lasers that excite a single atom into the Rydberg state cannot excite both atoms at the same time. This effect is called Dipole blockade. Our excitation scheme is as follows. After optically pumping the atom in the state $|g\rangle = |5s_{1/2}, F = 2, m_F = 2\rangle$, we drive a two-photon transition using a π-polarized laser close to the D1-line of Rb (795 nm) which is detuned by 400 MHz with respect to the $|5p_{1/2}, F = 2\rangle$ level and a second σ_+ -polarized laser at a wavelength of 475 nm. We observe that the excitation of both atoms at the same time is largely suppressed[5][6]. In addition we find that the Rabi frequency for oscillations between the ground state $|gg\rangle$ towards one and only one atom excited in the Rydberg state is $\sqrt{2}\Omega$, where Ω is the Rabi frequency for oscillation to the Rydberg state for one atom alone. This enhancement of a factor $\sqrt{2}$ shows that we obtained the entangled state $|\psi\rangle = \frac{1}{\sqrt{2}}(|gr\rangle + e^{i\mathbf{k}\Delta\mathbf{r}}|rg\rangle)$, where $\mathbf{k}$ is related to the wave vectors of the exciting lasers and $\Delta\mathbf{r}$ is the distance between the atoms. However the variation of the interatomic distance from shot-to-shot leads to a random phase in the produced entangled state. As a consequence any Bell test like measurement or state tomography would give the same results as completely mixed states. We are now working on mapping the Rydberg state onto another ground state $|g'\rangle$. If we can do this fast enough so that the atoms do not move, this random phase must cancel. The resulting state is then the entangled state $(|gg'\rangle + |g'g\rangle)/\sqrt{2}$. Since we have Raman beams that individually address the atoms and drive Raman transitions between the hyperfine levels of the $5s_{1/2}$ ground state they will be used to do the rotations of the measurement basis for a Bell test or for state tomography. The status of the experiment will be reported.

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20 - Quantum Learning by Measurement and Feedback

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We investigate an approach to quantum computing in which quantum gate strengths are parametrized by quantum degrees of freedom. The capability of the quantum computer to perform desired tasks is monitored by measurements of the output and dually improved by successive feedback odifications of the coupling strength parameters. Our proposal only uses information available in an experimental implementation, and is emonstrated with simulations on search and factoring algorithms.

21 - High fidelity entangling gate on trapped ions

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In ion trap based quantum information processing, faithful initialization, read out and high fidelity single qubit operations have been demonstrated over the last years. A major hurdle remaining is the implementation of a high fidelity entangling gate, capable to meet the requirements set for quantum error correction. Recently we implemented an entangling gate operating on two $^{40}Ca^{+}$ ions, creating Bell states with a so far unmatched fidelity of 0.993(1). We have extended the gate to act on three ions to create GHZ states with a fidelity of 0.978. In these experiments, the qubit was formed by two electronic states separated by an optical transition, limiting the achievable coherence times. In a new experiment we perform the entangling gate on two $^{43}Ca^{+}$ ions. This makes it possible to encode the quantum information in two hyperfine clock states. In this way coherence times of up to 80 ms or 10^3 times the gate duration are achieved. We use the gate to create Bell states with a fidelity of 0.967(3).

22 - Decoherence of multipartite entanglement

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Decoherence of quantum states is a fundamental obstacle for implementations of quantum information processing. Therefore, it is interesting to know how the entanglement of a multiparticle quantum state is affected by decoherence and how this depends on the state and the number of qubits. This is, however, difficult to investigate, since most entanglement measures are practically impossible to compute for mixed states. In this contribution we present a method to determine the decay of quantum correlations as quantified by the geometric measure of entanglement under the influence of decoherence. With this, one can compare the robustness of entanglement in GHZ, cluster, W and Dicke states of four qubits and show that the Dicke state is most robust. Furthermore, the method allows to compare different decoherence models and to investigate the scaling of the entanglement decay for an increasing number of particles.

23 - Cavity optomechanics with a Bose-Einstein condensate

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In our experiment we study the coupling between a Bose-Einstein condensate and an ultrahigh-finesse optical cavity. The tremendous degree of control over atomic gases achieved in Bose-Einstein condensates combined with the rich field of cavity quantum electrodynamics opens access to a wealth of new physics, ranging from studies of the coupling between quantized light and coherent matter to the implementation of tools for quantum communication. In the dispersive regime, our system realizes a model of cavity optomechanics. This research field typically studies the coupling of the mechanical degree of freedom of one of the cavity mirrors to the light field via radiation pressure. In our case, the mechanical oscillation is given by a coherent and periodic density modulation of the atomic cloud driven by dipole forces due to the cavity light field. We have observed this density modulation and very strong optical nonlinearities, present even at the single photon level. Furthermore our micro-mechanical oscillator naturally starts in its ground state, from which a single motional excitation can cause a shift of the cavity resonance on the order of the cavity linewidth. Our system is therefore promising to study the quantum regime of cavity optomechanics. We hope to reveal signatures of the quantum nature of the light and matter fields in further experiments.

24 - Simulation of an Acoustic Black Holes on an Ion Ring

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In this article we present results on the simulation of acoustic black holes on an ion ring. Ion rings, which have already been realized experimentally, represent ion chains with periodic boundary conditions. If the ions are rotating with a stationary and inhomogeneous velocity profile, regions can appear, where the ion velocity exceeds the group velocity of the phonons. In these regions phonons are trapped like photons in black holes.
Exploiting this analogy known for hydrodynamic systems, we give evidence for the prediction of the thermal distribution of Hawking radiation and present a realistic experimental scenario to measure Hawking radiation. Thus, we propose for the first time an experiment to detect Hawking radiation in a discrete analogue of spacetime with a nonlinear dispersion relation.

25 - Employing Trapped Cold Ions to Verify the Quantum Jarzynski Equality

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We propose a scheme [1] to investigate the nonequilibrium work distribution [2] of a quantum particle under well controlled transformations of the external potential [3], exploiting the versatility of a single ion in a segmented linear Paul trap. We describe in detail how the motional quantum state of a single ion can be prepared, manipulated, and finally readout to fully determine the free energy difference in both harmonic and anharmonic potentials. Uniquely to our system, we show how an ion may be immersed in an engineered laser-field reservoir. Trapped ions therefore represent an ideal tool for investigating the Jarzynski equality [4] in open and closed quantum systems.

