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Redworth Hall

Conference Handbook

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Scope of the Conference

Ion traps are used as a basic tool in a wide variety of experiments today, and ion trappers with different applications often deal with very similar challenges. This conference addresses researchers interested in the various experimental and theoretical aspects of ion trapping, including quantum information, atomic and molecular spectroscopy, metrology, high-precision determination of atomic ground state properties, cavity QED experiments as well as the production of cold molecules. A significant fraction of the week will be devoted to scientific discussions in this pleasant and peaceful environment.

Venue

The 2010 European Conference on Trapped Ions (ECTI2010) will be held at the historic Redworth Hall in County Durham, England. Situated in the beguilingly beautiful heart of the English countryside, this old country manor is laced with intrigue, with a history spanning the last five centuries. It is also known to be haunted—expect sightings of the supernatural!

Built originally as the family home of George and Eleanor Crosier in 1693, this extravagant residence was inhabited by the Crosier and then Surtees families of the English aristocracy before being renovated by Henry Edward Surtees in 1863. Contemporary Georgian fixtures were integrated into the house, and a Baronial Hall was added, adding to this building's castle like appearance. With an old tower and crenellated balconies, one is reminded of historic battles and deeds of heroism when one looks down from the battlements.

The hall is now a hotel of exemplary contemporary standards. This hotel is designed with the most indulgent modern luxuries, and the most lavish traditional comforts, only fitting for a residence of the aristocracy. Redworth incorporates its illustrious past with state of the art facilities. These include a 17m indoor pool, a Jacuzzi, sauna and steam rooms, a cutting edge fitness suite and even outdoor tennis courts. Expect to live like a King.

It is rumoured that Redworth Hall is often the site of paranormal happenings—a building with such a colourful past can only be expected to be haunted! Corridors echo with ghostly footsteps, and ectiplasm (excuse the typo) flows through the house's aged walls. Two spectres are reputed to walk the halls of Redworth, the first being a jilted lover who threw herself from the tower and now roams the house, with a particular fondness for bedrooms... The other is that of a child of the Surtees' deemed to be 'ill of mind' as a boy he spend many nights chained to the fireplace in the great hall. It is said that his laughter and crying can still be heard on the darkest of evenings.

Invited Talks Abstracts

Sub-Doppler cooling of trapped ions

David Lucas

Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK

I will discuss various methods (and their practical implementation) for sub-Doppler cooling of trapped ions close to the ground state of motion, including resolved sideband cooling (see for example [1]), "EIT" cooling [2], and recent proposals for fast cooling [3].

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Faster approaches for quantum information processing with trapped ions

Nikolay V. Vitanov

Department of Physics, Sofia University, 5 James Bourchier blvd, 1164 Sofia, Bulgaria

The model of quantum information processing based on sequences of one- and two-qubit gates has been established as the standard model of the future *universal* quantum computer. The number of *physical* operations required in this model, however, appears too large even for elementary demonstrations of quantum algorithms and conditional quantum gates. Viewing the quantum computer as a quantum simulator, we have developed a pool of alternative approaches that use the intrinsic symmetries of an ensemble of trapped ions, which have allowed us to design much faster implementations, with much fewer steps than in the standard model. For example, a linear chain of ions in a Paul trap is ideally suited for running the Grover's quantum search algorithm because the collective propagator of such a system, under certain conditions, is the reflection about the mean [1], which is the kernel of Grover's algorithm [2]. In another example, the Hamiltonian of a ring of ions possesses a circulant symmetry, which implies that the respective propagator is directly related to the quantum Fourier transform, which is the essential part of Shor's factorization and other algorithms [3]. In this way, the individual mathematical steps in Grover's and Shor's algorithms can be realized in such a *single-purpose* quantum computer with a *single* laser pulse, rather than by a sequence of a great number of pulses as in the standard model. Similar arguments have been used for the design of techniques for single-shot generation of various highly-entangled many-particle states, such as Dicke states [4] and cluster states [5].

Another approach along this line is based upon the so-called *composite pulses*, which have been used for a long time in nuclear magnetic resonance and, since recently, in single-qubit rotations of trapped ions. A composite pulse is represented by a sequence of pulses, each with a specific area and a well-defined phase. These phases are used as free parameters, which are determined from the conditions for a specific unitary operation. The result is a transition profile, which combines very high fidelity of gate operations with robustness vs parameter variations. Motivated by the objective to optimize the manipulation of the ion qubits we have developed a pool of composite pulses for single- and multi-qubit gates by using a novel approach based on SU(2) transformations [6] instead of the more cumbersome traditional Bloch sphere O(3) rotations. We have used these to design new realizations of multiply-conditional gates, e.g. C-NOT, Toffoli, and generally C^N-NOT, which require much fewer physical interactions than in the standard approaches, essentially a single composite pulse [7]; moreover, these implementations are robust against variations in the pulse area and the Lamb-Dicke parameter.

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Quantum Information Experiments with Ion Crystals in Penning Traps

John J. Bollinger[1], Michael J. Biercuk[1,2], Hermann Uys[1,3], Joseph W. Britton[1], Wayne M. Itano[1], and Nobuyasu Shiga[1,4]

[1] National Institute of Standards and Technology, Boulder, CO 80305, USA
[2] School of Physics, Univ. Sydney, Australia
[3] Council for Scientific and Industrial Research, Pretoria, South Africa
[4] National Institute of Information and Communications, Tokyo, Japan

Two and three dimensional periodic arrays (crystals) of trapped ions form naturally in Penning traps [1,2]. We discuss several quantum information experiments that we are pursuing with planar (two-dimensional) arrays of trapped ^{9}Be$^+$ ions. Our qubit is the 124 GHz electron spin-flip transition in the ground state of ^{9}Be$^+$ in a 4.5 T magnetic field. High fidelity ($>$ 99.9 %) qubit rotations are performed with a phase-locked microwave source at 124 GHz. We measure a T2 free induction decay coherence time of approximately 2 ms limited by fast ($\sim$100 Hz) magnetic field fluctuations of the superconducting magnet.

We have used this system to study the noise filtration capabilities of different dynamical decoupling sequences [3,4]. Of particular interest is the performance of the recently proposed Uhrig dynamical decoupling (UDD) pulse sequence [5] which uses unevenly spaced π-pulses, in contrast to the standard Carr-Purcell-Meiboom-Gill (CPMG) mulitpulse spin echo which uses evenly spaced π-pulses. We engineer the noise environment of our trapped ion qubits to mimic the environment of qubits realized in other technologies. We find strong agreement between experimental data and theoretical predictions for qubit coherence. Further we are able to confirm that in noise enviroments dominated by high-frequency spectral components, the novel UDD sequence outperforms standard CPMG in suppressing error and prolonging qubit coherence. In addition we show that further improvements in performance can be obtained through variation of the inter-π-pulse delays through a real-time feedback optimization.

We also describe progress towards using state-dependent optical dipole forces on planar crystals of several hundred ions to generate entangled states through a spin-squeezing interaction. In initial experiments we observed a larger than expected decoherence due to spontaneous emission. We demonstrate that this decoherence is due to elastic Rayleigh scattering of off-resonant light which dominates decoherence due to Raman scattering for our conditions. Specifically we calculate and experimentally verify that the elastic-scattering decoherence rate of a two-level system is given by the square of the difference between the elastic scattering *amplitudes* for the two levels, and that for certain detunings of the light, the amplitudes can interfere constructively, even when the elastic scattering *rates* are equal [6].

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1 -, 2 - and 3 D - ion structures in traps of different geometry

M Marciante, C Champenois, G Hagel, M Houssin, O Morizot, J Pedregosa, M Knoop

Physique des Interactions Ioniques et Moléculaires, CNRS-Aix-Marseille Université,
Centre de Saint Jérôme, Case C21, 13397 Marseille Cedex 20, France

One of the major strengths of ion traps is the possibility to vary the number of probed atoms from a single one to a cloud of over 10^6 in a reduced volume. Moreover, the very high level of control of internal and external degrees of freedom has opened the way to a large range of applications - from quantum information to the creation of cold molecules [1].
To minimize perturbations of the atoms and broadening of their spectral linewidths, laser cooling is applied and allows to reach the Lamb-Dicke regime only for single ions or chains of single ions in quadrupole traps. In trapping potentials of different geometry, this can also be achieved for 2D structures. In a linear octupole trap, ions are expelled from the center, and tend to form hollow structures when laser-cooled. The most simple shape is a ring of ions, centered around the trap axis and interesting for high-precision measurements due to its symmetry. Various applications can be imagined, and we have started to look into an eventual use for metrology [2].
With larger ion numbers, the stable structures that can be reached by laser-cooling depend on the geometry of the trapping potential and the number of ions, various configurations can be reached. Our first point of interest for the investigation of 3D structures is the efficiency and rapidity of the applied laser-cooling. We have evaluated the impact of a single cooling laser on the temperature of an ion cloud by means of molecular dynamics simulation in a quadrupole potential, for different values of size and shape of the cloud [3]. We are also interested in getting insight into questions of sympathetic cooling in these structures.
In parallel, we are setting up a double trap juxtaposing a quadrupole and an octupole potential in order to investigate structures of different geometry experimentally.

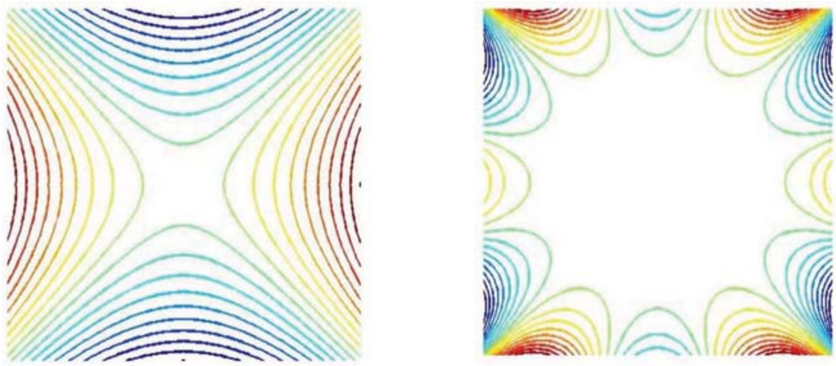

Figure 1: Shape of the potential in a quadrupole trap (*left*) and a dodecapole trap (*right*)

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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.
Rainer.Blatt@uibk.ac.at
Tel: +43-512-507-6350, Fax: +43-512-507-2952

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 fourteen 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. High fidelity CNOT-gate operations are investigated towards fault-tolerant quantum computing and decoherence of multi-qubit GHZ states was investigated. First experiments implementing repetitive quantum error correction will be reported. As applications of quantum information processing, quantum simulations of the Dirac equation were implemented and a quantum walk with a trapped ion was realized.

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Protecting a single ion against decoherence using π-pulses: dynamical decoupling and measurement uncollapse.

S C Webster, M J Curtis, D J Szwer, D T C Allcock, A H Burrell, T P Harty, H A Janacek, N M Linke, J A Sherman, D N Stacey, D M Lucas, A M Steane

Department of Physics, University of Oxford, Oxford OX1 3PU, UK

There are many techniques available to protect qubit states from decoherence, from using decoherence-free subspaces to full quantum error correction, however these often require encoding a logical qubit in multiple physical qubits. We will present results from two different single Ca^+ ion experiments which demonstrate the use of simple spin-echo like techniques to protect a single physical qubit from two different types of decoherence: random phase noise and leakage of the qubit outside of the computational basis.

The phase coherence of a single qubit experiencing a constant arbitrary phase shift can be preserved using a single Hahn spin-echo pulse. For a time-varying phase shift, the Carr-Purcell-Meiboom-Gill (CPMG) sequence of repeated π-pulses has long been used. More recently the Uhrig Dynamical Decoupling (UDD) sequence has been discovered to offer greater protection against low frequency phase noise. We will present an intuitive derivation of the UDD pulse sequence and show the effectiveness of the CPMG and UDD pulse sequences in protecting a qubit encoded in the hyperfine ground state of a $^{43}Ca^+$ ion.

Another form of decoherence is the leakage of population from the computational basis $|0\rangle, |1\rangle$ into another of the ion's internal states. Here we consider the case where only one of the basis states couples to a third state $|2\rangle$ (e.g. by decay from $|1\rangle$ to $|2\rangle$). If we prepare a qubit state and then leave it for some period of time, then there is a possibility of leakage. We can make a measurement to see if the ion has evolved to be in $|2\rangle$, and if it has then the qubit has been destroyed. Even a null measurement, however, does not mean that we retain the original qubit, which instead has undergone a non-unitary evolution caused by the asymmetry of the interaction of the states $|0\rangle$ and $|1\rangle$ with state $|2\rangle$. The effect of this non-unitary evolution can however be reversed by performing this wait-then-measure procedure twice, flipping the qubit state with a π-pulse after each measurement. If both measurements give a null result then the qubit is still in the computational basis and will have been returned to its original state. We have demonstrated such a model of qubit leakage in a $^{40}Ca^+$ ion, and will show that qubit coherence can be preserved even in the case of a strong coupling between $|1\rangle$ and $|2\rangle$.

New Approaches To An Indium Ion Optical Frequency Standard

K. Hayasaka

National Institute of Information and Communications Technology,
4-2-1 Nukui-kitamachi, Koganei, Tokyo, 184-8795, Japan

Implementation of Dehmelt's optical frequency standards based on ions with alkali-earth metal electron structures has been difficult due to needs for VUV radiation used to laser-cool and to detect the ions. This barrier has been removed by quantum logic spectroscopy (QLS), with which an unprecedented fractional uncertainty of 10^{-18} in frequency measurement has been demonstrated using Al^+ [1]. Another candidate for such high accuracy is indium ion($^{115}In^+$). We report on new approaches including QLS to an In^+ optical frequency standard.

Previously, efforts have been made to establish a single In^+ optical clock using rather weak $^1S_0$-$^3P_1$ transition at 230 nm for laser-cooling as well as for detection, instead of strong $^1S_0$-$^1P_1$ transition at 159 nm. However, reported uncertainties are limited to about 2 parts in 10^{13} [2]. In order to exploit the immunity of the clock transition to external perturbations, we introduce new approaches to cooling and to detection. Sympathetic cooling with another ion is used to supply continuous cooling of In^+. Proper choice of the refrigerator ion would supply better cooling without giving too much shifts to the clock transition, and also a faster way of compensating micromotion. Detection of the In^+ after clock laser irradiation is implemented in the following three different ways. The first method is QLS, and this is expected to work fine as in the case with Al^+ [1]. The second method is direct excitation of the 159-nm transition. A single-mode VUV source is still difficult to realize, but multimode pulses are enough for detection. Such VUV pulses might be generated by high harmonic generation. The third method is detection at 230 nm as previous works. This supplies only slow detection, but if a clock laser stabilized to an optical lattice clock via optical comb is used, this method would realize both stability of the optical lattice clock and accuracy of the single-ion clock.

Experimentally, initial setup for the third method is under construction with $^{40}Ca^+$ as the refrigerator ion. Ion chains consisting of Ca^+ with In^+ at specified locations have been generated in a linear trap. A 2.0 mW of 230-nm radiation has been obtained by two stages of frequency doubling of a 100-mW diode laser at 922 nm. The clock laser is based on a diode laser at 943 nm and a relative stability of 10^{-15} at one second is expected by locking it to a novel cubic ULE cavity. QLS is being studied in collaboration with Prof. Urabe's group at Osaka University. A Ca^+-In^+ chain has been generated, and sideband cooling down to the ground state is in progress. For the VUV method the 5th harmonic of a 795-nm femto-second Ti:S laser has been generated in a passive enhancement cavity with Xe gas as nonlinear medium. With these developments we expect prototypes of the In^+ clock will start to operate in a year or two.

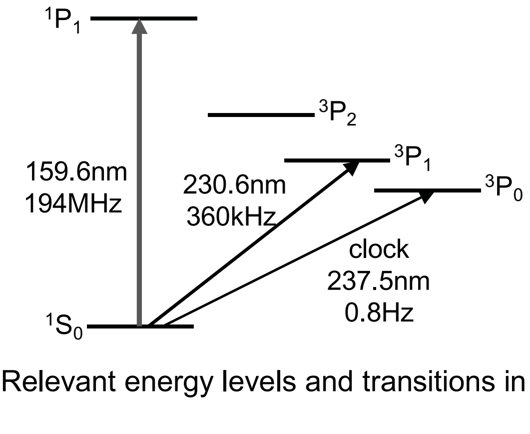

Figure 1. Relevant energy levels and transitions in In^+

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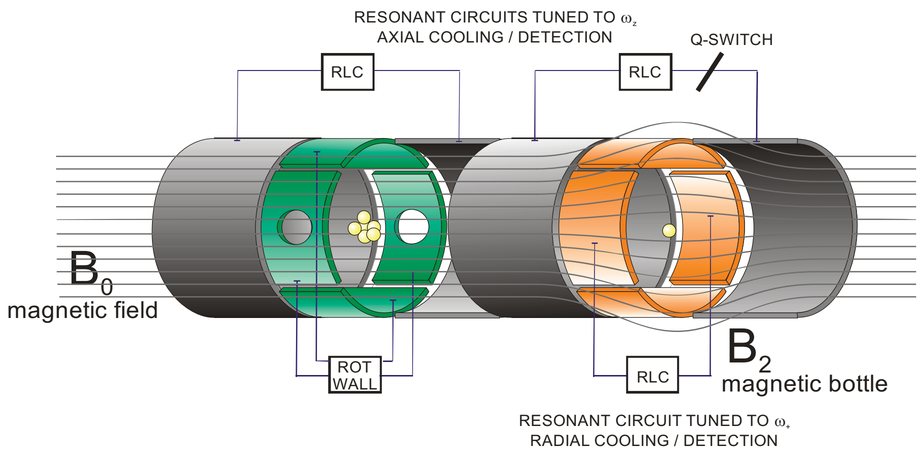
Trap-assisted Precision Spectroscopy of Highly Charged Ions

W. Quint and M. Vogel

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
Ruprecht-Karls-Universität Heidelberg, Germany

Highly charged ions feature a number of interesting properties other than the mere high charge state. Especially in few-electron ions the extremely strong electric field of the nucleus changes the properties of the electronic system such as energy level spacings, lifetimes and magnetic moments drastically [1]. In turn, the electrons serve as sensitive probes for nuclear properties such as size, magnetic moment and spatial distribution of charge and magnetization. The energy of forbidden transitions such as fine structure and hyperfine structure transitions strongly depends on the nuclear charge and shifts from microwave domains into the optical domain. Thus, they become accessible for laser spectroscopy and its potentially high precision. Zeeman splittings of electronic energy levels due to external magnetic fields, as they are typical for charged particle traps such as Penning traps, are in the microwave domain and become accessible for precision microwave spectroscopy [2].