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26 - Demonstration of a geometric two ion/qubit phase gate on the radial modes of motion

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Phonons in a linear chain of ions can provide interactions/a data bus between spins/qubits for quantum simulations(QS)/computation(QC).
So far, experimentalists only exploit the axial degree of freedom in linear traps, i.e. the phonons of the axial normal modes of motion. We want to open up the radial degrees of freedom, exploring the(dis)advantages with respect to QC and QS. For an increasing amount of ions it becomes, for example, more difficult to place the ions at the correct relative positions to experience identical laser phases of a standing or travelling axially propagating wave, which provides the conditional motional excitations. Pushing the ions radially renders the system insensitive to the mutual ion distance. Additionally, the frequencies of the radial modes can be adjusted to be similar. The required ground state cooling of all motional modes might hence be possible by one common cooling cycle.
To calibrate our interactions for future QS, we implemented a two-qubit phase gate with a fidelity exceeding 90%. We are able to laser-cool five ions to the radial motional ground states, a first step towards simulations with increased amounts of ion spins required in QS of systems of interest, like the Bose-Hubbard Hamiltonian. It also gives perspectives to 2D lattices of spins provided in potential surface trap arrays.

27 - Quantum jumps and continuous spin measurement in a strongly coupled atom-cavity system

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In our experiment, we study the coherent interaction between a predetermined, small number of atoms and the light field inside a high-finesse optical resonator in the strong coupling regime. To this end, we trap caesium atoms in a high-gradient magneto-optical trap and transport them into the center of the resonator mode, using an optical dipole trap [1].
By monitoring the transmission of a probe laser resonant with the cavity, we are able to measure the spin state of a single atom in a short time without changing it. Continuous observation reveals quantum jumps between the two hyperfine states. Utilizing this non-destructive detection method, we record the interaction induced normal mode splitting of the atom-cavity system by probing the atomic state.
We further demonstrate conditional dynamics of the internal states of multiple atoms, simultaneously coupled to the resonator field.
Our non-destructive state detection is the first step towards a quantum non-demolition measurement of the atomic spin as is required for probabilistic atom-atom entanglement schemes.
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28 - Preparing Excited Many-Body States: The η-state as an experimental example

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We show how to prepare a particular excited eigenstate of the Fermi-Hubbard model, the eta-condensate, using two-species fermionic atoms confined in optical lattices, assuming realistic experimental conditions. The aim of this work is for the η-condensate to serve as benchmark state for the ability of lattice-confined atoms to serve as a quantum simulator for the dynamics of the two-species Fermi-Hubbard model, which is of great interest in condensed matter theory. Towards this end, we simulate the formation of the η-condensate by adiabatic transfer, including the possibilities of defects and presence of a trapping potential, and calculate the effect of various possible error sources on the fidelity of the final state as well as experimentally measurable signatures.

29 - Atoms in micro-fabricated optical cavities

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Optical cavities offer an opportunity to enhance the interaction between atoms and light.
We use optical microcavities formed at one end by a micro-fabricated mirror etched on a silicon wafer. The other end of the cavity is a dielectric mirror glued onto the front facet of a single-mode optical fibre. This arrangement is inherently scalable and allows direct coupling of the cavity mode to the fibre, enabling efficient collection of photons emitted by atoms in the cavity.
Using this system, we are able to study the interaction between atoms and the cavity by detecting cavity-enhanced fluorescence. We present the latest results from this experiment.

30 - Deterministic purification of an entangled state using a single copy

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Two remote parties cannot prepare any entangled quantum state if the communication between them is limited to be classical. However, if both parties initially share an entangled state it is possible to prepare with a probability of one any state from a certain family of entangled states. While –by definition– the entanglement cannot increase in such a scenario, it might well be possible to achieve a pure final state, even if starting from a mixed initial state [1]. We consider conditions and examples for such purification protocols and study the interlink to the entanglement-preserving distinction of pure states [2].

[1] E. Chitambar et al., arXiv:0811.3739
[2] S. Cohen, Phys. Rev. A 75, 052313 (2007)

31 - State preparation using dissipation and unitaries

B. Kraus [1], H.P. Büchler [2], S. Diehl [1,3], A. Kantian [1,3], A. Micheli [1,3], C. Kruszynska [1], and P. Zoller [1,3]

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We investigate the possibility of using a dissipative process to prepare a quantum system in a desired state. We derive for any multipartite pure state a dissipative process for which this state is the unique stationary state and solve the corresponding master equation analytically. For certain states, like the Cluster states, we use this process to show that the jump operators can be chosen quasi–locally, i.e. they act non–trivially only on a few, neighboring qubits. We demonstrate the general formalism by considering MPS–PEPS states. In particular, we show that the ground state of the AKLT-model can be prepared employing a quasi-local dissipative process. Furthermore, we discuss a dissipatively driven Bose-Einstein Condensate, where for non-interacting atoms a pure state exhibiting long range order is generated as the steady state by quasi-local coupling to an environment with finite correlation length. Applying standard linearization schemes in the weakly interacting situations, allows us to determine the solution of the master equation, revealing a steady state with properties similar to bosons in thermal contact to a heat bath. Furthermore, we consider a special class of states, called locally maximally entangleable states and discuss their applications for quantum information tasks. The generation of those states using either dissipative processes, or unitary evolutions is presented.

32 - Quantum Information Processing with Atoms in Arrays of Dipole Potentials

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Quantum information processing with neutral atoms represents an important experimental approach complementing systems based on trapped ions. By using ultra-cold atoms in two-dimensional dipole trap arrays, one can realize highly controllable and scalable systems with long coherence times.
In our experiment, we use sets of optical micro-potentials created by micro-fabricated lens arrays as the architecture for a scalable quantum processor. Due to the large lateral separation of neighboring potential wells, each trap is individually addressable. For flexible architectures, we implement a liquid crystal display in front of a microlens array as a pixel-addressable intensity modulator. By this we are able to control each potential well separately and produce arbitrary trap configurations.
We demonstrate the flexible site-specific initialization and coherent manipulation of separated small ensembles of ^{85}Rb atoms in two-dimensional trap arrays by applying coherent Raman coupling between hyperfine ground states, representing the qubit states.
Advanced schemes for scalable atom observation allow us to detect single atoms in two-dimensional sets of dipole traps with high efficiency and reliability.

33 - Photon-mediated entanglement of trapped ions

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Ions confined in a radio-frequency trap are presently the most advanced system for quantum information processing. Quantum bits are stored and manipulated in the internal electronic states of the ions. One limitation is that quantum operations can be performed only locally. A significant gain is expected from connecting multiple processing nodes through quantum channels, capable of distributing quantum information over long distances. Obvious candidates for the realization of quantum links are photons, the qubit-carriers successfully employed in quantum communication. The principal challenge is to establish a coherent interface between photons and ions to reliably map quantum information between two systems which interact only weakly in free space.
Coherent coupling of single photons to ions has been achieved in cavity-QED by placing the ions in a high-finesse cavity. In this way, unprecedented control over the production of single photons was demonstrated [1]. By linking the two basis states of ionic qubits to different polarizations of the emitted light, atom-photon state mapping can be achieved which is in principle reversible. The technology has a number of potential applications: efficient distribution of entanglement among remote trapped ions can be achieved using either probabilistic (measurement-based) or deterministic schemes. The ultimate goal is to establish a quantum internet, in which qubits are transferred between distant quantum computers. These techniques are presently being implemented at the University of Sussex with trapped calcium ions coupled to a high-finesse infrared cavity.
[1] M. Keller, B. Lange, K. Hayasaka et al, Continuous generation of single photons with controlled waveform in an iontrap cavity system, Nature 431, 1075 (2004).

34 - Developing atom-photon interfaces for single-photon generation and storage

Jerome Dilley, Daniel Ljunggren, Peter Nisbet, Gunnar Langfahl, Genko Vasilev and Axel Kuhn

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Single-photon sources and quantum memories are essential components of future quantum networks. We present experimental work using two types of controlled atom-photon systems for their implementation. (i) Through the process of vacuum stimulated Raman scattering, single neutral atoms in optical cavities can produce photons with well defined temporal and spectral properties, which are (ii) suitable for storage in atomic ensembles using the effect of electromagnetically induced transparency (EIT). The first atom-photon system includes a magneto-optical trap and atomic fountain, which cool and launch rubidium atoms into a high-finesse cavity, enabling long interaction times between a single atom, laser control field, and cavity field, to deterministically produce single photons with a narrow frequency bandwidth. By precisely controlling the interaction, the quantum system of successively emitted (or absorbed) photons and atoms can become entangled, and thus act as an interface for flying and stationary qubits. To implement and verify storage in the second atom-photon system, the emitted photon's state is first written into the collective state of a hot ensemble of rubidium atoms, and then read out to check coherence with a successive (non-stored) emission. Theoretical work towards optimisation of the storage and retrieval process is presented.

35 - Hybrid Quantum Systems: Integrating Atomic and Solid-State Qubits

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For quantum information to emerge as a valuable technology, it is mandatory to pool the strengths of different systems to bridge their weaknesses. For example solid-state devices allow very fast processing and promise dense integration, but have very short coherence times. Atomic systems are slow, but exhibit very long coherence of quantum states if they are stored in hyperfine states. An ensemble of ultracold atoms would thus be an ideal quantum memory. Placing an ensemble of 10^6 ultracold atoms in the near field of a superconducting coplanar waveguide resonator (CPWR) with $Q \sim 10^6$ one can achieve strong coupling between a single microwave photon in the CPWR and a collective hyperfine qubit state in the ensemble with $g_{eff}/2\pi \sim 40$ kHz larger than the cavity line width of $k/2\pi \sim 7$ kHz. Integrated on an atomchip such a system constitutes a hybrid quantum device, which interconnects solid-state and atomic qubits.

36 - Perfect state transfer and entanglement generation and distribution in FM long-range interacting spin chains

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We investigate the most general conditions under which a generic N spin system achieves unitary fidelity and the shortest transfer time in transmitting an unknown input qubit. We individuate a set of maximum conditions which provides a deeper insight into spin system dynamics and lead us to point out an ideal spin system. However, these two spin system is unpractical due to the rapid decrease of interaction strength with distance. Therefore, we propose a scheme which, by means of a finite long-range interacting spin chain, allows to closely approach the ideal behaviour, while keeping the interaction strength still reasonably high. Our scheme is scalable, not experimentally demanding and easy to generalize to higher excitation subspaces. Moreover, our scheme, differently from other approaches to perfect state transfer, allows the channel to generate and distribute maximally entangled states. By these means we propose the double-hole chain as a channel for two uses, according to the time at which the measurement is performed.

37 - p-wave superfluidity and Topological Quantum Computation in a Bose-Fermi mixture

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p-wave superfluids of spinless fermions constitute a platform to develop Scalable Quantum Computing. These systems are particularly appealing because their excitations have a non-local "topological" character which provides an intrinsic protection from decoherence, thereby opening the way to Topological Quantum Computation. We show here how p-wave superfluidity may be obtained by means of a Bose-Fermi mixture in an optical lattice. The critical temperature T_C for this transition should be under experimental reach. In addition, we discuss how Universal Topological Quantum Computation may be physically implemented in these systems.

38 - Mesoscopic Rydberg gate based on Electromagnetically Induced Transparency

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We demonstrate theoretically a parallelized CNOT gate which allows to entangle a mesoscopic ensemble of atoms with a single control atom in a single step, with high fidelity and on a microsecond timescale. Our scheme relies on the strong and long-ranged interaction between Rydberg atoms triggering Electromagnetically Induced Transparency (EIT). By this we can robustly implement a conditional transfer of all ensemble atoms among two logical states, depending on the state of the control atom. As an application, a many body interferometer, which allows a comparison of two many-body quantum states by performing a measurement of the control atom, is presented. Perspectives of the gate as a building block for quantum simulators of Hamiltonians with few-body interactions are outlined.