A specific combination of optical and microwave spectroscopy is presented together with a number of novel experimental applications [3,4,5]. They yield experimental access to transition energies and magnetic moments of bound electrons with relative accuracies in and potentially beyond the part per billion regime. Simultaneously, properties of the nucleus such as its magnetic moment can be measured with a part per million accuracy and for the first time in the absence of diamagnetic shielding. This offers access to fundamental quantities with unprecedented accuracy and yields the possibility for highly sensitive tests of bound-state QED calculations and of shielding models. At the same time, the number of possible candidates for such measurements is substantially increased since the need for detection of fluorescence photons can be circumvented ('blind spectroscopy'), thus broadening the accessible transition wavelength domain [4,5].

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Precision optical spectroscopy of radioactive Be isotopes produced in projectile fragmentation

M. Wada[1], A. Takamine[1,2], T. Sonoda[1], K. Okada[3], P. Schury[4] and SLOWRI Collaboration

[1] Nishina Acclelerator-Based Research Center, RIKEN, Wako, Saitama, Japan
[2] Department of Physics, Aoyama Gakuin University, Fuchinobe, Sagamihara, Japan
[3] Department of Physics, Sophia University, Kioicho, Chiyoda, Tokyo, Japan
[4] Department of Physics, Tsukuba University, Tsukuba, Ibaragi, Japan

Precision optical spectroscopy of radioactive Be isotopes has been performed at prototype SLOWRI facility of RIKEN RI-Beam Factory. Radioactive Be ions produced in nuclear fragmentation at ≈1 GeV were separated by an in-flight separator RIPS and decelerated and cooled in an RF-carpet ion guide gas cell [1, 2]. They were extracted from the cell by a combination of inhomogeneous RF fields and DC fields in the cell. The extracted ions were stored in a linear RF trap and further cooled by laser cooling down to ≈10 mK. Such a factor of 10^{-15} reduction in the kinetic energy of ions allowed us to perform high precision optical spectroscopy of radioactive nuclear ions.

The ground state hyperfine constants of ^{7}Be^{+} [3] and ^{11}Be^{+} [4] were determined with relative accuracies of 6×10^{-7} and 3×10^{-8}, respectively, by laser-microwave double resonance spectroscopy of laser-cooled ions in a trap. Simple structure of the hyperfine levels of the ground state ^{11}Be^{+} ion allowed us to measure a field independent transition even under a weak magnetic field resulting higher accuracy than other isotopes. The optical transition energies from the ground S-state to the excited P-state of Be isotope ions were also measured to determine the nuclear charge radii from the isotope shifts [5].

The purpose of these experiments is to study neutron halo structure of ^{11}Be with nuclear-model-independent optical probes. In a naive picture, the charge radius corresponds to the core size while the magnetization radius, which can be deduced from the isotope shifts of the ratio of the hyperfine constants to the nuclear g-factors, corresponds to the radius of the halo neutron. To complete this study, we still need to determine the nuclear g-factor of Be isotopes accurately [6].

We will also discuss about the new low-energy RI-beam facility which is under development at RIKEN [7]. The new facility — SLOWRI — will provide slow or trapped radioactive isotope ions of all elements by using an in-flight separator BigRIPS and the RF-carpet ion guide technique. SLOWRI will have an additional capability to provide low-energy RI-beams *parasitically* (PALIS) [8] using resonance ionization in a gas cell.

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Quantum Information Processing with Trapped Ions: An Overview†

Dietrich Leibfried[1]

[1] National Institute of Standards and Technology, Boulder, CO 80305, USA

This tutorial lecture will provide a general overview of quantum information processing (QIP) with trapped ions, and also review key demonstrations from labs around the world. The topic is treated more formally and exhaustively in several recent review articles (for an incomplete list see [2]), so I will try to invoke an intuitive understanding for the foundations of QIP with trapped ions and present exemplary realizations taken from many different laboratories along the way. Since the general topic is rather wide, some subtopics, for example ground state cooling and heating in ion traps, quantum simulations and quantum metrology, will not be covered in this lecture, but will be discussed in other tutorials within the ETCI meeting [3].

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[3] See the abstracts for other tutorial talks in this meeting.

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Quantum Information Processing with Ions

Ferdinand Schmidt-Kaler, QUANTUM, Institute for Physics, Staudingerweg 7,
Johannes Gutenberg Univ. Mainz, Germany,
http://www.quantum.physik.uni-mainz.de/

Superpositions of quantum logic states |0> und |1> are stored and manipulated in the electronic excitation of ions for a future quantum computer [1]. So far, we know how to deal with a single, two [2,3], and up to eight qubits. For a realization of a scalable quantum device we employ a linear segmented micro-structured Paul-trap [4], see figure below. Especially in such µm-scale trap devices we use the ion as a sensitive local probe of electric and magnetic fields [5]. Using Raman light fields, we implement a Spin qubit [6], realize fast single qubit rotation and spin dependent forces for generating a Schrödinger cat state where we precisely analyze the entangled wave packet trajectory [7].

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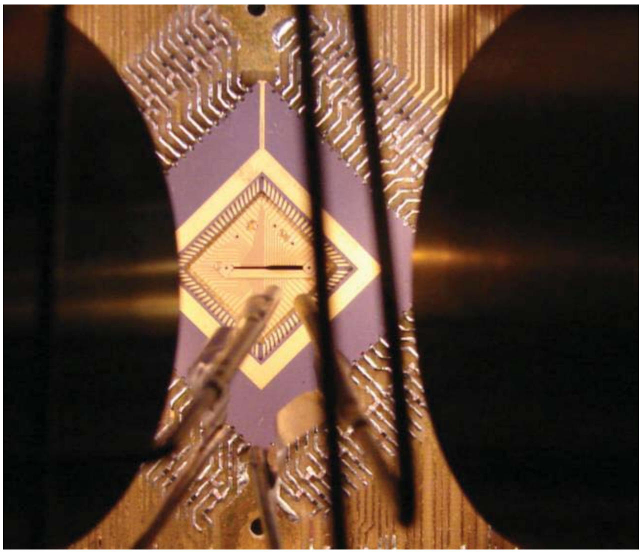
Mainz 3D segmented micro ion trap



Robust Microwave-Dressed States with Trapped Ions

N Timoney, I Baumgart, M Johanning, A Varon, C Wunderlich

Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany

Laser cooled atomic ions confined in an electrodynamic cage have been successfully used for quantum information science (QIS) as is evident from the contributions to this conference. For ion trap QIS, the use of laser light for *coherent manipulation* gives rise to fundamental issues, notably, unavoidable spontaneous emission that destroys coherences [1], and to technical difficulties in steering and accurately controlling a large number of laser beams (e.g. [2,3,4]) that hinder scalability. The difficulty in cooling several ions to their motional ground state, and the time needed for such a process in the presence of spurious heating of Coulomb crystals further limit the fidelity of quantum logic operations in laser-based quantum gates, and thus present difficulties for scalability.

Recently, laser-less addressing of ions [5,6] and Magnetic Gradient Induced Coupling (MAGIC) between ion spins and their motion [5] using radio-frequency radiation has been demonstrated for the first time. By using MAGIC, and thus avoiding the use of laser light for coherent manipulation, technological and fundamental hurdles on the path towards a scalable trapped ion quantum processor or simulator can be overcome [2,3,5].

An issue that MAGIC shares with optical schemes is the use of magnetic field sensitive states that are susceptible to ambient noise fields limiting their coherence time. Here, we report on the progress of ongoing experiments with $^{171}Yb^{+}$ ions showing that the use of microwave dressed states as qubits makes them (almost) immune against magnetic field fluctuations and thus enhances their coherence time. Dressed states were prepared and probed using adiabatic microwave pulse sequences and their coherence time was investigated as a function of pulse parameters.

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Quantum zigzag transition in ion chains

E Shimshoni[1], G Morigi[2,3] and S Fishman[4]

[1] Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel
[2] Theoretische Physik, Universität des Saarlandes, D 66041 Saarbrücken, Germany
[3] Department de Física, Universitat Autònoma de Barcelona, E 08193 Bellaterra, Spain
[4] Department of Physics, Technion, Haifa 32000, Israel

A string of trapped interacting ions at zero temperature ($T = 0$) exhibits a structural phase transition to a zigzag structure, tuned by reducing the transverse trap potential or increasing the particle density. The transition is driven by transverse, short wavelength vibrational modes [1]. We propose a quantum field–theoretical description of this transition by the one dimensional Ising model in a transverse field [2]. Based on the mapping to this model, we estimate the quantum critical point in terms of the system parameters, and find a finite, measurable deviation from the critical point predicted by the classical theory presented in [1]. A measurement procedure is suggested which can probe the effects of quantum fluctuations at criticality. These results can be extended to describe the transverse instability of ultracold polar molecules in a one dimensional optical lattice.

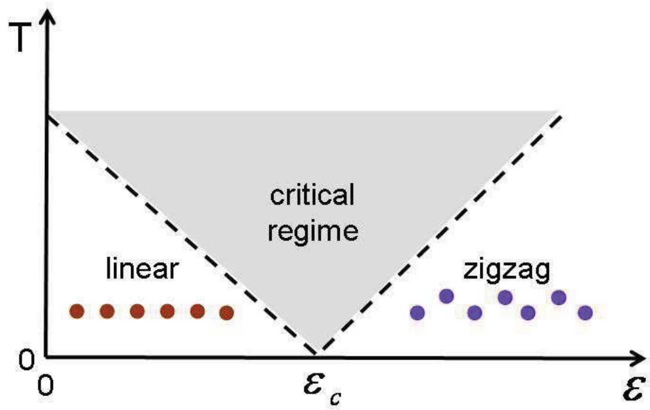

Figure 1: Sketch of the phase diagram for a linear-zigzag transition, according to the mapping to the 1D model of a quantum Ising transition. The dimensionless parameter ε is tuned by the confining potential or the interparticle distance, while T is the temperature of the sample. The mechanical instability of the linear chain is at $\varepsilon = 0$ [1]. The quantum critical point, at $\varepsilon_c > 0$, separates the linear chain from the zigzag phase at $T = 0$. In $0 < \varepsilon < \varepsilon_c$ quantum fluctuations dominate, and the crystal is in the linear (disordered) phase. The dashed lines indicate the boundaries of the quantum critical region, where thermal fluctuations dominate.

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Anderson Localization of Phonons in Ion Chains

A Bermudez, M A Martin-Delgado and D Porras

Departamento de Fisica Teorica I, Universidad Complutense de Madrid, 28040 Madrid, Spain

Trapped ions are an ideal system for the quantum simulation of Condensed Matter problems, since quantum states can be prepared and measured with high fidelity at the single particle level, and a variety of interactions between particles may be induced by optical means.

In this work we show that the radial vibrations of a chain of trapped ions can be used to explore the physics of Anderson localization. In our scheme, a laser induces a shift in the local vibrational energy which depends on the internal state of each ion. Thus, the quantum statistics of the internal levels determine the statistical properties of the vibrational Hamiltonian. In this way, the radial phonons of the chain experience a disordered potential and show the phenomenology of particles moving in a disoreded system, such as the existence of localized states.

We also show how to explore different situations, such as disorder correlated between different ions, and localization in the presence of phonon-phonon interactions. Anderson localization of phonons may be detected by means of the measurement the resonance fluorescence, something that does not require individual addressing to detect the localization of the phonon wavefunctions.

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A trapped single ion inside a Bose-Einstein condensate

Michael Köhl

Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, UK

In recent years, ultracold atoms have emerged as an exceptionally well controllable experimental system to investigate fundamental physics, ranging from quantum information science to simulations of condensed matter models. Here we go one step further and explore how cold atoms can be combined with other quantum systems to create new quantum hybrids with tailored properties. Coupling atomic quantum many-body states to an independently controllable single-particle quantum system gives access to a wealth of novel physics and to completely new detection and manipulation techniques. In the talk, we will report on recent experiments in which we have for the first time deterministically placed a single ion into an atomic Bose Einstein condensate. A trapped ion, which currently constitutes the most pristine single particle quantum system, can be steered with nanometer precision within the atomic cloud and can be observed and manipulated at the single particle level. In the created single-particle/many-body composite quantum system we show sympathetic cooling of the ion and observe chemical reactions of single particles in situ. An outlook into possible future developments will be given.

Cold collisions of atoms, molecules, and ions

Paul S. Julienne

Joint Quantum Institute, NIST and the University of Maryland, Gaithersburg, MD 20899-8423 USA

The availability of sources of cold and ultracold atoms has been extraordinarily fruitful in a wide range of science from precision measurement to novel few-body, many-body and condensed matter systems. In part, this is because the interactions between such atoms can be understood and controlled very precisely, especially by using tunable scattering resonances [1]. Recently, sources of ultracold molecules have become available, as well as experiments that mix atoms and trapped ions. These new experimental systems offer the prospects of extending the success with atoms to systems with very different interaction and collisions properties. This talk describes progress towards relatively simple and robust theories of the collisions and reactions of atoms with ions based on key simplifying assumptions made possible by the many orders of magnitude variation in interaction strength during the course of a collision.

Collisions among cold, trapped atoms, molecules, or ions have both similarities and important differences. While strong short range interactions can vary greatly for interactions between different kinds of species, the net result of a collision is the removal of some of the incident scattering flux from the initial collision channel and a phase shift in the wave scattered back into the initial channel. Both the loss and phase can be controlled by tunable scattering resonances. However, a major difference between collisions of different types of species that is especially important in the cold and ultracold domain is the character of the long range potential between the species. The long-range potential sets the characteristic length and energy scales that determine the basic character of the near-threshold bound and scattering states of the system [1,2]. This is where atomic, molecular, or ionic collisions can be profoundly different.

A very simple framework for atom-atom [3], atom-molecule or molecule-molecule [4], or atom-ion [5] collisions can be set up using a quantum defect framework based on the long range potential. In this way, a very minimal number of independent parameters, together with the analytic properties of the long range potential, determine all of the threshold scattering and bound state properties. In particular, this talk will illustrate the theory for elastic and loss collisions of free (untrapped) cold ions and atoms, including the character of the spectrum of Feshbach resonances and loss processes, using Ca^+ $+$ Na as an example [5], where only three quantum defect parameters are needed, plus a parameter to characterize the strength of short range charge transfer. The theory also shows where it is appropriate to use semiclassical approximations to the full quantum dynamics. Atomic, molecular, and ionic collisions will be compared and contrasted.

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Quantum Metrology with Trapped Ions.

Piet O. Schmidt

QUEST Institute for Experimental Quantum Metrology
Physikalisch-Technische Bundesanstalt and Leibniz University Hannover, Germany

During the past years, tremendous progress has been made in optical precision spectroscopy, culminating in a recent frequency ratio measurement of two optical clocks with an accuracy of 18 digits [1]. Such measurements provide a means to test fundamental theories beyond the standard model, e.g. by probing possible temporal changes in fundamental constants. I will present new metrology methods based on techniques developed for quantum computers based on trapped ions [2]. For this, the spectroscopy ion is stored together with a logic ion in the same trap. The Coulomb interaction between the ions strongly couples their motion. This allows sympathetic cooling of the spectroscopy ion via laser cooling of the logic ion. Moreover, the logic ion can be utilized to prepare and read out the internal state of the spectroscopy ion [3,4]. Quantum logic also serves to entangle atoms with the promise of improved insensitivity against external fields and stability beyond the standard quantum limit [5]. These techniques open the door for precision spectroscopy of a variety of previously inaccessible atomic and molecular species with interesting physical properties.

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Antiparticle Trapping for Antihydrogen Physics

M. Charlton[1]

Physics Department, School of Physical Sciences, Swansea University, Swansea SA2 8PP, United Kingdom

Over the last decades it has become routine to form beams of positrons and antiprotons and to use such sources to produce trapped samples of both species for a variety of purposes: see e.g. [1-3]. Positrons can captured efficiently, for instance using the buffer-gas system developed by Surko and co-workers [4], and in such quantities to form dense, single component plasmas [5,6] useful for antihydrogen formation [7]. The latter was made possible using developments of techniques for dynamically capturing and then cooling [8, 9] antiprotons ejected from the Antiproton Decelerator at CERN.

This talk will review recent advances towards antihydrogen trapping, principally with respect to progress made by the ALPHA collaboration. Trapping, which is thought to be a pre-requisite for spectroscopic comparisons of antihydrogen with hydrogen, causes extra complications by introducing a magnetic minimum neutral atom trap in the same region that the antiparticles are held. We will describe how clouds of antiprotons can be compressed and evaporatively cooled [10, 11] in preparation for antihydrogen formation [12] in such an environment. Progress towards detecting trapped antihydrogen will be summarised. Aspects of positron accumulation will be described, including recent progress with a new technique [13, 14] to use rotating electric fields to compress pre-plasma clouds to facilitate controlled ejection from an accumulator onto targets to promote efficient positronium formation.