39 - Single atom for QIP

Dieter Meschede

Universitaet Bonn

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40 - Few-body physics in an ultracold Bose-Bose mixture

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We report on the creation of heterospecies bosonic molecules. Using a resonantly modulated magnetic field, bosonic KRb dimers are associated from an ultracold Bose-Bose mixture of ^{41}K and ^{87}Rb close to Feshbach resonances. We determine the binding energy of the weakly bound molecular states depending on the Feshbach field and we explain nontrivial features of the association spectrum, as the broadening and the asymmetry due to the thermal distribution of the unbound atoms. Furthermore, next to the Feshbach resonance at 38 G, we observe heteronuclear Efimov resonances for both the KKRb and KRbRb channels.

41 - Optimized atom transport for quantum gates in optical lattices

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By means of optimal control techniques we model and optimize the control over the external quantum state of atoms trapped in adjustable optical potentials. We consider in detail the cases of both non interacting and interacting atoms moved between neighboring sites of a double-well optical lattice, which can be used for realizing two-qubit quantum gates with neutral atoms and to achieve interaction-mediated entanglement of atom pairs. The control sequences for the optical potential that we find with the optimization technique allow to perform the transport with significantly larger fidelity and on shorter times than one could obtain with processes based on adiabatic transport.

42 - Fast Excitation and Photon Emission of a Coupled Atom-Cavity System

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Single atoms coupled to optical cavities provide unique systems to study light-matter interaction in the quantum regime. Naturally, these systems are well suited for atom-photon entanglement and distributed quantum networks [1].
We report on the fast excitation of a single Rb atom coupled to an optical cavity using laser pulses much shorter than all relevant processes [2]. The system subsequently displays an oscillatory energy exchange between atom and cavity field leading to pronounced amplitude modulations of the emitted single photons [3]. We further show that the cavity frequency can be used as a parameter to design the single photon shape and spectrum, e.g. in a superpostion of two tunable frequencies.
[1] T. Wilk et al., Science 317, 488 (2007)
[2] J. Bochmann et al., Phys. Rev. Lett. 101, 223601 (2008)
[3] C. DiFidio et al., Phys. Rev. A 77, 043822 (2008)

43 - Communicating at the quantum speed limit using optimal control

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Optimal control theory is a promising candidate for a drastic improvement of the performance of quantum information tasks. We explore its ultimate limit in the case of a one-dimensional chain of coupled spin-1/2 particles, and demonstrate that it coincides with the ultimate speed limit allowed by quantum evolution (the quantum speed limit), such that optimal control reaches the best performance allowed by the laws of quantum mechanics.

44 - Two Photons strongly coupled to one atom in cavity quantum electrodynamics

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The interaction between photons and atoms plays an important role in fundamental physics. Understanding it contributes to the concrete development of quantum information technology. When the photons interact with two isolated internal states of one atom, the interaction mimics the spin-boson model of particle physics, thereby allowing one to address physics of importance even beyond atom optics. Of particular interest is the limit when the interaction becomes so strong that one, two or three photons bind to only one atom to form a new energy structure different from the sum of its parts. When one photon couples to the atom, the resulting interaction can be largely explained using Maxwell's classical theory. When two photons couple to the atom simultaneously, however, atomic and field quantization is required for the understanding of the structure of the system. Experimentally, at optical frequencies, such two-photon-one-atom states have never been observed until now. We report on two experiments [1,2] where such states are evidenced with a single rubidium atom cooled and trapped in a high-finesse optical cavity. The light transmitted through the cavity was detected in a Hanbury-Brown and Twiss configuration, allowing us to measure the coincidences between photon detection events as well as the overall transmitted intensity. In this contribution we show the advantages of a specially-developed scan technique to get clear spectroscopic evidence of the two-photon states [1]. Moreover, we measure a new photon-correlation function [2] which peaks if the two-photon states are excited; allowing us to demonstrate large bunching of cavity output photons at the two-photon resonance.

[1] I. Schuster, A. Kubanek, A. Fuhrmanek, T. Puppe, P. W. H. Pinkse, K. Murr, and G. Rempe, "Nonlinear spectroscopy of photons bound to one atom," Nature Physics 4, 382 (2008).
[2] A. Kubanek, A. Ourjoumtsev, I. Schuster, M. Koch, P.W.H. Pinkse, K. Murr, and G. Rempe, "Two-photon gateway in one-atom cavity quantum electrodynamics," Phys. Rev. Lett. 101, 203602 (2008).

45 - High-Fidelity Readout of Trapped-Ion Qubits and Qunybbles

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We have recently demonstrated single-shot qubit readout with a fidelity sufficient for fault-tolerant quantum computation [1]. For an optical qubit stored in the $(4S_{1/2}, 3D_{5/2})$ levels of a trapped Ca^{40} ion we achieve 99.991(1)% average readout fidelity in one million trials using time-resolved photon counting with a photomultiplier tube. An adaptive measurement technique allows 99.99% fidelity to be reached in a 145 μs average detection time. The main source of readout error is due to spontaneous decay of the of the $3D_{5/2}$ state which has a 1.2s lifetime. The readout errors for each state are therefore asymmetric: detection of the $4S_{1/2}$ state can be performed with over 99.9998% fidelity in an average time of 91us, whilst retaining 99.975(2)% for the $3D_{5/2}$ state in 292 μs. This asymmetry could be exploited for quantum error correction. In Ca^{43}, we propose and implement an optical pumping scheme to transfer a long-lived hyperfine qubit to the optical qubit, capable of a theoretical fidelity of 99.95% in 10 μs. We achieve 99.87(4)% transfer fidelity and 99.77(3)% readout fidelity. In addition, we present a demonstration of the high-fidelity readout of a four-qubit "qunybble" using an Electron-Multiplying CCD camera. We first investigate the readout of a single Ca^{40} ion using the camera, achieving a fidelity of 99.991(3)% for a single 400 μs exposure and a similar fidelity for a time-resolved analysis using six 200 μs exposure sub-frames. Secondly, we investigate the simultaneous readout of a string of four ions separated by $\sim$18 μm. Here, cross-talk between neighbouring ion images (present at the $\sim$2% level) might be expected to reduce the readout fidelity. In an experiment designed to measure the cross-talk error without the effect of decay from the $3D_{5/2}$ state (but with the same 400 μs exposure time), we find an average fidelity of 99.94(1)% per ion using a simple threshold to discriminate between ion states. We then show that by using a spatial maximum-likelihood analysis which takes into account the states of neighbouring ions, we are able to compensate for the cross-talk and achieve >99.999% readout fidelity (<1 error in 114606 trials). Together, these experiments imply a fidelity of 99.990(3)% for simultaneous qubit readout in an ion string.
This work was supported by EPSRC (QIP IRC), DTO, the European Commission (SCALA, MicroTrap), and the Royal Society.
[1] A. H. Myerson, et al., Phys. Rev. Lett. 100, 200502 (2008).