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Quantum Information and Metrology with RF Traps at NIST

D. J. Wineland[1]

[1] Ion Storage Group, NIST Time and Frequency Division, Boulder, CO 80305-3328

Recent experiments at NIST that use RF traps for Quantum Information Processing (QIP) are described. We have been developing methods for QIP that can be incorporated in large-scale systems, including trap fabrication and ion transport [1, 2], qubit detection [3], and operation sets [4, 5]. Current projects include extensions of these topics and work towards microwave-induced gates [6], simulation [7], spectroscopy and atomic clocks that utilize quantum logic [8], and transfer of quantum information between different ion species [9] and/or ions located in separate trap potentials.

The RF-trap QIP work at NIST involves the contributions of many people; current and recent past group members include Jason Amini[1], Brad Blakestad[2], John Bollinger, Ryan Bowler, Joe Britton, Kenton Brown, James Chou, Yves Colombe, David Hanneke, Jonathan Home[3], David Hume[4], John Jost, Didi Leibfried, Yiheng Lin, Christian Ospelkaus, Till Rosenband, Aaron VanDevender, Ulrich Warring, and Andrew Wilson. The work is supported by IARPA, ONR, DARPA, NSA and the NIST Quantum Information Program.

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[1]Present address: Georgia Tech Quantum Institute, Atlanta, Georgia 30332
[2]Present address: JQI, U. Maryland
[3]Present address: ETH, Zürich
[4]Present address: Optical Frequency Measurements Group, NIST, Boulder, CO

Cavity Electromagnetically Induced Transparency with ion Coulomb crystals

M. Drewsen

Danish National Research Foundation, Center for Quantum Optics - QUANTOP,
Department of Physics and Astronomy, The University of Aarhus,
Ny Munkegade 120, DK-8000 Aarhus, DENMARK

Electromagnetically Induced Transparency (EIT) is a widely-used quantum interference effect to control absorption and dispersion properties of a medium [1]. Enclosing an EIT medium in an optical cavity offers an enhanced interaction of the medium with well-defined spatio-temporal modes of the electromagnetic field. This scenario can be exploited to realize high-efficiency quantum memories [2,3], as well as to enhance the “giant” non-linearities associated with EIT [4], and to produce spectacular non-linear effects at the few photon level, such as single photon blockade mechanisms [5], single-photon quantum phase gates [6] and highly-entangled states [7].

Ensembles of ions, laser-cooled to form a Coulomb crystal, represent a near-ideal medium to investigate cavity EIT phenomena due to their excellent stability and controllable coherent coupling to light field [8].

Here, we report on the observation of cavity EIT with ion Coulomb crystals ($^{40}Ca^+$ ions) enclosed in a moderately high-finesse (~3000) linear cavity in a novel configuration where both the probe and the control field are injected into the cavity. The weak probe field (single photon level), and the more intense control field originate from the same laser and are both tuned to the same atomic transition ($3d^2D_{3/2}$-$4p^2P_{1/2}$), but with opposite circular polarizations to address separate Zeeman sub-states of the $3d^2D_{3/2}$ level (pump: m_J=-1/2, probe: m_J=+3/2).

In the collective strong coupling regime [8], we observe the predicted symmetric triple-mode splitting of the cavity reflectivity spectrum for the probe, when the cavity and control fields are resonant with the atomic transition. The central EIT feature reaches nearly perfect transparency, while at the same time having a width as low as a few tens of kHz. The width of the EIT window is much narrower than the bare cavity line width (~2.2 MHz) and two orders of magnitude smaller than in previous cavity EIT experiments with neutral atomic gas [9,10]. Combined with the effective optical depth of the sample (~10) these results are very promising for e.g. the realization of quantum memories based on cavity EIT [2,3], and for observing photon blockade effects at the single photon level.

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The Electrostatic Cryogenic Storage Ring CSR - a storage device for atomic, molecular and cluster ion experiments

R. von Hahn, K. Blaum, F. Fellenberger, M. Froese, M. Grieser, C. Krantz, M. Lange, S. Menk, F. Laux, R. Repnow, A. Shornikov, A. Wolf

Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

The electrostatic **C**ryogenic **S**torage **R**ing CSR (see Fig. 1), a new and technologically challenging project, is presently under construction at the Max-Planck-Institute for Nuclear Physics in Heidelberg. Liquid helium cooling of the entire CSR inner vacuum chambers with a circumference of 35 m will provide a low temperature environment of only a few K, with extremely low blackbody radiation and residual gas density. These conditions are comparable with those in interstellar space and thus open up new research opportunities in many diverse fields ranging from fundamental quantum chemistry and molecular biology (properties of large bio molecules) to astro- and nuclear astrophysics (star formation and interstellar molecular clouds). In order to test the cryogenic, vacuum and mechanical concepts of the CSR, a 4 m long electrostatic ion beam trap operating at around 10 K was successfully developed and commissioned. Serving as a prototype for the CSR, we achieved a residual gas pressure in the 10^{-14} mbar range [1]. The trap is now being used as a new atomic physics instrument to investigate molecular and cluster dynamics at cryogenic temperatures. In addition to its larger linear dimensions and beam energies the CSR will also be equipped with an electron cooling device and act hence as a prototype for the **U**ltra Low Energy **S**torage **R**ing USR, which is planned by the FLAIR (**F**acility of **L**ow Energy **A**ntiprotons and **I**ons **R**esearch) collaboration at FAIR/GSI as a decelerator for antiprotons. The design and status of the CSR project will be reported.

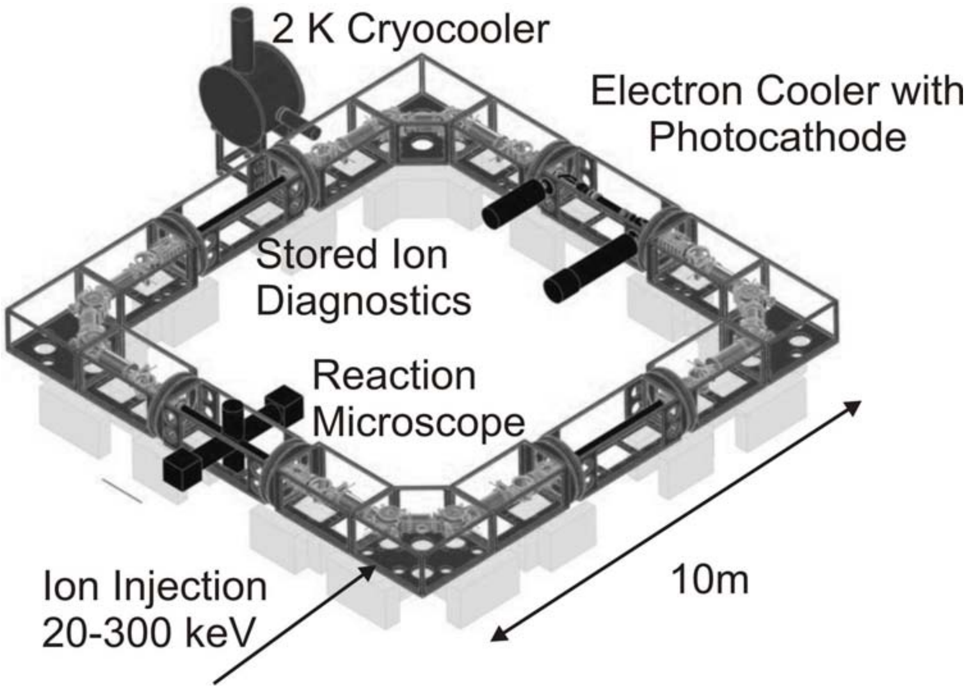

Figure 1: Schematic of the CSR with the connection to the cryocooler and with in-ring experiments. Only the inner cryogenic chambers and outer cryostat chambers are shown, all thermal shields are omitted for better visibility

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Experimental Quantum Simulation with trapped ions

T.Schaetz, Ch.Schneider, M.Enderlein, T.Huber, S.Duewel, J.Stroehle

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

I will provide an overview of the expanding field of experimental quantum simulation with trapped ions reviewing the work that has been done by the dedicated groups.

Experts in the field distinguish between experimental quantum simulations of two different classes. One class deals with problems that are efficiently solvable on classical computers. However, the quantum simulator provides an analogue that allows to experimentally address intriguing questions that are not directly trackable in the laboratory. Examples are described in reference [1] and [2]. The second class of simulations deals with objectives that are (probably fundamentally) not accessible via classical computation, for example, the complex quantum dynamics in solid state systems. However, the aim is not to simulate the effects including all disturbances and peculiarities. Experimental quantum simulations are predicted to allow for investigating "simple" Hamiltonians under very controllable conditions[3,4]. This could allow to test whether simplifying the underlying physics (Hamiltonian) to its suspected basics is capable to reproduce and explain the observed complex behaviour. The obtained results might therefore provide deeper insight, for example, into quantum-phase transitions.

The tutorial will focus on the second class of simulations. In particular, I will reveal the difficulties in describing a quantum system classically for the case of a quantum magnet. I will try to explain the complete mode of operation of a quantum simulator on the basis of this simple model case and refer to experimental results[5]. I will introduce and explain the role of superposition states, entanglement and tunneling (quantum fluctuations) by means of the experimental data gained by the simulation.

Furthermore, I will try to elucidate, how analogue quantum simulations differ from the alternative approach to calculate their results on a future universal quantum computer[6] and discuss the related advantages and disadvantages.

Trapped ions provide one approach towards quantum simulations for many purposes with several advantages compared to other systems. The main challenge of the field remains to achieve scalability towards 50-100 ions and beyond. A simulated system of this size would outperform classical computation and already allow to address questions of interest. Some possible approaches for scaling will be discussed[7,8].

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Laser spectroscopy of trapped thorium ions: Towards a nuclear optical clock

E. Peik, O. A. Herrera Sancho, M. Okhapkin, Chr. Tamm, K. Zimmermann

Physikalisch-Technische Bundesanstalt, Bundesallee 100,
38116 Braunschweig, Germany

The ^{229}Th nucleus possesses an excited state at an energy of only 7.6(5) eV [1], connected with the ground state by a magnetic dipole transition in the VUV ($\approx$160 nm wavelength) with a natural linewidth in the mHz range. This transition may provide the reference for an optical clock that is highly immune to field-induced systematic frequency shifts [2]. Possible systems in which to study optical spectroscopy of the nuclear transition are ions stored in a trap [2,3] or doped into a transparent crystal [2,4,5]. Despite various experimental efforts, so far nobody has succeeded in directly observing this transition and efficient search methods are needed to obtain more precise information on the transition energy. The very dense electronic level structure of Th$^+$ ions [6] will lead to a strong enhancement of the nuclear transition rate via the interaction of the nucleus with the electron shell [7]. In addition, this electron bridge process can be used for an efficient two-photon excitation of the nucleus, so that it is not necessary to work with a VUV laser at this stage.

In our experiment, more than 10^5 ions of the naturally occuring isotope ^{232}Th$^+$ are stored in a linear ion trap after creation by laser ablation from thorium metal. Helium buffer gas is used for collisional cooling and quenching of low-lying metastable electronic levels [9]. Laser excitation of the strong resonance line at 401.9 nm and at several other transitions around 400 nm wavelength has been observed. The next experimental steps will be the investigation of two-photon excitation of the electron shell in order to study the electronic level structure in the energy range of the nuclear excitation. Further optimisation of loading and trapping conditions is required to allow experiments with the more strongly radioactive ^{229}Th$^+$ (halflife 7880 years) with a minimal amount of material.

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Ultrafast Pulsed Laser Gates for Atomic Qubits

W C Campbell, D Hayes, J Mizrahi, D N Matsukevich, Q Quraishi, P Maunz, C Senko, D Hucul, S Olmschenk, and C Monroe

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

Pulsed optical fields from femtosecond mode-locked lasers have found widespread use as tools for precision quantum control of systems with complex spectra, such as diatomic and even polyatomic molecules. Trapped atomic ions, however, have significantly simpler internal structure, and comparatively modest *pico*second mode-locked lasers can provide high power in the UV and are well suited for driving fast quantum gates in trapped ion qubits.

We experimentally demonstrate two distinct regimes of the interaction between hyperfine ^{171}Yb^{+} qubits and stimulated Raman transitions driven by picosecond pulses from a far off-resonant mode-locked laser. In the weak pulse regime, the coherent accumulation of successive pulses from an optical frequency comb performs single qubit gates and sideband cooling and is used to entangle two trapped atomic ion qubits by driving a Molmer-Sorensen gate [1]. In the strong pulse regime, a single pulse is used to implement a fast (< 50 ps) π-pulse with greater than 99% population transfer [2]. The 355 nm center wavelength of the pulse ensures that there is negligible excited state spontaneous emission or differential AC Stark shifts due to the $\mathrm{S} \leftrightarrow \mathrm{P}$ transitions at 369 nm and 329 nm. We also discuss the extension of the strong pulse interactions to obtain full ultrafast single-qubit control and to produce spin-dependent momentum kicks. Such coupling between the qubit state and motion should enable ultrafast entanglement of multiple qubits [3,4].

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Sympathetic cooling and isotopic enrichment in a large Sr+ Coulomb crystal .

S. Guibal, T. Coudreau, L. Guidoni, J.-P Likforman, B. Dubost

Laboratoire Matériaux et Phénomènes Quantiques
Université Paris Diderot, CNRS UMR7162, Bâtiment Condorcet, case 7021
10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex13

We present an experimental setup for trapping Sr^+ ions, laser-cooled down to the Coulomb crystal transition. The setup is based on a linear Paul trap loaded by photo-ionization of a strontium atomic vapor by ultrafast pulses [1]. This efficient loading technique allows for the formation of multi-isotope Sr^+ Coulomb crystals [2] containing more than 10^6 ions.

The isotopic spatial separation inside the crystal is observed by fluorescence imaging. One can identify $88Sr^+$ (82.6%), $87Sr^+$ (7%), $86Sr^+$ (9.9%) and even the rare $84Sr^+$ (0.56%) isotope.

We show that sympathetic cooling can be efficient enough to maintain a large ordered sample by applying laser-cooling only to the $86Sr^+$ ions.

We demonstrate a method for controlling the ratio between the various strontium isotopes population in the ion ensemble. This method is based on a selective radiation pressure force combined to a modulation of the trapping voltage, it leads to the controlled ejection of the unwanted species. We demonstrate the realization of pure crystals with $88Sr^+$ or $86Sr^+$ as well and the control of their ratio.

The very large number of trapped ions available in this setup, the possibility to vary the isotopic composition of the sample, and the efficiency of sympathetic cooling by less than 10% of the total ion number, makes it a suitable tool for quantum optics experiments with non-perturbed ions, or cold molecular ions formation and spectroscopy.

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Structural defects in ion crystals by quenching the external potential: the inhomogeneous Kibble-Zurek mechanism

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Alex Retzker

Institut für Theoretische Physik, Universität Ulm, D-89069 Ulm, Germany

The non-equilibrium dynamics of an ion chain in a highly anisotropic trap is studied when the transverse trap frequency is quenched across the value at which the chain undergoes a continuous phase transition from a linear to a zigzag structure. Within Landau theory, an equation for the order parameter, corresponding to the transverse size of the zigzag structure, is determined when the vibrational motion is damped via laser cooling. The number of structural defects produced during a linear quench of the transverse trapping frequency is predicted and verified numerically. It is shown to obey the scaling predicted by the Kibble-Zurek mechanism, when extended to take into account the spatial inhomogeneities of the ion chain in a linear Paul trap.

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Polyatomic ions in traps: from molecules via clusters to nanoparticles.

D Gerlich

Charles University in Prague, Faculty of Mathematics and Physics 121 16 Prague, Czech Republic

Many trapping instruments have been developed in the last decades for studying the structure of molecular ions, various collision processes with ions (bimolecular reactions, radiative association, growth of clusters), and the physics and chemistry of charged nanoparticles. Long storage times (days and longer) lead to extreme sensitivities. Experiments have been performed at pressures ranging from the extreme UHV to atmospheric conditions and over a wide range temperatures. While buffer gas cooling is used to cool molecular ions to a few Kelvin, continuous CO_2 laser heating of a stored ensemble allows one to determine physical and chemical properties at several thousand Kelvin.

A major part of storage devices is based on inhomogeneous rf fields created by suitable multi electrode arrangements [1]. While quadru-, hexa-, octo- or 22-poles gain more and more popularity, ring electrode traps (see Figure 1) or more complex geometrical structures such as ion labyrinths are less common.