46 - Atomic Schroedinger cat states via optical probing

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We analyze the performance of a protocol to prepare an atomic ensemble in a superposition of two macroscopically distinguishable states [1]. The protocol relies on conditional measurements performed on a light field, which interacts with the atoms inside an optical cavity prior to detection, and we investigate cavity enhanced probing with continuous beams of both coherent and squeezed light.
[1] Anne E. B. Nielsen, Uffe V. Poulsen, Antonio Negretti, Klaus Mølmer, Atomic quantum superposition state generation via optical probing; arXiv:0812.4048.

47 - Cold-atom experiments with integrated optics

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This poster describes two of the experimental progams at Imperial which use integrated optics with laser-cooling and atom-chip technology: an atom chip with tapered fibres, and a chip with built-in optical waveguides.
Tapered fibres (which focus light to a 1.9 micron spot) were used in an attempt to trap and detect cold-atom clouds close to a chip surface. Magneto-optically trapped clouds were brought close to the fibre tips. As few as 30 atoms could be detected by fluorescence transmitted via the fibres, with trap lifetimes decreasing rapidly as atom-fibre distance decreased.
A commercially-built waveguide chip (Centre for Integrated Photonics, Ipswich, UK) has 12 parallel waveguides for 780-830nm light. A 20 micron deep, 16 micron gap has been etched transverse to the waveguides. We will use this chip in conjunction with a current-carrying sub-chip, capable of evaporative cooling in a magnetic trap. Bose-Einstein condensates will be introduced into the gap, then interrogated with light carried by the waveguides, and detected by the same means.

48 - Mesoscopic entanglement in cold gases

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Universitat Autónoma de Barcelona

It has been shown that two mesoscopic atomic samples can be entangled after the interaction with a detuned light beam and a following homodyne detection[1-2]. We propose a scheme to generalize this result and create entanglement between an arbitrary number of mesoscopic atomic samples prepared in optical micropotentials[3]. This setup provides a very versatile framework where a very rich physics can be explored. In particular, it is possible to create different kinds of entangled states such as bound states. Because of the scalability and the possibility of addressing every single trap, would also be possible to simulate new kinds of many-body systems.

[1]Jusgaard et al., Nature 413, 400 (2001);
[2]Duan et al.,PRL 85, 5643 (2000);
[3]A. Lengwenus et al., Appl. Phys. B 86, 377 (2007).

49 - A single ion interacting with single spontaneous parametric down-conversion photons

Nicolas Piro, Felix Rohde, Carsten Schuck, Marc Almendros, Jan Huwer, Albrecht Haase, Morgan W. Mitchell, Francois Dubin, and Jürgen Eschner

ICFO - The Institute of Photonic Sciences

We present a tunable, frequency-stabilized, narrow-bandwidth source of frequency degenerate, entangled photon pairs and their interaction with a single trapped ion. The source allows to resonantly address two D-P transitions in $^{40}Ca^{+}$ ions, at 850 and 854 nm. The absorption of the photons by the single ion is detected through quantum jumps.

50 - A Spin Qubit in a Segmented Micro-Ion Trap

Ulrich Poschinger, Gerhard Huber, Frank Ziesel, Markus Deiss, Max Hettrich, Ferdinand Schmidt-Kaler

Universität Ulm

Microstructured ion traps promise a way towards scalable quantum information and simulation and investigation of the quantum behavior of micro- and nano-objects. We present results for the preparation, readout, manipulation and decoherence of qubits in our segmented microtrap, where the qubit is encoded in the Zeeman levels of the groundstate of ^{40}Ca ions. The qubit manipulation is achieved by means of a Raman transition between the spin states, and a narrow optical quadrupole transition is used for auxiliary tasks. Furthermore, we show results for close-to groundstate cooling and the heating behaviour of the ions. Additionally, we present first results for transport operations.

51 - Small atomic ensembles interacting with light

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Collective effects can significantly enhance the emission and absorption of light by an ensemble of two-level atoms. This enables realistic protocols for storing a single photon in the ensemble even without the use of a cavity. We study the natural spatio-temporal modes of light interacting with various arrangements of atoms or ions. Introducing a time-dependence of the coupling as an extra handle, we show how one can shape these modes.

52 - Quantum phases of strongly interacting polar molecules

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We discuss how to realize quantum phases and quantum simulations with cold polar molecules prepared in the electronic and vibrational groundstate.

53 - Single atom preparation on atom chips

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A source providing a single atom in the ground state of a trap is the one tool that is still missing in the atom chip "toolbox" for quantum engineering. We work towards this goal using a using a novel fiber-based high-finesse cavity that we have developed and combined with an atom chip. This cavity has allowed us to study collective coupling of BECs, but it can also act as a high-contrast single atom detector. This is how we use it in the present experiment. We prepare a Bose-Einstein condensate inside the cavity mode, where we can position it in a single, well-defined antinode of the standing-wave cavity field. Then we prepare a single atom using a weak microwave pulse. The BEC serves as a reservoir; its atoms are initially in a state that is not resonant with the cavity mode. The microwave pulse transfers less than one atom on average to another hyperfine state, which is strongly coupled to the cavity mode. The atom can thus be detected, with high contrast, by observing the transmitted light of the cavity. In this way we demonstrate a non-deterministic single atom preparation method. It is expected to prepare the atom in the ground state of the trapping potential, as required for collisional phase gates. The method is nondeterministic because it produces zero atoms in most "shots". This is fully analogous to the attenuated laser pulses that are used to provide single photons in quantum key distribution. We are currently analyzing in more detail the atom number statistics of our source. Future work will be directed towards a deterministic source.