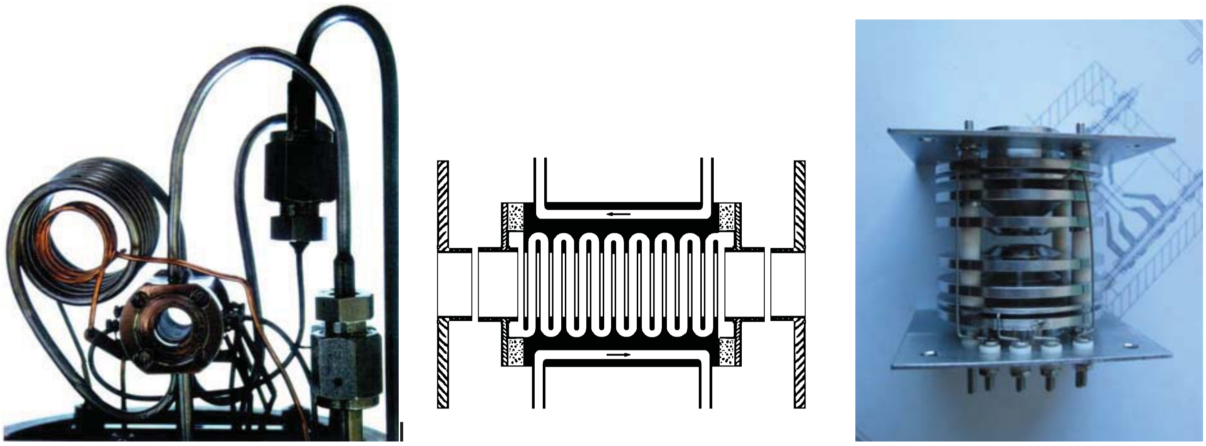

Figure 1. First (1988)l-N2 cooled rf - RET (ring electrode trap), our new SRET

A rather young and unexplored field is the confinement of individual charged nano- or micrometer sized particles and their interaction with electrons, atoms and/or photons. These stored objects are observed either via light scattering, laser induced fluorescence or thermally emitted photons. Recording their motion in a harmonic potential allows one to determine the mass to charge ratio with high resolution (NPMS technique, $\Delta m/m<10^{-6}$, see [2]).

In this tutorial talk I will start with a short introduction into the trapping technology and its history and give some practical hints and advices. Then, I will present a collection of highlights from the past illustrating the wide range of applications in fundamental physics, spectroscopy, astro-chemistry, mass spectrometry and material science. I also will mention a few interesting low temperature processes which have been summarized recently in the book, entitled *Low temperatures and cold molecules* [3]. Ongoing and planned new developments include buffer gas cooling below 1 K, superimposing rf and magnetic fields, and the development of small compact traps using superconducting material.

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ClusterTrap: A Penning trap for cluster research

Lutz Schweikhard

Institute of Physics, University of Greifswald, D-17387 Greifswald, Germany

Ion traps can be used as “wall-less containers” to study the properties of free clusters. In particular, they allow extended interactions periods, time-resolved measurements in the tens-of-ms regime, and the application of (several) preparatory steps such as accumulation and size selection of the cluster ensemble, cooling of the ion motion, or transfer of the clusters to charge states not provided by the ion source. After the potential of such advices had been envisioned [1] a dedicated Penning-trap setup was built in the 1990’s [2].

In the following years several types of cluster investigations have been performed as indicated in Fig. 1: Collision-induced dissociation [3], electron-impact ionization/dissociation [4], attachment of sensor molecules followed by IR-laser detachment [5], as well as ns-pulsed laser excitation for the monitoring of delayed dissociations in connection with radiative-cooling studies [6] or the determination of dissociation energies [7].

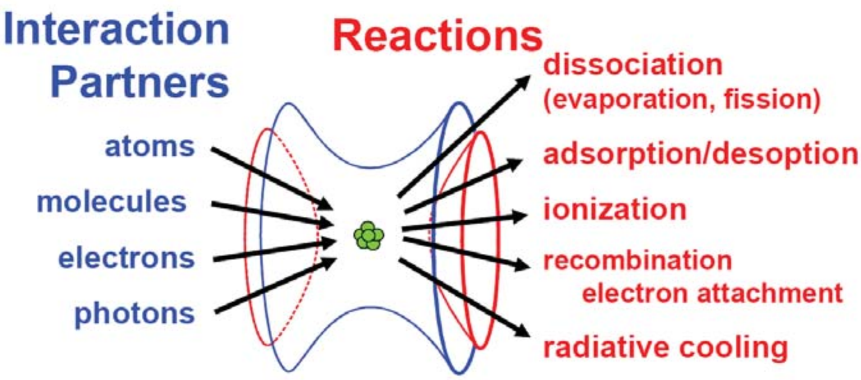

Figure 1. Overview of interaction partners of stored cluster ions and resulting reactions.

After the invention of a method to attach further electrons to already negatively charged species [8], the ClusterTrap experiments have concentrated on the production and study of multiply-negatively charged clusters [9], including the first observation of tri- and of tetra-anionic aluminum clusters [10]. When the setup was recently moved to a new location several modifications have been implemented. The contribution will give an overview of the earlier studies as well as a description of the new features.

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Hot Topics Abstracts

Optical Trapping of an Ion

S. Duewel[1], T. Huber[1], C. Schneider[1], J. Stroehle[1], M. Enderlein[1] and T. Schaetz[1]

[1] Max-Planck-Institut for Quantum Optics, Garching, Germany

Direct experimental access to some of the most intriguing and puzzling quantum phenomena is difficult due to their fragility to noise. Their simulation on conventional computers is impossible, since quantum behavior is not efficiently translatable in classical language. However, one could gain deeper insight into complex quantum dynamics via experimentally simulating the quantum behaviour of interest in another quantum system, where not all but the relevant parameters and interactions can be controlled and robust effects detected sufficiently well. One example is simulating quantum-spin systems with trapped ions. We had been able to perform the proof of principle experiment by simulating the transition of a quantum magnet with two spins. A promising approach to reach scalability is based on an array of rf-surface traps. An alternative approach might be to combine the advantages of trapped ions with optical lattices.

As a first experimental step, we were able to trap an ion in an optical dipole trap. We initialize the ion via trapping and laser cooling in our linear Paul trap (A), turn on the optical dipole trap and switch off the Paul trap (B). The ion's survival is detected via resonance fluorescence in the reactivated Paul trap. The measured lifetime of milliseconds allows for hundreds of oscillations within the optical potential. It is mainly limited by heating due to photon scattering. Recently we achieved trapping of an ion in a 1D optical lattice.

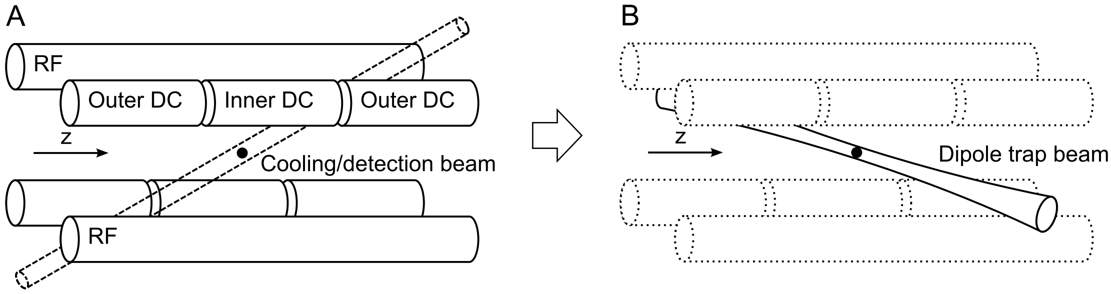

Figure 1: A) Ion confined in a conventional Paul trap B) Ion trapped an optical dipole trap, whereas the RF trap is completely disabled. The confinement along the axial direction of the dipole trap beam is provided by DC voltages

In the near future, we plan to realize cooling to increase the lifetime and to investigate the limitations on the coherence times. Loading two ions and/or one ion and atoms into the identical one-dimensional optical lattice could be explored. This approach demonstrates not only the feasibility of optically trapping ions, but allows to dream of scalable quantum simulations providing long range interaction and individual addressability. In addition, a new class of quantum simulations might become accessible, based on the potentially intriguing interplay between neutral and charged particles in common optical lattices. Furthermore, confining an ion and atoms in one common optical dipole trap might allow to investigate the most interesting physics of ultra cold collisions without the limitations set by radio-frequency driven micro-motion.

Quantum simulation with trapped atomic ion spins

E. E. Edwards[1], R. Islam[1], S. Korenblit[1], K. Kim[1], M.-S. Chang[1], C. Monroe[1] G.-D. Lin[2], L.-M. Duan[2], J. Freericks[3]

[1]Joint Quantum Institute: Department of Physics, University of Maryland, and National Institute of Standards and Technology, College Park, Maryland 20742, USA
[2] MCTP, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA
[3]Department of Physics, Georgetown University, Washington DC 20057, USA

A quantum simulator has the ability to start in a well-known state and adiabatically follow a changing Hamiltonian, whose ground state at a later time may describe a complex, often classically incalculable state. To achieve this goal, we first experiment with finite-sized systems where the ground state and all parameters can be calculated, and subsequently increase the system size in a controlled manner.

We experimentally simulate the transverse-field long range Ising model using a collection of trapped atomic $^{171}Yb^{+}$ ions [1,2,3,4]. The phase diagram contains interesting features such as quantum phase transitions (QPT) and first order transitions due to frustration *i.e.*, competition between spin-spin couplings. The ground-state spin order is a function of the signs and strengths of the Ising couplings, which are precisely controlled through the detuning of bichromatic Raman laser beams from the motional modes [5,6]. In the simplest version of this experiment the spin-spin couplings are ferromagnetic and, in the thermodynamic limit, the system exhibits a QPT from a paramagnet to a ferromagnet. In this special case, the Ising couplings are ideally uniform and the ground state can be calculated for N>100 spins. However, the calculation becomes intractable for N>20 when inhomogeneities from the ion trap and/or explicit anisotropic spin couplings are included. In the experiment, the spins are initially polarized along a transverse effective magnetic field and the Ising interactions are switched on, while the transverse field is adiabatically reduced. The probabilities of different magnetic orders for system sizes of up to ~10 spins are measured through state-dependent fluorescence. Because the interactions are mediated through transverse modes of motion, this system is scalable to much larger numbers of spins where classical simulations of the Ising model are intractable. We also report progress on implementing anharmonic, multi-segment micro- and surface-traps that can stably hold larger numbers of nearly equally spaced ions. These architectures will also potentially allow us to extend the simulation to other spin models and individual address qubits.

This work is supported by the Army Research Office (ARO) with funds from the DARPA Optical Lattice Emulator (OLE) Program, IARPA under ARO contract, the NSF Physics at the Information Frontier Program, and the NSF Physics Frontier Center at JQI.

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H_2^+ spectroscopy : vibrational ground state preparation by UV photodissociation

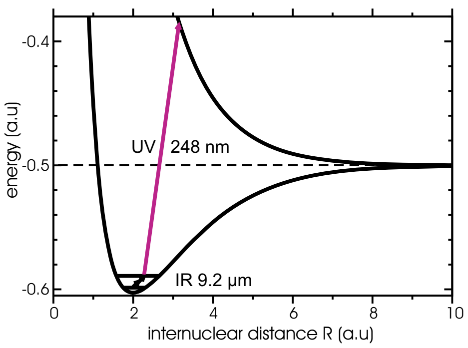
L Hilico, R Osseni, A Douillet, J-Ph Karr

Laboratoire Kastler Brossel, UPMC-Paris 6, ENS, UEVE, CNRS ; Case 74, 4 place Jussieu, 75005 Paris, France

The H_2^+ metrology project aims at observing and measuring a Doppler-free two-photon vibrational transition in order to provide a direct optical measurement of the electron to proton mass ratio with a relative accuracy at the 0.1 ppb [1] level by resonance enhanced multiphoton dissociation (REMPD). As shown in figure 1a, two infrared photons at 9.2 μm drive the vibrational transition while 248 nm photons photodissociate the ions.

Several challenges have to be overcome. The first one is the realization of a kHz width cw infrared laser [2,3]. The second one is the preparation of a trapped H_2^+ ion cloud in the vibrational ground state $v = 0$ by v selective UV photodissociation [4].

We will present the present status of the experiment and focus on the photodissociation process analysis (see figure 1b). Our recent results concerning vibrational state selected H_2^+ ion production show that we are able to produce an ion cloud with 93% in the v=0 level and 7% in the v=1 level. We will finally discuss the expected two-photon transition signal with the present experiment and further improvements of the setup, especially concerning H_2^+ production by a REMPI process from H_2 molecules.



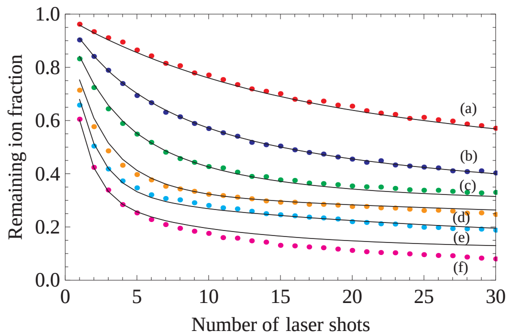


Figure 1: (a) H_2^+ electronic energy curves at the Born-Oppenheimer approximation. (b): Remaining H_2^+ ion fraction after a 1 s creation and 0.3 s photodissociation process versus the number of UV laser pulses. The pulse energies are indicated in the figure. Full lines (a) to (e) are obtained by a global fit of the data by a simple model taking into account the UV beam and ion cloud geometry. Full line (f) is an extrapolation of that model at high energy.

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A single-ion Quantum Lock-in amplifier

S. Kotler, N. Akerman, Y. Glickman, A. Keselman, Y. Dallal and R. Ozeri

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Invented by Robert Dicke, the lock-in amplifier is a phase sensitive detector that can extract a signal with a known carrier frequency from an extremely noisy environment. Here we use a single trapped Sr^+ ion as a quantum lock-in amplifier. We modulate a Zeeman, ground-state, superposition of the ion and are thus able to measure magnetic field fluctuations at the modulation frequency with a, projection noise limited sensitivity bellow 100 pT/√Hz. With a modulation frequency of around one kHz we are thus able to maintain phase coherence up to a time exceeding one second. A theory is developed to interpret the phase visibility due to signals in the strong coupling regime where the accumulated superposition phase shift is larger than 2π.

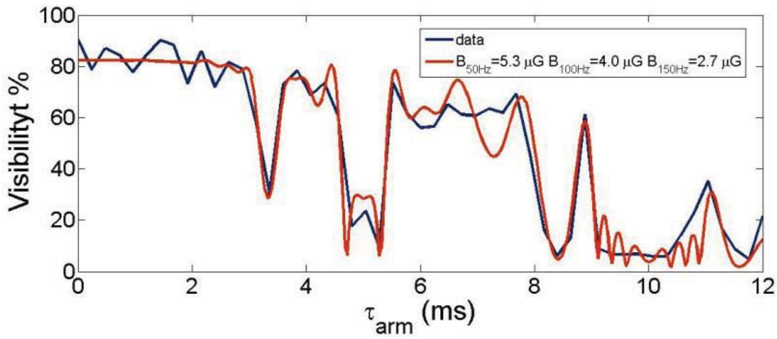

Figure 1. Phase contrast Visibility as a function of the lock-in modulation period. Signature of magnetic field noise components at 50, 100 and 150 Hz are apparent. Blue solid line is data, red solid line is the best fitted theory.

Using the same method we measure the light shift induced by a laser close to resonance with a narrow quadruple transition. Light shifts are measured with a, projection-noise limited, sensitivity of 2 Hz/√Hz.

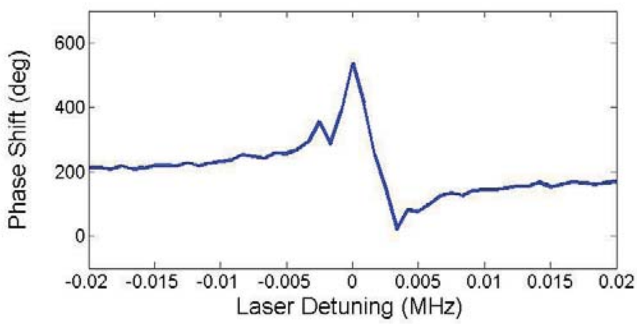

Figure 2. Phase shift due to the accumulate light shift of an intensity modulated laser vs. the laser detuning from a narrow quadruple transition. Here a maximal light shift value of 50 Hz is measured roughly 1 kHz from resonance.

Quantum simulation of the Klein paradox

B. Lanyon[1,2], R. Gerritsma[1,2], G. Kirchmair[1,2], F. Zahringer[1,2], C. Hempel[1,2], J. Casanova[3], J. J. García-Ripoll[5], E. Solano[3,4], R. Blatt[1,2] and C. F. Roos[1,2]

[1] Institute for Quantum Optics and Quantum Information (IQOQI), Innsbruck, Austria
[2] Institut für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria
[3] Departamento de Química Física, Universidad del País Vasco - Euskal Herriko Unibertsitatea, Apartado 644, 48080 Bilbao, Spain
[4] IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain
[5] Instituto de Física Fundamental, CSIC, Serrano 113-bis, 28006 Madrid, Spain

In 1929 Oskar Klein obtained a surprising result when investigating the scattering of a relativistic electron from an electrostatic potential barrier using the Dirac equation. Klein found that the electron can propagate through the barrier, without damping, and that the probability for this happening increases with the barrier height — a result now commonly known as the Klein paradox. Since direct experimental investigations are lacking, and would be very challenging, the Klein paradox remains a much debated and investigated topic in relativistic quantum mechanics. Driven by the experimental inaccessibility of relativistic quantum systems there has been recent interest in performing quantum simulations. In this talk I will present experimental results from a quantum simulation of a relativistic particle interacting with various external potentials, using a pair of trapped ions, and the subsequent observation of Klein tunneling.

Super-fast Laser Cooling of Trapped Ions

S Machnes[1,2], M B Plenio[2], B Reznik[1], A M Steane[3] and A Retzker[2]

[1] Department of Physics and Astronomy, Tel-Aviv University, Tel Aviv 69978, Israel
[2] Institut für Theoretische Physik, Universität Ulm, D-89069 Ulm, Germany
[3] QOLS, The Blackett Laboratory, Imperial College London, Prince Consort Rd., SW7 2BW, UK

Currently laser cooling schemes are fundamentally based on the weak coupling regime. This requirement sets the trap frequency as an upper bound to the cooling rate. In this work we propose a novel method of cooling in the strong coupling regime, allowing for cooling rates that are significantly faster than the trap frequency, with experimentally feasible parameters, capable of cooling medium sized ions chains close to the ground state.

We begin with an insight for a cooling procedure designed for the experimentally infeasible impulsive limit. Then, using optimal-control techniques to search over the space of realizable coupling-sequences between the phonons and the ion's internal levels, we are able to adapt the infeasible procedure to feasible parameters, producing red-sideband -like operations and achieving cooling at a rate higher than the trapping frequency. A detailed numerical study proves the proposed method to be robust in the face of noise in laser timing, power and imperfect reinitializations of the ions, thus fulfilling the requirements for a good experimental technique [1].

Furthermore, the underlying insights described above are applicable to a very wide range of systems and for a wide range of applications, such as super-fast acting gates and super-fast cooling of nano-mechanical oscillators, where its application may allow reaching the ground state, overcoming the limitation imposed by the finite Q factor.

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Controlled Interaction of a Single Trapped Ion with Heralded Single Photons

Nicolas Piro, Joyee Ghosh, Jan Huwer, Marc Almendros, Felix Rohde, Carsten Schuck, Francois Dubin, **Jürgen Eschner**

Experimental Quantum Optics Group, ICFO -- Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

A key task in quantum networks is the distribution of entanglement between distant atomic qubits that serve as nodes. Recently, this has been demonstrated experimentally [1] through an approach that uses the projective measurement of the photons emitted by the two distant atoms to entangle them. Another strategy to implement this efficiently is to generate entangled photon pairs by spontaneous parametric down-conversion (SPDC), and make them interact with the distant atoms, transferring the entanglement from photon to atomic qubits [2, 3]. We present a step towards such entanglement transfer: the absorption of a single down-conversion photon by a single $^{40}Ca^{+}$ ion, heralded by the partner photon.

Using type-II spontaneous parametric down-conversion in a ppKTP crystal, we generate time-correlated, frequency and polarization-entangled photon pairs [4]. One photon mode is coupled into a filtering line consisting of two cascaded Fabry-Perot cavities, which are tuned to the 854 nm transition in $^{40}Ca^{+}$. The light transmitted through these cavities matches the atomic transition linewidth of 22 MHz and is monitored by a single-photon detector. The second, correlated, photon mode is focused onto a single trapped $^{40}Ca^{+}$ ion through a high-numerical-aperture lens. The ion trap setup is described in [5].

A photon absorption event induces a quantum jump, detected as a sudden change in the fluorescence rate of the ion [6]. The photons detected behind the filter cavities herald the presence of a resonant partner photon at the ion. The correlation function of the arrival times of the filtered photons and the quantum jumps introduced by the partner photons reveals coincidences between the two events. Additionally, the polarization dependence of this process is demonstrated after suitable preparation of the ion in Zeeman substates [7], showing its suitability as a tool in quantum optical information technology.

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Scalable quantum technology with trapped Ytterbium ions

A. H. Nizamani[1], J. J. McLoughlin[1], J. D. Siverns[1], R. C. Sterling[1], M. D. Hughes[1], B. Lekitsch[1], B. Stein[1], S. Weidt[1], M. Bevan-Stevenson[1], P. Srinivasan[2], H. Rattanasonti[2], D. Brown[3], K. Schwab[3], M.Kraft[2] and W. K. Hensinger[1]

[1]Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK
[2]School of Electronics and Computer science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[3]Department of Applied Physics, 219 Steele, Caltech, 1200 E. California Blvd, Pasadena, CA 91125, USA

Ion trapping provides a promising tool towards the implementation quantum information processing, with long coherence times and quantum algorithms having been demonstrated. At Sussex, we are concentrating on scaling up ion trap quantum technology. Microfabricated ion trap chips are the most feasible architecture for scalable ion trap quantum information processing. We present progress on the design and fabrication of multi-zone surface-electrode ion trap arrays using micro-electromechanical (MEMS) fabrication technologies. One such array consists of a silicon-on-insulator (SOI) wafer in which all dielectrics are optically and electrically shielded. Another design consists of multi-layered gold electrodes resulting in a cantilever design which overlaps lower lying electrodes allowing the shielding of the dielectric layer from the ion.

The separation of ions within an ion trap array is crucial for most quantum information implementations with trapped ions. We show how such ion trap structures have to be designed for optimal separation to occur and how surface ion traps can be optimised for optimal trap depth [1]. We also report on our studies for the development of optimal junctions within ion trap arrays.

Two-dimensional lattices of trapped ions have been proposed as a suitable system for performing quantum simulations of spin systems. Using Bio-Savart-like analytical field calculation, in the gapless plane approximation, we show how to optimise a 2D array of island electrodes and show our progress in fabricating such structures.

We present the design and operation of an ytterbium ion trap experiment with a setup offering versatile optical access and 90 electrical inter-connects that can host advanced surface and multi-layer ion trap chips mounted on chip carriers. We operate a macroscopic ion trap compatible with this chip carrier design and characterise its performance, demonstrating secular frequencies $>$1 MHz, and trap and cool nearly all of the stable isotopes, including ^{171}Yb^{+} ions, as well as ion crystals. We measure the motional heating rate of this particular ion trap and obtain a spectral noise density $S_E(1$ MHz) = 3.6(9)$\times10^{-11}$ V^{2}m^{-2}Hz^{-1} at an ion electrode spacing of 310(10) μm, and we observe $\langle \dot{n} \rangle \propto 1/\omega^2$ behaviour. We describe the experimental setup for trapping and cooling Yb^{+} ions and provide frequency measurements of the $^2S_{1/2}\leftrightarrow^2P_{1/2}$ and $^2D_{3/2}\leftrightarrow^3D[3/2]_{1/2}$ transitions for the several stable Yb^{+} isotopes which are more precise than previously published work [2].

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Sympathetic cooling of rovibrationally state-selected molecular ions

Xin Tong, Alexander H. Winney and Stefan Willitsch

Department of Chemistry, University of Basel, Klingelbergstrasse 80, 4056 Basel, Switzerland

We present a new method for the generation of rotationally and vibrationally state-selected, translationally cold molecular ions in ion traps. Our technique is based on the state-selective threshold photoionization of neutral molecules followed by sympathetic cooling of the resulting ions with laser-cooled calcium ions. Using N_2^+ ions as a test system, we achieve > 90 % selectivity in the preparation of the ground rovibrational level and state lifetimes on the order of 15 minutes limited by collisions with background-gas molecules. This technique can be employed to produce a wide range of apolar and polar molecular ions in the ground and excited rovibrational states. Our approach opens up new perspectives for cold quantum-controlled ion-molecule-collision studies, frequency-metrology experiments with state-selected molecular ions and molecular-ion qubits.

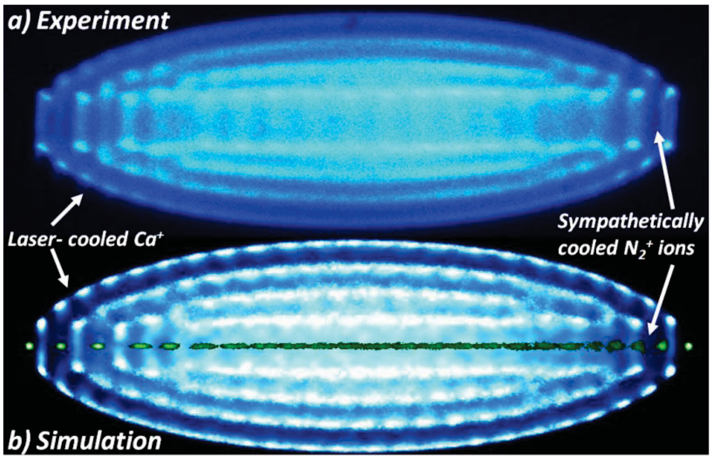

Figure 1. Bicomponent Coulomb Crystal of Ca^+ and state-selected N_2^+ ions**.**

A single ion in line with an optical fiber

A Wilson, H Takahashi, A Riley-Watson, A Mortensen, F Orucevic, P Blythe, D Crick, N Seymour-Smith, E Brama, M Keller, and W Lange

Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK

Interfacing quantum information between ions and photons is a task of central importance for the realization of quantum networking [1], which promises to combine the advantages of ion-trap quantum information processing with long-distance transmission of qubits via optical fibers.

A requirement for an interface is the efficient coupling between ions and photons without compromising the stability of the trap. This can only be achieved by a tight integration of trapping structures and optical fibers. We have realized a compact setup, based on a miniature Paul trap (endcap trap) in which a single ion is stored between two rf-rods [2]. By using tubular rods, optical fibers can be run inside the electrodes and therefore brought into close proximity with the ion (250 μm in this case) without any disturbance to the trapping field (Fig. 1). We have reliably stored and cooled single ^{40}Ca^{+} ions in this way and compensated the rf-micromotion.

The setup has a wide range of applications. We have employed the two fibers for high efficiency collection of fluorescent light, generated by driving the ion with a 397 nm laser perpendicular to the trap axis and repump lasers. Two photomultipliers at the end of each fiber serve as detectors. We were able to capture 6% of the solid angle (cf. [3]) with an excellent signal to background ratio of better than 50. With a single ion emitter, nonclassical light with antibunched photon statistics is generated. We have demonstrated this by measuring the cross-correlation of photon counts at the fiber outputs.

The experiment is an important step on the way to coupling a single ion to a fiber-optical cavity [4]. Towards this goal, the end facet of one fiber will be machined to a concave shape with short CO_2-laser pulses and both facets coated with a low-loss reflective coating.

Ion-photon interaction can also be used to create local entanglement between multiple qubits coupled to a single cavity mode. In two separate experiments, we combine linear traps and minature conventional mirrors as used in Ref. [5] to investigate probabilistic and deterministic schemes for entanglement generation.

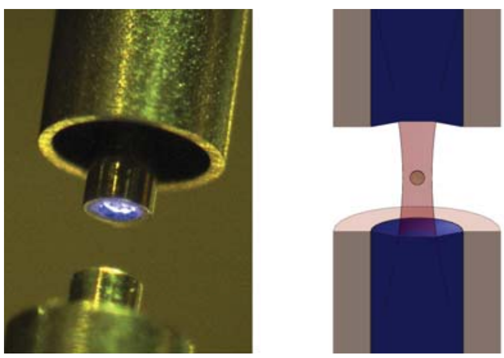

Figure 1.

Highly integrated trap-fiber setup: a single ion is trapped between the two electrodes of an endcap trap. The end facets of a fiber inside the hollow electrodes collect the ion's fluorescence with high efficiency. The image shows the central rf-electrodes containing the fiber, surrounded by cylindrical ground electrodes.

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Poster Abstracts

A single-ion nonlinear mechanical oscillator

N. Akerman, S. Kotler, Y. Glickman, A. Keselman, Y. Dallal and R. Ozeri

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

A driven, damped, nearly harmonic oscillator with a small cubic term in the force, is known as the Duffing oscillator. The Duffing oscillator shows various interesting features of non-linear response such as bistability and hysteresis. Several features of the Duffing instability have been recently measured using superconducting qubits and nano-mechanical resonators. Linear Paul traps can be well approximated as harmonic but have a small an-harmonicity due to their deviation from an ideal quadruple geometry. We study the steady state motion of a single trapped Sr^+ ion, subject to a near-resonance drive and dissipation in a linear Paul trap with a small anharmonicity. The driving force is applied by an oscillating voltage on the trap end-caps.

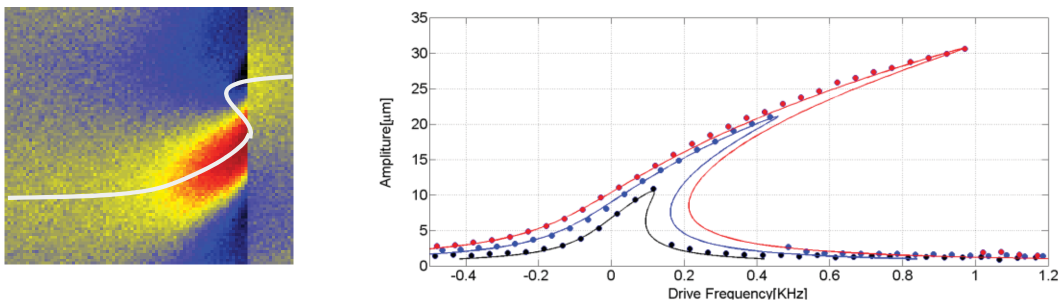

Figure 1. On the left, a two-dimensional map showing the phase of the ion-oscillator vs. drive frequency. A clear phase jump is apparent at the nonlinear critical point. White solid line shows the theoretical Duffing prediction. On the right is plotted the amplitude of the ion-oscillator for three different drive force amplitudes vs. drive frequency. Solid lines are the Duffing equations solutions for our experimental parameters.

Dissipation is the result of laser Doppler cooling. We measure both the amplitude and phase of the driven oscillations and find a good agreement with the Duffing oscillator model. When the cooling laser is close to resonance the standard Duffing model has to be extended to account for non-linearity in the dissipative force. Both the linear and the nonlinear terms of the dissipative force for various cooling laser detunings are determined by the line-shape of the - cooling transition and the cooling laser intensity and can therefore be conveniently controlled.

The Oxford Planar Ion Trap Project

D T C Allcock, T P Harty, H A Janacek, D J Szwer, J A Sherman, D N Stacey, A M Steane and D M Lucas

Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK

The Oxford Planar Ion Trap project currently involves three traps:

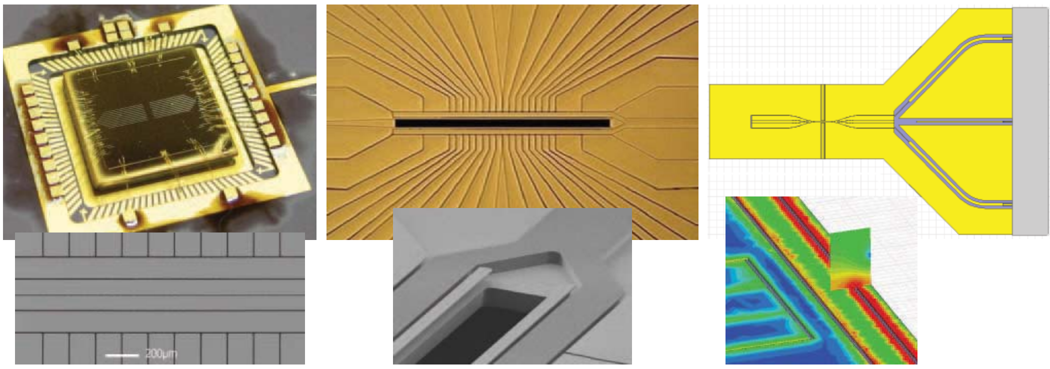

Figure 1: Trap 1 (left) and detail of trapping region (inset). Trap 2 (centre) and detail of electrode structure (inset). c) Trap 3 (right) and simulation of microwave currents and fields (inset).

Trap 1: A gold-on-quartz surface trap with a 150μm ion-surface separation, designed and fabricated at Oxford. This trap was used to develop the capability to design, fabricate and operate planar traps within the group. The trap incorporates a split centre dc electrode to allow the principle axes of radial motion to be rotated to optimize laser cooling. Improved methods for micromotion compensation and heating rate measurement were also developed using this trap [1].

Trap 2: Sandia National Laboratories have fabricated a monolithic silicon half-size revision of Trap 1. This fabrication method allows the removal of all dielectrics with line-of-sight to the ion and may reduce anomalous heating and trap charging effects. The trap incorporates a slot that in a future version will be able to accommodate a fiberized optics package for laser delivery and fluorescence collection. This trap is currently under test and preliminary results will be presented.

Trap 3: This trap is currently being fabricated using the same process as Trap 1 and will be used to implement microwave-driven two-qubit gates. The qubit will be a hyperfine ‘clock’ transition in ^{43}Ca^{+} and the gate will be a Mølmer-Sørensen gate as described in [2]. In order to reduce the required microwave drive power we have designed a chip which incorporates a microwave build-up cavity into its structure. As the gate requires no lasers or sub-Doppler cooling the reduction in experimental overhead over laser-driven gates will be substantial.

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Precision Spectroscopy of Highly Charged Ions at SPECTRAP

Z. Andjelkovic[1], S. Bharadia[2], D.M. Segal[2], R.C. Thompson[2] and M. Vogel[1]

for the SPECTRAP collaboration

[1]GSI Helmholtzzentrum für Ionenforschung, Darmstadt, Germany
[2] Imperial College London, United Kingdom

Highly charged ions (HCI) feature a number of interesting properties other than the mere high charge state. Especially in few-electron ions the extremely strong electric field of the nucleus drastically changes the properties of the electronic system such as energy level spacings, lifetimes and magnetic moments. In turn, the electrons serve as sensitive probes for nuclear properties such as size, magnetic moment and spatial distribution of charge and magnetization. The energy of forbidden transitions such as fine structure and hyperfine structure transitions strongly depends on the nuclear charge and shifts from the microwave domain into or close to the optical domain. Thus, they become accessible to laser spectroscopy and its potentially high precision. The SPECTRAP experiment at GSI, Darmstadt, aims at a high-precision measurement of such optical transitions by laser spectroscopy of cooled ions confined in a Penning trap at cryogenic temperatures.