54 - Entanglement distribution between a trapped atom and two photons

Stephan Ritter, Bernhard Weber, Holger P. Specht, Tobias Müller, Jörg Bochmann, Martin Mücke, David L. Moehring, and Gerhard Rempe

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While atoms make an excellent qubit for the storage of quantum states, photons are naturally well suited for the distribution of quantum information. Therefore efficient atom-photon interfaces are an important prerequisite for distributed quantum computing networks. Here, we report on the implementation of a deterministic entanglement protocol. In a first step, entanglement between a single atom trapped within a high-finesse optical cavity and an emitted photon is created. Subsequently, the atomic quantum state is mapped onto a second photon, allowing for photon-photon entanglement. The entanglement has been verified using both a Bell inequality measurement and full quantum-state tomography [1]. Trapping of the atom within the cavity mode and repeated cooling stages result in an increase in the number of atom-photon entanglement events per atom by a factor of 10^5 compared to previous experiments [2]. In addition, the presence of exactly one atom in the cavity can be detected with greater than 99,% fidelity.

[1] B. Weber *et al.*, PRL (in press), arXiv:0811.3612 (2009).
[2] T. Wilk *et al.*, Science bf317, 488 (2007).

55 - Quantum-Hall States in Cold Atomic Rotating Traps with Strong Dissipation

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Bosonic gases made of cold atoms confined in harmonic traps at high rotation speeds, display a rich variety of fractional quantum Hall phases.
The paradigmatic example is the 1/2-Laughlin state where the energy contribution of two-body repulsion is minimized at the price of a high angular momentum. At filling fraction $\nu = 1$, it exists the Moore and Read paired state, also called Pfaffian state, which is known to have the lowest energy inside the kernel of 3-body pointlike interactions. The Pfaffian state plays an important role in topological quantum computation, since its anyonic excitations obey non-abelian braiding statistics. A considerable experimental effort with cold atoms has been spent in this direction, even if the quantum Hall regime seems to be quite elusive, so far. In this work, we first show numerically for few particles that elastic 3-body collisions stabilize the Pfaffian state for a wide interval of trap rotation speeds. Subsequently, we consider the more realistic situation of 3-body dissipation, which is tunable independently of the 2-body collisions and it is commonly considered an unwanted effect in physics of condensates since it yields to particle losses. By means of a quantum jump approach, it is shown that 3-body losses allow for designing some realistic strategies for preparing the Pfaffian state with a reasonably good fidelity. The mechanism of inducing Pfaffian-like correlations relies in the fact that dissipation suppresses 3-body superpositions, while permitting pairing. Finally, we examine the experimental observables that signal distinctive properties of the Pfaffian state.

56 - Operational Quantification of Continuous-Variable Correlations

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We quantify correlations (quantum and/or classical) between two continuous-variable modes as the maximal number of correlated bits extracted via local quadrature measurements. On Gaussian states, such "bit quadrature correlations" majorize entanglement, reducing to an entanglement monotone for pure states. For non-Gaussian states, such as photonic Bell states, photon-subtracted states, and mixtures of Gaussian states, the bit correlations are shown to be a monotonic function of the negativity. This quantification yields a feasible, operational way to measure non-Gaussian entanglement in current experiments by means of direct homodyne detection, without a complete state tomography.

57 - Rapidly-converging methods for the location of quantum critical points

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Analyzing in detail the first corrections to the scaling hypothesis, we develop accelerated methods for the determination of critical points from finite size data. The output of these procedures are sequences of pseudo-critical points which rapidly converge towards the true critical points. In fact more rapidly than previously existing methods like the Phenomenological Renormalization Group approach. Our methods are valid in any spatial dimensionality and both for quantum or classical statistical systems. Having at disposal fast converging sequences, allows to draw conclusions on the basis of shorter system sizes, and can be extremely important in particularly hard cases like two-dimensional quantum systems with frustrations or when the sign problem occurs. We test the effectiveness of our methods both analytically on the basis of the one-dimensional XY model, and numerically at phase transitions occurring in non integrable spin models. In particular, we show how a new Homogeneity Condition Method is able to locate the onset of the Berezinskii-Kosterlitz-Thouless transition making only use of ground-state quantities on relatively small systems.

58 - Optimal Surface-Electrode Trap Lattices for Quantum Simulation with Trapped Ions

Roman Schmied

Max Planck Institute of Quantum Optics

Trapped ions offer long internal state (spin) coherence times and strong interparticle interactions mediated by the Coulomb force. This makes them interesting candidates for quantum simulation of coupled lattices. To this end it is desirable to be able to trap ions in arbitrary conformations with precisely controlled local potentials. We provide a general method for optimizing periodic planar radio-frequency electrodes for generating ion trapping potentials with specified trap locations and curvatures above the electrode plane. A linear-programming algorithm guarantees globally optimal electrode shapes requiring only a single radio-frequency voltage source for operation. The optimization method also guarantees that final electrode shapes are smooth and exhibit low fragmentation. Such characteristics are desirable for practical fabrication of surface electrode trap lattices.

59 - A Quantum Random Walk in a Paul Trap

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We present the implementation of a quantum random walk in an ion trap. We use a single ion's motional amplitude to encode the steps of the walk. The two sides of a quantum coin are realized by two electronic states (qubit). The tossing of the coin is provided via a coupling of these two states. A pi/2-pulse allows for the preparation of the superposition state |head> and |tail>. A state dependend optical dipole force created by two Raman laser beams commits the steps.
Our experiment testifies for the signature of the quantum random walk in agreement with the theroretical predictions—the predictions for the occupation probabilities of the Hilbert space of motion (steps) and qubit (coin). We report on the limitations imposed by leaving the Lamb-Dicke-regime and identify a way to circumvent these limits with the objective to expand the number on possible steps.
The realisation of quantum random walks are expected to allow for new quantum algorithms which might outperform their classical counterparts.