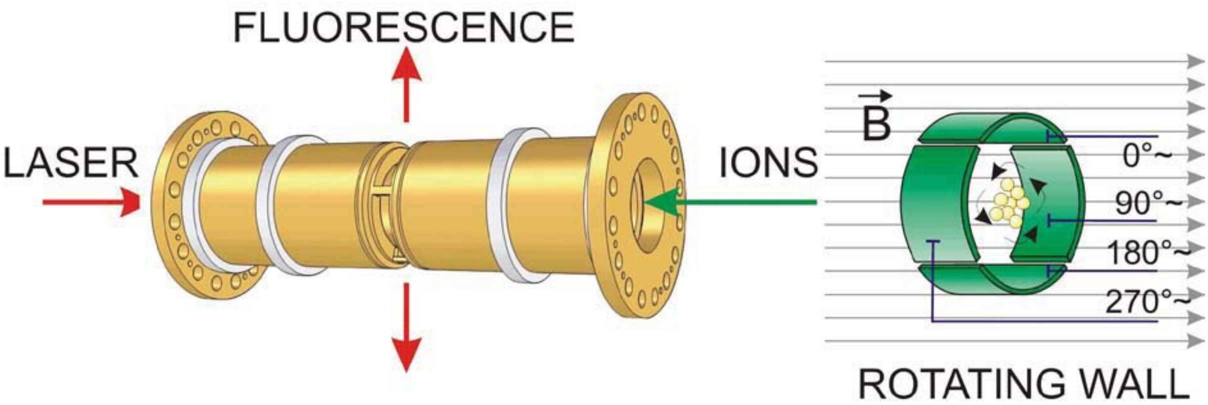

Figure 1. Schematic of the Penning trap used for the experiments (left) and the scheme for the “rotating wall” used for radial compession of the ions inside the trap (right).

We have built two identical traps - one under test at GSI for use with HCI and one being used for preliminary experiments at Imperial College. This latter trap is used with Ca^+ ions that can be laser cooled and imaged through a hole in the ring electrode. We are using this trap to gain experience with the rotating wall technique. We present the setup currently being tested at GSI and related results obtained at Imperial College London.

Experimental multiparticle entanglement dynamics induced by decoherence

J. T. Barreiro,[1]* P. Schindler,[1] O. Gühne,[2,3] T. Monz,[1]
M. Chwalla,[1] C. F. Roos,[1,3] M. Hennrich,[1] and R. Blatt[1,3]

[1]Institut für Experimentalphysik, [2]Institut für Theoretische Physik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
[3]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

Multiparticle entanglement leads to richer correlations than two-particle entanglement and gives rise to striking contradictions with local realism, inequivalent classes of entanglement, and applications such as one-way or topological quantum computing. When exposed to decohering or dissipative environments, multiparticle entanglement yields subtle dynamical features and access to new classes of states and applications. Here, using a string of trapped ions, we experimentally characterize the dynamics of entanglement of a multiparticle state under the influence of decoherence. By embedding an entangled state of four qubits in a decohering environment (via spontaneous decay), we observe a rich dynamics crossing distinctive domains: Bell-inequality violation, entanglement superactivation, bound entanglement, and full separability (see Fig. 1). We also develop new theoretical tools for characterizing entanglement in quantum states. Recent quantum-computing, state-engineering, and simulation paradigms driven by dissipative or decohering environments [1] can benefit from the environment engineering techniques here demonstrated.

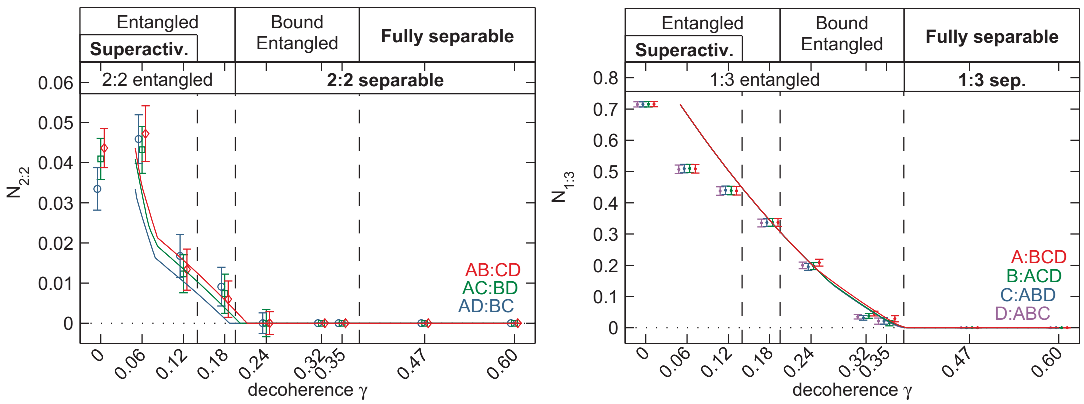

Figure 1. Negativity for each 2:2 and 1:3 bipartition as a function of decoherence. Bipartitions data were slightly offset horizontally for clarity, but all visible groups correspond to the same amount of decoherence indicated by the tick marks. The solid lines were calculated by decohering the initial state with a 0.05 offset in γ. The properties shown in bold were determined by tests independent of the plotted data.

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Interfacing Ions with Nanofibres.

M Brownnutt[1], B Ames[1], A Rauschenbeutel[2], and R Blatt[1,3]

[1] Institut für Experimentalphysik, Uni. Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria

[2] QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz

[3] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria

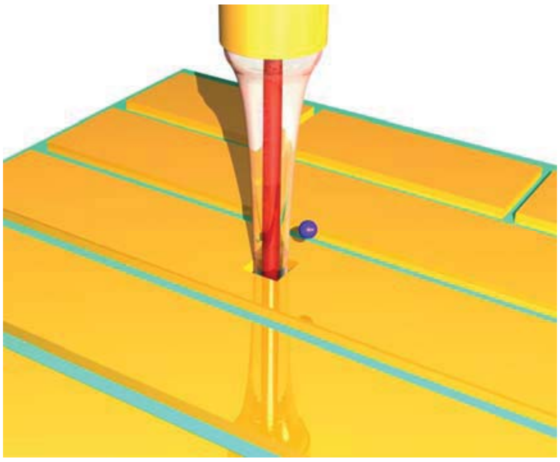

Figure 1. Nanofibre through a surface-design Paul trap, to interact with an ion via evanescent -wave coupling.

In creating scalable quantum networks, one would like to be able to transfer quantum information between a number of separate qubit registers. Given the advances made in trapped ion quantum information processing, ions make a natural choice of physical qubit in a register. By contrast, the ability to reliably transmit light over long distances makes photons a natural choice for flying qubits to connect the registers. The best way to interface these two systems remains an open question. Nano-fibres–with a diameter smaller than an optical wavelength–can support an evanescent field extending significantly outside the fibre. Recent work has shown progress in coupling neutral atoms to such an evanescent field [1], and many new research avenues could be made available by extending such work to ion-fibre coupling.

Implementation of such an ion-fibre system is not without technical and physical challenges, and its realisation requires work in a number of areas. New trap designs must be constructed to allow trapping of the ion so close to a surface (e.g. Fig. 1). Further work is required in understanding the causes and suppression of anomalous heating – an ion-heating mechanism by which the heating rate increases dramatically with reduced ion-surface separation. This must be addressed as the few hundred nm separation required for interaction with the evanescent wave will set a new proximity record for ions. Approaching the issue from the other direction, superfast cooling techniques could be investigated and applied, by which the cooling rate can be significantly higher than the ion's motional frequency [2]. These challenges will be discussed and a number of possible solutions proposed.

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Scalable simultaneous multiqubit readout using an EMCCD camera with 99.99% single-shot fidelity

A H Burrell, D J Szwer, N M Linke, S C Webster, A M Steane and D M Lucas

Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK

We have recently demonstrated high-fidelity single-shot readout of a trapped-ion multi-qubit register using an Electron-Multiplying CCD camera [1]. For an optical qubit stored in a single $^{40}\mathrm{Ca}^+$ ion we measure $0.9(3) \times 10^{-4}$ readout error in $400\,\mu$s exposure time, limited by the qubit's decay lifetime. For a four-qubit register, we measure an additional cross-talk error of only $0.1(1) \times 10^{-4}$ per qubit, despite the presence of 4% optical cross-talk between neighbouring qubits. This is achieved by applying a maximum likelihood analysis which takes into account the known spatial distribution of the fluorescence and the states of nearest-neighbour ions. Since we only find it necessary to include the effects of nearest-neighbours, the method scales readily to large arrays. A typical CCD could simultaneously read out ~ 10000 qubits, with a typical readout time of $\sim 1\,\mu$s per qubit.

We present simulations exploring the parameter space associated with the problem of qubit measurement by resonance fluorescence detection, including the effects of CCD resolution, CCD noise and ion separation [2]. In particular, we note that the maximum likelihood analysis allows a significant improvement in state inference (compared to a standard thresholding technique), even when ions are spaced at or below the diffraction limit. A cross-talk error below 1×10^{-4} is possible with the ions separated by just one Airy radius.

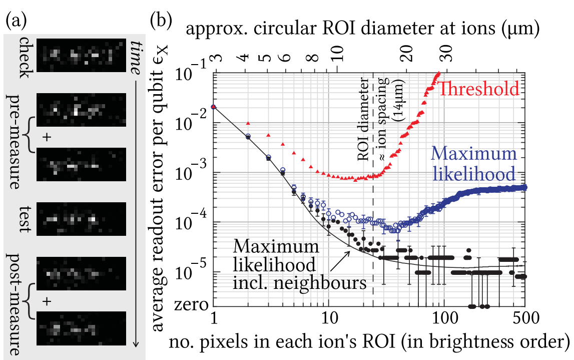

Figure 1: Four-ion readout experiment. (a) Experimental sequence, showing a typical trial. (b) Cross-talk error ϵ_X per qubit averaged over trials of all 16 four-ion states.

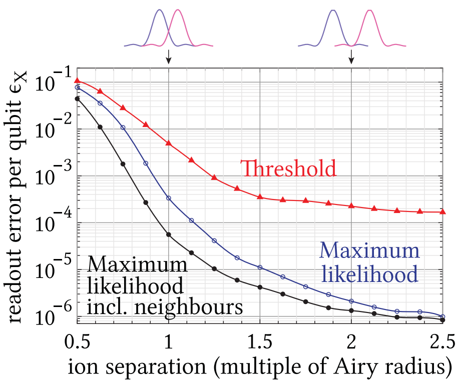

Figure 2: Simulations showing how cross-talk error ϵ_X depends on ion separation for a four-ion string imaged by a diffraction-limited imaging system.

Further recent results will also be reported. This work was supported by EPSRC (QIP IRC), DTO, the European Commission (SCALA, MicroTrap), and the Royal Society.

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Fast and Robust Cooling of Trapped Ions

J Cerrillo, A Retzker and M B Plenio

Institute for Mathematical Sciences, Imperial College London, SW7 2PE, UK
Blackett Laboratory, Imperial College London, Prince Consort Rd., SW7 2BW, UK
Institut für Theoretische Physik, Universität Ulm, D-89069 Ulm, Germany

We present a robust and fast laser cooling scheme suitable for trapped ions, atoms or cantilevers [1]. Based on quantum interference, generated by a special laser configuration, it is able to rapidly cool the system such that the final phonon occupation vanishes to zeroth order in the Lamb-Dicke parameter in contrast to existing cooling schemes.

It is formally based on the combination of two laser cooling schemes: Electromagnetically Induced Transparency (EIT) cooling [2] and the Stark-Shift (SSh) cooling [3]. Both use an intrinsic dark state of the system for decoupling from the carrier transition, thus avoiding one of the sources of heat. By means of optimal tuning of the Lamb-Dicke parameters of both EIT and SSh cooling, also the blue sideband transition can be blinded. This cancels all phonon heating processes up to first order in the Lamb-Dicke parameter expansion, allowing the system to reach the ground state of the motional degrees of freedom without further constrains on the physical parameters.

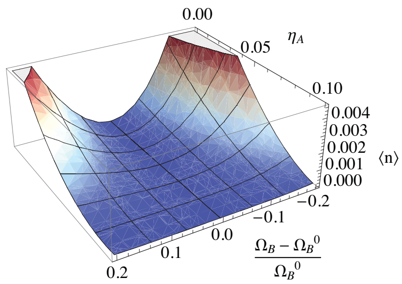

Figure 1: Expected value of occupation $\langle n \rangle$ as a function of the fluctuations of the Rabi frequency of the SSh laser (Ω_B) with respect to its optimal value (Ω_B^0) as well as the value of the Lamb-Dicke parameter of EIT cooling (η_A). When $\eta_A \to 0$ EIT cooling vanishes and only SSh cooling acts on the system. The effect of fluctuations of the laser intensity have a much worse effect for SSh cooling alone than for the combination of SSh and EIT cooling.

A remarkable feature of this proposal is a higher robustness with regard to fluctuations of the laser intensities. As is shown in figure (1), under a given value of the fluctuations of the laser intensities, the final mean occupation decreases abruptly as one moves away of the SS-only or EIT-only regimes. This guarantees promising performance under real experimental conditions, making it a reliable scheme for cooling of trapped systems.

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Optical pumping in a gas–filled linear Paul trap for laser spectroscopy of radioactive isotopes.

B. Cheal[1], J. Billowes[1], P. Campbell[1], F.C. Charlwood[1], D.H. Forest[2], D. Johnson[1], I.D. Moore[3], R. Powis[2], M. Reponen[3], G. Tungate[2], J. Äystö[3]

[1] School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK
[2] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK
[3] Department of Physics, University of Jyväskylä, Jyväskylä, PB 35 (YFL) FIN-40351, Finland

Nuclear sizes, shapes, magnetic moments and quantum state spins can all be studied through the analysis of atomic hyperfine structure. Collinear laser spectroscopy is a fast and sensitive technique, capable of systematic studies across the chart of the nuclides [1]. Radioactive isotopes with sub-millisecond half lives are electro-statically transported from the point of production to the laser spectroscopy station where the beam of particles is overlapped with a laser beam and fluorescence photons detected as the laser frequency is scanned [2]. The use of fast (~ 30 keV) beams suppresses the velocity spread in the forward direction, enhancing the spectral resolution.

In recent years the technique has been critically improved by passing the beam through a gas–filled linear Paul trap, known as an ion beam cooler/buncher. Such a device reduces the longitudinal energy spread and transverse emittance of the beam before re-acceleration for laser spectroscopy. These properties reduce further the spectral Doppler width and enable the formation of a narrow, low divergence beam at the point of laser–ion overlap, respectively. For the same laser power density, less laser power is therefore required, leading to less spectral background counts from the scattering of laser light into the photomultiplier tube. Moreover, the cooler allows the radioactive ions to be accumulated using a trapping potential before release as an ion bunch. Only photons detected within a window corresponding to the laser–ion bunch interaction time are accepted, permitting a reduction in the background (dominated by the continuous scattering of laser light) by four orders–of–magnitude. These devices have now been used for many laser spectroscopy experiments at international radioactive ion beam facilities, such as the University of Jyväskylä Accelerator Laboratory, Finland [3,4] and now also at ISOLDE, CERN [5,6].

Laser spectroscopy of ionic beams is generally performed on transitions from the electronic ground state or low–lying metastable states due to their natural population. In some elements this has hindered optical spectroscopy. Transitions from such states may in some cases be inefficient, have unsuitable atomic spin quantum numbers or be inaccessible to high–resolution continuous–wave lasers. A new technique of optical pumping inside the ion beam cooler [7,8] solves these problems. The slowly travelling focal point of ions in the vicinity of the extraction region of the cooler provides an ideal location for efficient optical pumping, irrespective of the strength of the transition. Broad–band pulsed lasers (which can readily access higher harmonics and therefore a greater wavelength range) can be used to excite ground state transitions, the subsequent decay from which enhances the population of a selected metastable state from which high–resolution laser spectroscopy can then be achieved.

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Laser trapping and cooling of charged particles

Cecilia Cormick[1] and Giovanna Morigi[1]

[1] Universität des Saarlandes, Saarbrücken, Germany

One of the motivations for the realization of all-optical traps for charged particles is the possibility to use the same trapping mechanism for hybrid systems composed of both neutral and charged particles. The coupling of charged atoms to time-dependent fields is expected to pose limitations to the achievable temperatures [1]. Inspired by the recent success in confining an ion in a dipolar trap [2], this work theoretically discusses the efficiency of cooling and trapping charged particles by means of optical radiation. The system we consider consists of an ionized atom formed by a closed shell and a single external, valence electron. The interaction with the electromagnetic field includes the charge monopole and the internal dipole within a multipolar expansion of the interaction Hamiltonian. Specifically, we perform a Power-Zienau-Wolley transformation [3] generalized to the case of a charged particle, taking into account the quantum motion of the center of mass.

To lowest order in the multipolar expansion, the dipolar interaction responsible for optical trapping is found to be modified by the net charge in a simple way: in the atomic dipole, the electron charge is replaced by an effective charge $q = |e| + Qm_e/M$ with m_e the electron mass and M the total mass of the ion. Due to the fact that the particle is charged, there is also an extra coupling to the laser field which can be approximated by that of a point-like particle at the position of the center of mass. Within this model, we predict the ultimate limit to cooling which is introduced by this coupling.

Finally, we analyze the dipole-trap stability in presence of photon scattering [4], and discuss possible schemes which combine laser cooling with trapping and may stabilize the trapped particle in confined, low temperature states.

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Quantum Uncollapse of a ^{40}Ca^{+} D$_{5/2}$ Qubit

M J Curtis, J A Sherman, D J Szwer, D M Lucas, D N Stacey and A M Steane

Department of Physics, University of Oxford, Oxford OX1 3PU, UK

We present and implement a method to restore the state of a single qubit, in principle perfectly, after it has partially collapsed by a wide class of relaxation processes involving "leakage" of the quantum state out of the computational Hilbert space [1]. The method is reminiscent of the Hahn "spin echo", but works on a wider class of noise processes. The inevitable cost is that it is not guaranteed to work on every occasion. The successful occasions are signalled or "heralded".