60 - Towards a two-dimensional lattice of spins

Christian Schneider[1], Martin Enderlein[1], Thomas Huber[1], Hector Schmitz[1,2], Axel Friedenauer[1], and Tobias Schaetz[1]

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One of the state-of-the-art tools to investigate quantum algorithms/simulations is based on ions confined in a linear Paul trap. Recent experiments show that the bulky three-dimensional geometry of standard linear Paul traps can be translated into two-dimensional electrode setups on surfaces (but still being linear Paul traps) [1,,2]. Cryogenic conditions are shown to provide reduced heating rates allowing to further approach the surfaces [3]. A regular two-dimensional array of ions—small enough for sufficient interactions between the ions—could open a great new field of interesting experiments, e.g. the simulation of Quantum Spin Hamiltonians [4,5], like the Bose-Hubbard model [6], or spin frustrations. Based on the above developments we aim for realizing a surface trap allowing for the confinement of a two-dimensional ion crystal (being equivalent to a lattice of spins). Our first milestone is a proof-of-concept experiment with a 2×2 array of ions at mutual distances of 20μm.

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61 - Complexity of lattice time evolutions

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Evolutions of closed quantum systems are naturally described by possibly time dependent Hamiltonians. In agreement with the usual definition of gate complexity, the complexity of a Hamiltonian evolution can be measured by the number of elements of any universal gate set needed to approximate the associated unitary operator up to a suitable small error. We discuss possible choices how to measure the error and how the induced expressions measuring the complexity can be defined using only the Hamiltonian. Special attention is paid to Hamiltonian systems exhibiting local interactions. Our results then allow for an identification of physical relevant families of states which in most cases constitute only a small subset of the entire state space.

62 - A quantum interface between light and nuclear spins in quantum dots

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The coherent coupling of flying photonic qubits to stationary matter-based qubits is an essential building block for quantum communication networks.
We show how to realize a quantum interface between the polarized nuclear spin ensemble in a singly charged quantum dot and a traveling optical field. The coupling is mediated by the electron spin and the mode of a high-Q optical cavity to which the quantum dot is strongly coupled. Read-out is achieved via cavity decay while write-in is based on the generation of two-mode squeezed states of nuclei and output field and teleportation. For typical values of hyperfine interaction and cavity lifetimes, several ebit of entanglement can be generated long before internal nuclear dynamics becomes non-negligible.
H. Schwager, J. Ignacio Cirac and Géza Giedke, arXiv:0810.4488v1 [cond-mat.mes-hall]

63 - Ion shuttling and quantum jump statistics for Ca^+ ions in a miniature Penning trap array

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We will report on progress with our experiments aimed at evaluating ions stored in Penning traps as a resource for quantum information processing. We have built and operated a miniature multiple Penning trap array. This trap array consists of two pieces of ultra-high vacuum compatible circuit board with a gap of 5mm between them. Electrodes consist of copper pads on the surfaces of the boards. The current prototype generates three trapping zones in the gap between the boards. The electrode configuration allows the rapid switching of the electric field between the boards from the usual trapping arrangement to a field which allows the rapid transport of ions from one trapping zone to another. This novel shuttling scheme makes use of the q(v×B) part of the Lorentz force present in the Penning trap [1]. For the brief period during which transport occurs the potentials on the electrodes are set to give a near-linear electric field in the gap between the boards (typical electrode voltages range between -20V and +20V). This causes an ion to perform a cycloid motion. It starts from rest in one trap, first accelerates and then decelerates in the crossed electric and magnetic fields, coming to rest at the centre of the adjacent trapping zone. The potentials to the electrodes are then rapidly switched back to trapping mode. The transfer between trapping zones is accomplished in a time which is approximately one cyclotron period (2.5μs for Ca^+ with B=1T). The shuttling time is therefore independent of the trap dimensions. We have demonstrated single ion confinement in one of the trapping zones of the prototype array. We have also demonstrated successful repeated shuttling of small clouds of ions from one trapping zone to another. With a single ion held in one of the trapping zones we have investigated the statistics of quantum jumps in the presence of the large B-field of the Penning trap. This leads to some interesting features not seen in radiofrequency traps. As well as the usual Zeeman splittings the magnetic field leads to mixing of states with different values of the J quantum number. For typical laboratory fields the degree of mixing is very small and would normally be rather difficult to measure. Using a single Ca^+ ion held in a combined radiofrequency/Penning trap we show that use of Dehmelt's 'electron shelving' technique renders this small effect remarkably easy to detect. For applications in quantum information processing the J-mixing effect causes a degradation of the read-out fidelity. We show that this degradation is at a tolerable level for Ca^+ but is even less problematic for some other choices of trapped ionic species [2].

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64 - On superdense coding with noisy channels

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We study the capacity of a superdense coding protocol in the case of a noisy channel. We consider the case where the channel acts on Alice's side, and the one where it acts both on Alice's and Bob's side. In the latter case, the noise can be correlated or uncorrelated. We study various noise models and various bipartite input states, and derive the optimal capacity.