The relaxation processes under investigation can be modelled as unitary rotations followed by projection. For a qubit state $|\phi_0\rangle = a|0\rangle + b|1\rangle$ the unitary rotation carries the $|1\rangle$ part partially out of the computational Hilbert space, to $\cos\theta\,|1\rangle + \sin\theta\,|2\rangle$ where $\theta < \pi/2$. The state is then projected onto $|2\rangle$.

After this type of qubit relaxation, an "error detection" might consist, for example, of detecting whether or not population is found in $|2\rangle$. If it is not then the qubit has sustained a non-unitary error of size $O(p^2)$ where $p = \sin^2\theta$.

If the relaxation process is constant in time, the qubit can be perfectly re-cohered by dividing the noisy evolution period into two halves, with a detection and qubit flip at the end of each period. On those occasions where both detections yield a null result, the final state of the qubit is $|\phi_0\rangle$. This is like the reversal of a "weak" or partial measurement described in [2], but we are able to achieve an overall fidelity exceeding that which would be obtained by a single error detection. For error strength p up to 0.94 the initial state was recovered with state fidelity >0.8.

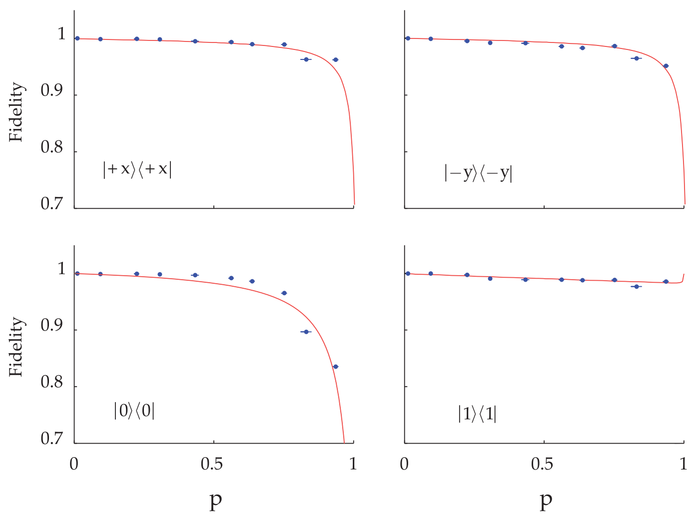

Figure 1: Fidelity of recovered qubit states after relaxation and recovery by the double detection process. The fidelity was measured by quantum state tomography for four different input states. The curves show the predicted outcome in the presence of a known limitation on the measurement process for our qubit in the D$_{5/2}$ manifold of ^{40}Ca^{+}.

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Towards Quantum Phase Transitions of Small Ion Coulomb Crystals in Penning and RF Traps.

S. Donnellan, S.Mavadia, D. Crick, D M Segal and R C Thompson

Blackett Laboratory, Imperial College London, London SW7 2AZ

We have developed techniques for controlling the orientation of small ion Coulomb crystals in Penning traps [1]. In particular we have shown that a two-ion Coulomb crystal can be forced to align either along the trap axis or in the radial plane by adjusting the frequency and amplitude of a weak oscillating radial quadrupole potential applied to a segmented ring electrode (axialisation). At the same time theoretical interest in ion Coulomb crystals has intensified partly due to their potential applications in performing direct quantum simulations of Hamiltonians of interest in other areas of physics, notably those of condensed matter systems. Work in linear radiofrequency traps has shown that ions form linear chains aligned along the trap axis provided the radial confinement sufficiently exceeds the axial confinement. If the axial confinement is increased beyond a critical value the linear chain develops kinks and a zig-zag arrangement is adopted. If one of the radial dimensions (say x) has weaker confinement than the other (say y) the zig-zag is pinned in the xz plane but has two possible orientations (see figure 1). The system can be described by a double-well potential in a normal co-ordinate, with the two possible crystal orientations described by states located in the different wells [2]. This double well is interesting because it is 'intrinsic' to the system and it can be controlled simply by varying the external potential applied using the trap electrodes.

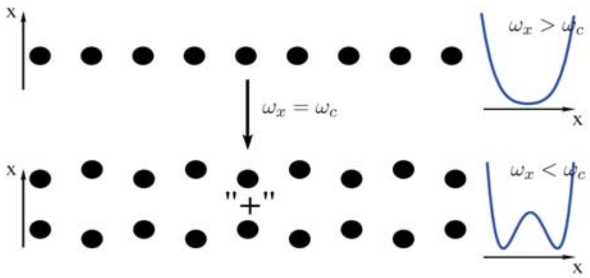

Figure 1: Zig-zag ion Coulomb crystal and the associated double well potential (taken from [2]). The "+" sign indicates that the system can be in a coherent superposition of the two orientations.

We have identified a number of experimental protocols that should allow quantum effects,such as tunneling, to be revealed in this system in both radiofrequency and Penning traps. We will present our experimental progress and plans for the future at the meeting.

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A Surface Electrode Trap for the Sympathetic Cooling of Molecular Ions

I M Georgescu and S Willitsch

Department of Chemistry, University of Basel,
Klingelbergstrasse 80, 4056 Basel, Switzerland

Originally developed for quantum information processing [1], Surface Electrode (SE) traps are now also used for the study of ultracold ion-neutral collisions [2] and cold chemistry. The open geometry together with the increased flexibility SE traps provide in manipulating the ions in one, two [3] and even three dimensions [4] are important advantages over traditional three-dimensional ion traps. However, SE traps have relatively low trapping depths and therefore ions are easily lost because of heating due to micromotion or stray electric fields caused by charged dielectrics. In this study we investigate how these issues affect the sympathetic cooling of molecular ions. Based on numerical simulation results we design and construct a novel SE trap for cold-chemistry experiments.

The RF and DC trapping potentials of one of the most common types of SE trap [4] were calculated numerically and then used to realistically model the dynamics of trapped ions via molecular dynamics simulations. In this way, we investigated the shape and structure of Coulomb crystals and studied the effect of static fields on the micromotion. We calculate the effective and secular temperatures of the ion crystals under various simulation conditions. Furthermore, we simulated the sympathetic cooling of molecular ions and studied the structure of two-component Coulomb crystals.

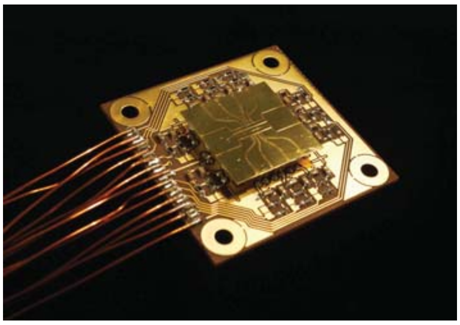

Figure 1: Compact SE trap and electronic circuit.

We have designed and constructed a SE electrode trap with large electrodes (750 μm) and small inter-electrode gaps (50 μm). The trap has six control electrodes and the overall dimension is about 18 mm $\times$ 18 mm. The trap is laser-cut in thin gold-coated stainless-steel foil mounted on a small insulator frame, which is fixed on a gold-plated circuit board with the RC-filter electronics (see Figure). No exposed insulator surfaces are present near the trap center, which is expected to minimize the effect of stray fields. The trap is operated at $>$ 8 MHz RF frequency and typical RF amplitudes of a few hundred volts.

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Ultra-stable high-finesse cavity for the stabilization of the 729 nm clock laser of a Ca^+ optical frequency standard

G Hagel, O Morizot, D Guyomarc'h, C Zumsteg, C Champenois, M Houssin and M Knoop

Université de Provence-CNRS, PIIM, Centre de Saint Jérôme, Case C21, 13 397 Marseille Cedex 20, France

Among all atomic candidates for an optical frequency standard, a single Ca^+ ion seems extremely attractive. Its electric quadrupole transition at 729 nm proposed as a frequency reference has a natural linewidth below 200 mHz corresponding to a quality factor of 2×10^{15}, and the wavelengths of the required lasers are all in the visible domain. A single Ca^+ ion, cooled in a miniature radiofrequency trap and confined in the Lamb-Dicke regime, is then an almost perfectly isolated atomic system well suited for long interrogation times. Frequency stability is then limited by the quantum projection noise and is expected to reach $2.5\times10^{-15}/\sqrt{\tau}$ [1]. The Ca^+ ion is expected to outperform the best microwave atomic frequency references, and to be competitive with other atomic optical frequency references.

Probing of the clock transition of a single ion is carried out using quantum jump statistics, which can require interrogation times of several seconds. The linewidth of the probe laser (local oscillator) should reach the hertz level for a duration at least as long as the interrogation time to take full advantage of the quality factor of the clock transition. Our local oscillator is a lab-built titanium-sapphire laser pumped with a 5 W *Verdi* laser. Pre-stabilization is made via a Pound-Drever-Hall lock onto a 30 cm Invar cavity, with a finesse of about 1000, isolated inside a vacuum chamber. Measurement by an auto-correlation technique after locking onto this cavity yields a linewidth below a few kHz with a resolution limited by the length of our optical fibre (10 km).

To further increase the frequency stability and precision of the local oscillator, it is then injected into an ultra-stable high-finesse ULE cavity [2] that we will present through this poster, together with its active and passive stabilization system. This vertical cavity has an overall length of 150 mm, resulting in a Free Spectral Range of 1GHz. Optimization of the cavity design has been carried out with a Finite-Elements Method, leading to expected relative length variations below 10^{-14} under the influence of gravity acceleration (1 *g*). The variation of different geometric parameters has been studied. An analysis of the different sources of noise shows that, for a regime superior to 100 mHz, the fast linewidth of the laser will not be limited by the cavity characteristics. The cavity has recently been installed in its temperature stabilized vacuum vessel. A finesse of about 140,000 was measured and a Pound-Drever-Hall error signal obtained. This should lead to a linewidth of the laser on the order of 120 mHz at best.

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Quantum information processing in a linear segmented ion trap

M Harlander[1], M Brownnutt[1], W Hänsel[2] and R Blatt[1,2]

[1] Institute for Experimental Physics, University Innsbruck
Technikerstrasse 25, A-6020 Innsbruck
[2] Institute for Quantum Optics and Quantum Information IQOQI, Innsbruck
Technikerstrasse 21a, A-6020 Innsbruck

Segmentation of ion traps is a promising route to allow the major results in trapped-ion quantum computing to be extended beyond individual traps, to many-ion-trap systems. Such segmented traps are typically realized with microstructured electrodes in either a two-dimensional (planar) or a three-dimensional (e.g. sandwich-type) geometry. There is still ongoing discussion which electrode and substrate materials offer the lowest ion heating rates. Here we report on the performance of a laser-machined gold-on-alumina microtrap (see figure 1) that has been manufactured within the European STREP project "Microtrap". Its sandwich-type assembly provides a comfortable trap depth of more than 1eV at trap frequencies in the range of a few megahertz. The heating rates for all three modes of motion have been measured, and a near groundstate cooling ($<n>=0.4$) has been achieved for one and two ions. Using a Mølmer-Sørensen quantum gate [1] a Bell state has been created in this trap.

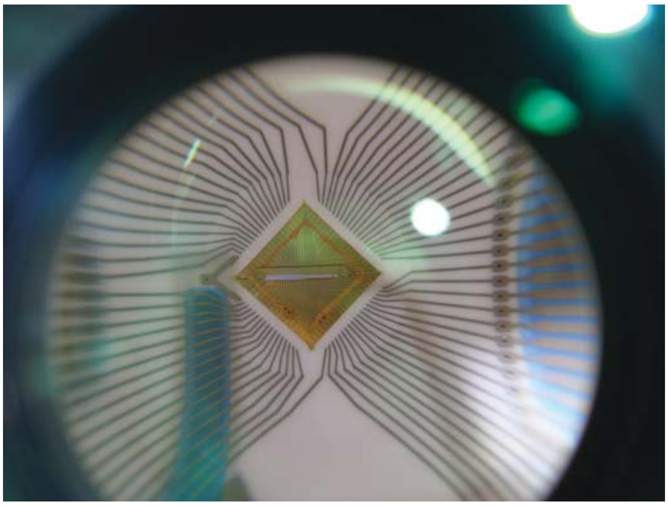

Figure 1: Top view of the assembled miniaturized ion trap mounted in vacuum

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Development of New Apparatus of Ion Trap with ICP-MS for Trace Isotope Analysis

Shuichi Hasegawa, Takuma Yoshida, Masanori Kitaoka, Kyunghun Jun

School of Engineering, University of Tokyo, Tokyo 1138656 JAPAN

We have developed a new apparatus for trace isotope analysis, which consists of an ion trap and an ICP-MS. Numerical simulations to design electrodes transporting ions from the ICP-MS to the ion trap were performed. Based on the simulations, the design and construction of the apparatus were conducted. Experimental results will be presented in the conference.

Trapped ions by electromagnetic fields with laser cooling have great advantages for isotope analysis because the ions can be manipulated with m/q (mass/charge) by the fields and isobars are well resolved by the lasers. Furthermore, the bandwidths of the cold isotopes of the element of interest are narrow enough for the cooling lasers to resolve and this enables us to observe single isotope ions. We proposed to use this technique to analyse trace isotopes and demonstrated the manipulations and observation of stable isotopes of Ca ions [1, 2]. In order to show the potentials of the techniques, we have developed a new apparatus to introduce mass-selected ions to a linear ion trap. As an ion source, we chose an Inductively Coupled Plasma Mass Spectrometry (ICP-MS), which supplies mass-selected ions generated by the ICP from a liquid sample. The ions flying through a quadrupole mass spectrometer are focused by an ion lens and introduced into a 90 degree deflector. The energy selected ions pass through a second ion lens and get at a segmented linear Paul trap. The trapped ions are laser cooled and observed with an ICCD. To achieve a high vacuum of the chamber where the trap is set up, we installed three differential pumping sections divided by the ion lenses, which have only a 4 mm diameter. With the optimized electric field condition, the numerical simulations of SIMION show more than 10 % transport efficiency. Based on these simulations, we designed and constructed the apparatus. The experimental results will be discussed in the conference.

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Theoretical study of Feshbach resonances and charge exchange process in ultracold atom-ion collisions

Z Idziaszek[1,2], A Simoni[2], T Calarco[3] and P S Julienne[4]

[1]Institute of Theoretical Physics, University of Warsaw, 00-681 Warsaw, Poland
[2]Institut de Physique de Rennes, UMR 6251 du CNRS and Université de Rennes, 35042 Rennes Cedex, France
[3]Institute of Quantum Information Processing, University of Ulm, D-89069 Ulm, Germany
[4]Joint Quantum Institute, NIST and the University of Maryland, Gaithersburg, Maryland 20899-8423, USA

We consider atom-ion scattering in the ultracold regime. Using a multichannel quantum-defect model [1] and close-coupled numerical calculations we investigate the occurrence of magnetic Feshbach resonances in elastic and charge exchange collisions. Focusing on two specific systems of experimental interest: ^{40}Ca^{+}-Na and ^{138}Ba^{+}-^{87}Rb, we predict that atom-ion interactions can be tuned using Feshbach resonances in the range of experimentally accessible magnetic fields. Performing a fully quantum-mechanical and semiclassical studies of the charge-exchange processes we show that charge-exchange rates should remain small even in the vicinity of resonances. Finally, we investigate the collisions rates at finite energies, analyzing the effects of Feshbach resonances in higher partial waves.

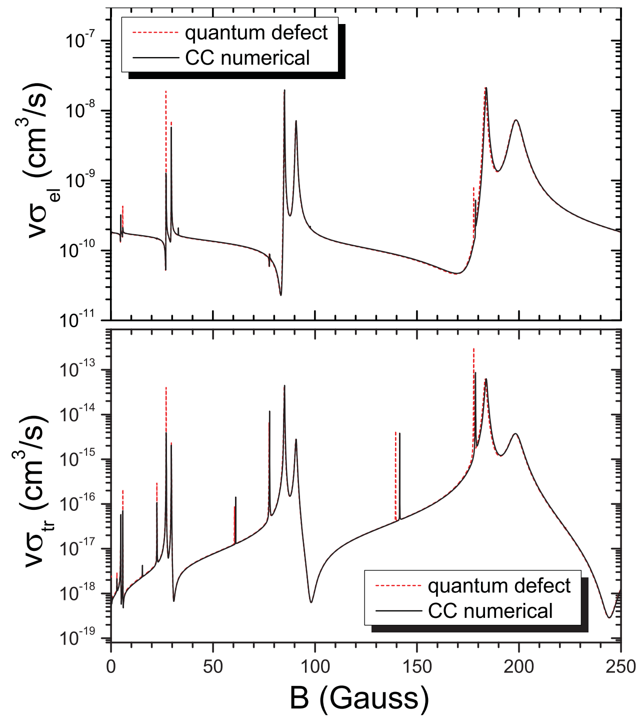

Figure 1: Elastic (upper panel) and charge exchange (bottom panel) collision rates for Na-Ca^{+} versus magnetic field, for energy $E/k_B = 1\mu$K and assumed singlet and triplet scattering lengths $a_s = 2081a_0$ and $a_t = -2081a_0$, respectively. Close-coupled numerical calculations (solid line) and the multichannel quantum-defect model (dashed line) are compared.

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Single shot implementation of multiply-conditional quantum gates in ion traps

S S Ivanov[1,2] and N V Vitanov[1]

[1]Department of Physics, Sofia University St. Kliment Ohridski, Bulgaria
[2]Institut Carnot de Bourgogne, Universite de Bourgogne, Dijon, France

We propose a new approach for implementation of highly conditional quantum gates in ion traps. The advantage of the method is that it requires a small number of pulses of small area and particular phase, addressing only one (target) ion. The implementation proposed is very insensitive to the applied Rabi frequency, thereby avoiding significant experimental obstacles: imprecise calibration, fluctuation and unfavourable spatial distribution of the laser intensity, etc. Furthermore one needs to work outside the Lamb-Dicke regime, the Lamb-Dicke parameter being used as a control variable.