65 - Investigation of the Energy Distribution and Cooling of a Single Atom in an Optical Tweezer

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Single neutral atoms trapped in tightly focused sub-micron optical tweezers provide a useful architecture for fundamental quantum atom optics research, for quantum information processing and potentially for quantum computation. The knowledge and control of the energy of a single trapped atom is important for many of these applications. As is the case for ions, it is important to reduce the energy of the trapped atom, to ultimately reach the ground vibrational state of the trapping potential. In the framework of quantum computing, for example, the entanglement of two atoms via controlled collisions usually requires ground state cooling (see e.g. [1]). In our experiment, we trap single ^{87}Rb atoms in a strongly focused dipole trap that has an optical waist of w=1.03±0.01 μm and is produced by focusing an 850 nm laser in the center of an optical molasses using a large numerical aperture (NA =0.5) aspherical lens [2]. A collisional blockade mechanism prevents two or more atoms from being trapped simultaneously due to inelastic collisions [3]. We experimentally investigate the energy distribution of a single atom in the optical tweezer under different cooling regimes [4]. We use two independent methods to measure the temperature of the atom, and show that the energy distribution of the radiatively cooled atom is close to thermal. After laser-cooling, the temperature of the atom is 33 μK in a 2.8 mK trapping potential. We then demonstrate how to further reduce the energy of the atom, firstly by adiabatic cooling, and secondly by truncating the Boltzmann distribution of the single atom. This provides a non-deterministic way to prepare the atom at low microKelvin temperatures, close to the ground state of the trapping potential. These results provide the right conditions to implement a protocol to entangle two similarly cooled atoms, based on the emission of a single photon by one of these two trapped atoms [5]. These results also place us in a good position to further cool the atom down to the ground state, for example by using Raman sideband cooling.

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66 - Cooling atoms into entangled states

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Dissipation can assist quantum computational tasks in many ways. For example, it can cause environment-induced measurements which result in the preparation of a desired highly entangled state. Here we discuss the possibility to prepare such states simply through cooling, thereby avoiding the necessity of having to register a measurement outcome. Our cooling mechanism transfers atomic qubits into the ground state of an applied interaction Hamiltonian. We calculate the achievable fidelities and cooling rates for concrete examples with one and two qubits.

67 - Universal quantum computation with the $D(S_3)$ anyon model

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Anyonic systems depend upon topological rather than local degrees of freedom, making them ideal for the fault-tolerant storage and manipulation of quantum information. Though this principle is the basis of many novel and exciting schemes for quantum computation, the majority are presented at an abstract level in terms of anyon models rather than in terms of the underlying physical system employed for their realization. It is for this reason that there is still only a limited understanding of how fault-tolerant computation with anyons actually works. Also, not all topological models are universal without the addition of non-topological operations, and little is known of how these affect the fault-tolerance. Here we present a scheme for a quantum memory using the $D(S_3)$ anyon model expressed explicitly in terms of the lattice model on which it is realized. We also propose a set of non-topological operations to allow universal quantum computation. This provides us with a opportunity to further our understanding of how anyons store quantum information in a fault-tolerant way.

68 - Entropic uncertainty and information complementarity

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New inequalities for the probabilities of projective measurements in M mutually unbiased bases (MUBs) of a qudit system are derived. These inequalities lead to wider ranges of validity and tighter bounds on entropic uncertainty inequalities than previously derived in the literature. The entropic uncertainty relations are used to study the complementarity of information sent via different MUBs, which in turn ensures the security in quantum key distribution.

69 - Optical quantum computing using ultracold polar molecules

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For optical quantum computing, the central question is how to add a nonlinear phase to entangle two photons, such that the setup could amount to a 2-qubit phase gate. Since photons do not interact directly, one has to mediate their interaction via a nonlinearly interacting gas – an ensemble of polar molecules with dipolar interactions. The two elements for this process are (i) efficient coupling of photons into and out of the molecular ensemble without losing the phase – e.g. via slow-light polaritons – and (ii) the state-dependent dipole-dipole interaction of polar molecules for creating a nonlinear phase. Step (ii) is based on the idea that the dipole-dipole interaction occurs only between molecules that are excited by interaction with the photons. We are explaining how to accomplish that, list the decoherence sources and suggestions on how to mitigate them.

70 - Microscopy of a molecular ^{6}Li-BEC

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We present first results obtained with our new experimental setup that will allow us to study an ultracold fermionic quantum gas in potentials that can be arbitrarily controlled to less than a micrometer. An ultracold gas of ^{6}Li is prepared by first loading 50 million atoms from a MOT into a high-finesse standing wave resonator. About 3 million atoms are transferred into an single-beam optical dipole trap. By translating the focussing lens, the thermal atoms are transported to a region of high optical access. Direct evaporation close to a Feshbach resonance allows us to create a BEC of up to 200000 molecules. The quantum degenerate gas is sandwiched between two microscope objectives, which will enable us to create arbitrary potentials and to locally probe the strongly interacting system. The current state of the experiment will be presented.

71 - Photonic interfaces based on single trapped atoms

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(3)ICFO-Institut de Ciencies Fotoniques, E-08860 Castelldefels, Barcelona, Spain.

We study the performances of schemes for entangling two distant atoms by measurement of emitted photons. We focus on protocols based on measurement of one [1] and two photons [2] and compare them in terms of the probability to obtain the detection events and of the conditional fidelity with which the desired entangled state is created. We also analyze the possibility to improve the entanglement generation by state purification.

We show that protocols based on one-photon detection are more efficient in setups characterized by low photon-detection efficiencies, while at larger values two-photon protocols are preferrable. We identify the threshold value of the detection efficiency, which separates the two regimes.

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Via Marangoni, 1, 32043 Cortina d'Ampezzo BL

1. Procedi in direzione **sudest** da **Via Marangoni** verso **Via dello Stadio**	43 m 43 m (totale)
2. Svolta leggermente a **destra** in **Via dello Stadio**	17 m 60 m (totale)
3. Svolta a **sinistra** in **Via Cesare Battisti/SS48** Circa 2 min	0,1 km 0,2 km (totale)
4. Svolta a **sinistra** in **Via Paolo Grohmann/SS51** Continua a seguire la SS51 Circa 2 min	0,1 km 0,3 km (totale)
5. Svolta a **sinistra** in **Corso Italia/SS51**	28 m 0,4 km (totale)
6. Svolta leggermente a **destra** in **Via Guglielmo Marconi**	43 m 0,4 km (totale)
7. Svolta a **sinistra** in **Via Guglielmo Marconi/SS51**	32 m 0,4 km (totale)
8. Svolta a **destra** in **Corso Italia/SS51** La tua destinazione è sulla sinistra Circa 3 min	0,2 km 0,6 km (totale)

Splendid Hotel Venezia
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