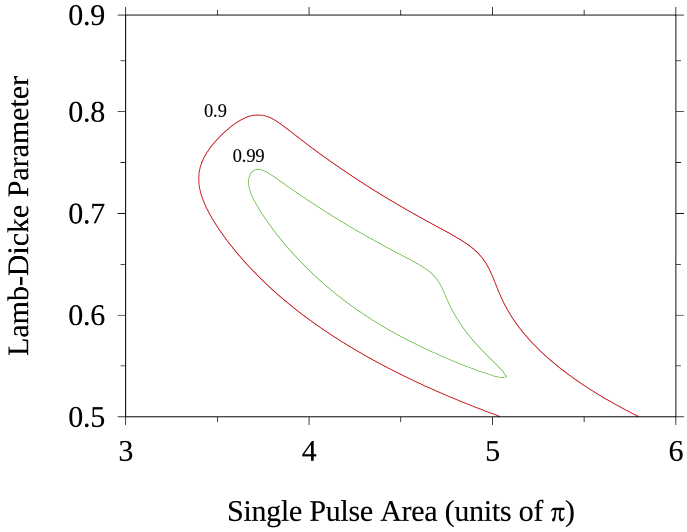

Figure 1: Numerically obtained fidelity of the Toffoli gate.

High-precision mass measurements with Penning traps

J. Ketelaer[1,2], T. Beyer[1], M. Eibach[2,3], Sz. Nagy[1,4], D. Neidherr[1], C. Smorra[2,3] and K. Blaum[1,3]

[1] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[2] Johannes Gutenberg-Universität, 55128 Mainz, Germany
[3] Ruprecht-Karls-Universität, 69120 Heidelberg, Germany
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

Atomic and Nuclear masses are one of the most fundamental quantities in nature since they are linked to the binding energies and, thus, reflect all interactions present. Various applications require new mass measurements across the entire chart of nuclides differing in the required precision, which ranges from $\delta m/m = 10^{-6}$ in nuclear astrophysics to better than 10^{-10} in atomic physics. The highest precision can be obtained using Penning traps to store charged particles and determine their mass through a measurement of the cyclotron frequency [1]. To this end, the Heidelberg group on 'Cooled and Stored Ions' focusses on Penning trap mass measurements on short-lived, long-lived, and stable nuclides. Several experiments dedicated to different physics cases in different regions of the nuclear chart are in operation or presently commissioned. New developments made here such as non-destructive ion detection, application of the Ramsey technique, as well as position-sensitive ion detection further improve sensitivity and precision.

One of the new facilities is the TRIGA-TRAP experiment [2] located at the research reactor in Mainz. Here, neutron-rich fission products will be available for mass measurements to push the limit of well-known masses further into the direction of the neutron drip-line. Prior to the on-line coupling of TRIGA-TRAP to the reactor, samples of actinoid nuclides heavier than uranium will be investigated, providing first direct links of these atomic masses to the standard ^{12}C. Moreover, stable nuclides are available and first results for rare-earth elements in the deformed region around $N \sim 90$ will be reported. TRIGA-TRAP also serves as a test-bench to develope new techniques which will be later implemented also at other facilities. One of those is a non-destructive image current detection system ultimately allowing for a mass measurement on a single singly charged ion stored in a Penning trap. The present status of the technical developments as well as mass spectrometric results will be presented.

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Metrology of Fundamental Particle Properties through Precision Spectroscopy of Trapped Molecular Hydrogen Ions

J C J Koelemeij, D W Noom, M A Haddad, D de Jong, K S E Eikema, and W Ubachs

Laser Centre Vrije Universiteit Amsterdam, Netherlands

From the viewpoint of fundamental physics, the molecular hydrogen ion and its isotopomers possess at least three features which make them an interesting object for study. Firstly, the structure of these molecules is relatively simple, which allows for high-accuracy *ab initio* calculations including high-order QED contributions. Secondly, they come with an electric charge. This makes them amenable to one of the most precise measurement methods to date, namely spectroscopy of trapped ions. Thirdly, the additional rotational-vibrational and hyperfine structure of molecular hydrogen ions provide a considerably wider view on the interactions between electrons and Z=1 nuclei than is the case for neutral atoms with Z=1.

At the LCVU Amsterdam we aim to exploit the above three features for tests of fundamental theories of physics, as well as for metrology of fundamental particle properties such as the proton-electron mass ratio. To this end, we have set up a linear radiofrequency trap for storage of cold molecular hydrogen ions. Cooling and detection of these ions relies on motional coupling to laser-cooled beryllium ions stored in the same trap [1]. We are currently exploring new pathways to vibrational (optical) and hyperfine (radiofrequency) spectroscopy to accurately determine the internal level structure of the molecular hydrogen ion. These experimental results should permit a stringent test of state-of-the-art *ab initio* level calculations provided by theorists [2]. If this test turns out to be successful, theory and experiment may be combined for improved determination of mass ratios [3] and the internal structure of elementary nuclei.

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Interacting 2 Dimensional Arrays of Ions Traps

Muir Kumph[1], Michael Niedermayr[1], Michael Brownnutt[1], and Rainer Blatt[1,2]

[1]Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria
[2]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

Scalability of ion trap quantum computers remains an elusive goal. One possible solution is to create a 2 dimensional array of traps and use the long range Coulomb force between traps to allow for nearest neighbour interactions[1]. A static array of ion traps suffers from the trade off between a strong trapping potential and strong ion-ion interaction. By placing adjustable radio-frequency control electrodes between the trapping sites, pairs of ions can be brought close to facilitate interactions, while a strong trapping potential is maintained throughout the array.

A 2 dimensional array of ion traps is implemented on a printed circuit board to test the principle of using control electrodes to control the nearest neighbour ion-ion interaction between trapping sites. The control electrodes are driven with an adjustable radio-frequency high-voltage source which remains in phase with the other radio-frequency electrodes on the ion trap. Technical details of the drive electronics and trap layout will be addressed as well as results trapping charged particles.

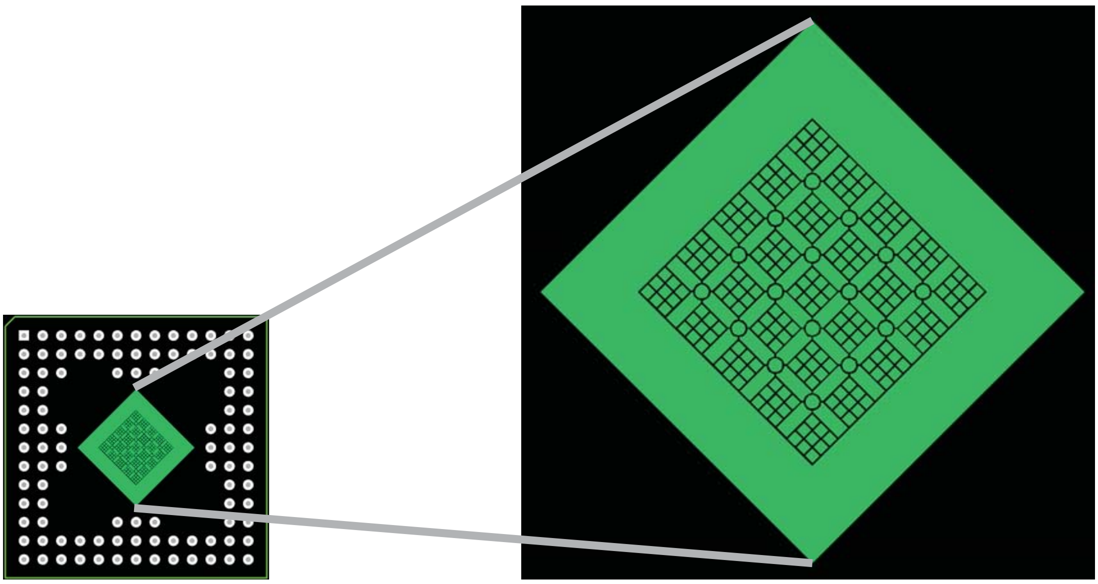

Figure 1. Overhead view of 2 dimensional array of spherical Paul traps in a 4 x 4 rectangular pattern. The ion trap is implemented as an array of planar surface traps in a PGA100 form factor (34mm x 34mm) with control electrodes between the trapping sites to allow for nearest neighbour interactions.

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Ion trapping and sonoluminescence

Andreas Kurcz[1], Antonio Capolupo[1,2], and Almut Beige[1]

[1]The School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, United Kingdom
[2]Dipartimento di Matematica e Informatica and I.N.F.N., Universitá di Salerno, Fisciano (SA)-84084, Italy

Sonoluminescence is the intriguing phenomenon of strong light flashes from tiny bubbles in a liquid. The bubbles are driven by an ultrasonic wave and need to be filled with noble gas atoms (c.f. Fig. 1). Approximating the emitted light by blackbody radiation indicates very high temperatures. Although sonoluminescence has been studied extensively, the origin of the sudden energy concentration within the bubble collapse phase is still controversial [1].

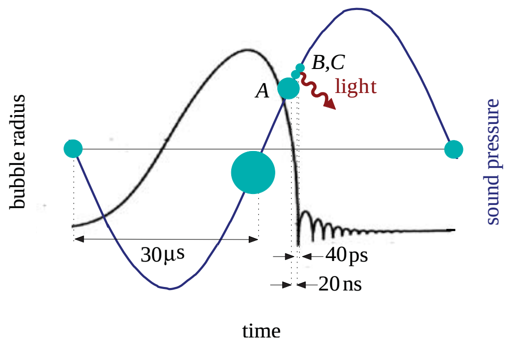

Figure 1: A typical single-bubble sonoluminescence cycle. Point A marks the beginning of the collapse phase. In point B, the temperature within the bubble is significantly increased and a strong light flash occurs. Point C denotes the beginning of the re-expansion phase.

Here we compare the physical situation of the strongly confined nobel gas atoms during the bubble collapse phase with trapped ions [2]. It is shown that the atoms in sonoluminescence experiments can be heated very rapidly by a highly inhomogeneous electric field as it might occur naturally during rapid bubble deformations. Modelling sonoluminescence experiments using quantum optical techniques which are usually used for the modelling of trapped ions, we point out that the origin of the considered heating mechanism are the counter-rotating terms in the atom-phonon coupling. Being quantum, these are more likely to create a phonon than to annihilate one.

Our model does not contradict current models for the description of sonoluminescence experiments, but explains certain controversial aspects of this phenomenon, like why it is necessary to have noble gas atoms inside the bubble. Our model moreover implies that it is possible to further increase the temperature of the confined atoms with the help of appropriately detuned laser fields for applications like sonochemistry and table top fusion. Similar energy concentrating mechanisms might soon become observable in atom-cavity systems [3] and do not violate the basic laws of thermodynamics [4].

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Quantum Coherence of Discrete Kink Solitons in Ion Traps

H. Landa[1], S. Marcovitch[1], A. Retzker[2], M. B. Plenio[2], and B. Reznik[1]

[1] School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel
[2] Institute for Mathematical Sciences, Imperial College London, London SW7 2PG, United Kingdom, and QOLS, The Blackett Laboratory, Imperial College London, London SW7 2BW, United Kingdom, and Institut für Theoretische Physik, Universität Ulm, D-89069 Ulm, Germany

We propose to realize quantized discrete kinks with cold trapped ions [1]. We show that long-lived solitonlike configurations are manifested as deformations of the zigzag structure in the linear Paul trap, and are topologically protected in a circular trap with an odd number of ions. We study the quantum mechanical time evolution of a high-frequency, gap separated internal mode of a static kink and find long coherence times when the system is cooled to the Doppler limit. The spectral properties of the internal modes make them ideally suited for manipulation using current quantum information processing technology. This suggests that ion traps can be used to test quantum-mechanical effects with solitons and explore ideas for the utilization of the solitonic internal modes as carriers of quantum information.

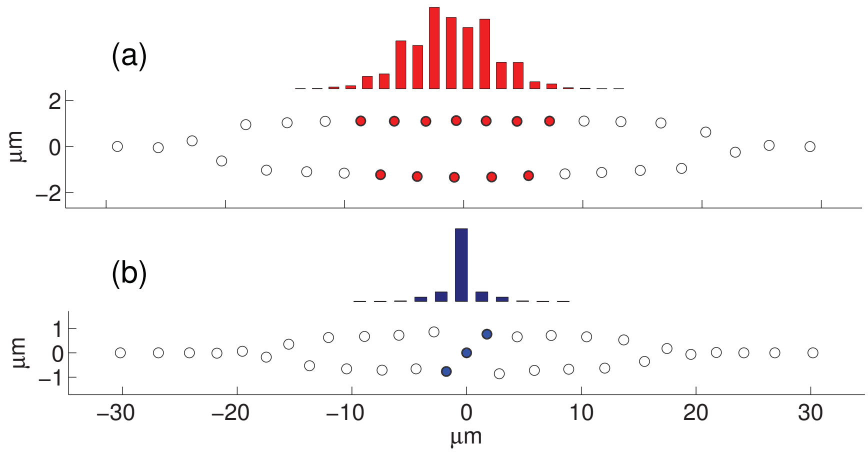

Figure 1. Metastable linear trap configurations with 33 ions. (a) An extended kink. The localized internal mode (red bars) involves ~10 ions. (b) A highly discrete ‘‘odd’’ kink. A localized internal oscillation (blue bars) involves ~3 ions.

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A high finesse cavity for Ion trap cavity QED experiments.

Chuah Boon Leng, Nick Lewty and M. D. Barrett

Center for Quantum Technologies, National University of Singapore.

We report the trapping of Barium ion's with a high finesse cavity suitable for cavity QED experiments. The cavity has a finesse above 70000 at both $493\,\mathrm{nm}$ and $650\,\mathrm{nm}$ corresponding to the $\mathrm{S}_{1/2}$ to $\mathrm{P}_{1/2}$ and $\mathrm{D}_{3/2}$ to $\mathrm{P}_{1/2}$ transitions respectively. The cavity decay rate is $\approx 200\,\mathrm{kHz}$ allows us to resolve vibrational sidebands and the single atom cooperativity of ≈ 1 makes it suitable for a range of cavity QED experiments. We report our progress towards remote entangle based on cavity assisted photon sources.

Dynamics of an electron in an ionic crystal

Weibin Li and Igor Lesanovsky

School of Physics and Astronomy, the University of Nottingham, Nottingham NG7 2RD

Trapping of charged particles has undergone significant achievements in the past decades. Single ions can be nowadays controlled with extreme precision and are applied as frequency standards or for the purpose of quantum information processing. Traditionally, ion traps are used to confine single ions or crystals of ions of the same charge. Simultaneous trapping of ions and electrons seems not possible at the first glance because either Paul trap or Penning trap confine only particles of a certain charge while the oppositely charged ones are repelled from the trap. We demonstrate that single electron can be trapped in the centre of an small-number ion crystal in a linear Paul trap. The stabilization of the electron trapping is achieved by an external magnetic field along the trap axis. The resulting electronic potential can be as deep as tens of GHz in the typical parameter region. The electronic dynamics will strongly couple the ions' motion which in principle permits the probing of the fast electronic dynamics by monitoring the vibrational motion of the ions.

Internal State Cooling of Trapped Molecular Ions

J. P. Marler, J. H. V. Nguyen, C-Y. Lien, Y-W. Lin, V. Rajagopal,
C. Seck, D. Tabor and B. Odom

Department of Physics, Northwestern University, Evanston, IL 60208 USA

Due to their complex internal structure, laser cooling of molecules requires overcoming many technological challenges as compared to atoms. Once full quantum state control of molecules can be achieved, techniques already developed to perform precision spectroscopy on single atoms can be extended to spectroscopy on single molecules. A wealth of new applications will then be possible, turning the rich molecular internal structure from being a disadvantage into an advantage.

Our approach to the problem is two-fold. In one direction we intend to sympathetically cool molecular ions with co-trapped Ba^+ ions. Results of ro-vibrational cooling of sympathetically translationally cooled MgH^+ and DH^+ have recently been published [1]. In both cases the optical pumping is done within the ground electronic state. In our approach to achieve internal cooling, we hope to take advantage of the excellent Franck-Condon overlap of molecules where the lowest electronic state is spin-orbit split and where coupling to a nearby electronic level makes transitions between these two levels no longer dipole forbidden. In this case a finite number of sweepable lasers (one per occupied vibrational level) should allow for P-branch optical pumping into the ro-vibrational ground state. Towards this end we have completed construction of a Ba^+ trap (see Fig.1) and continue to develop techniques for the molecular production, co-trapping and cooling.

Second we are also pursuing direct translational laser cooling of molecules. In order to compensate for the lack of a closed cycling transition, a SLM (Spatial Light Modulator) will be used to select multiple narrow frequency bands from a femtosecond laser pulse to P-branch optical pump on many transitions concurrently [2].

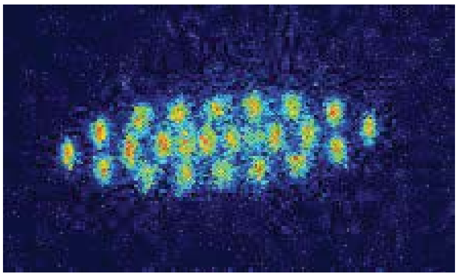

Figure 1: Fluorescence image of a Ba^+ ion crystal.

Finally, in development is a two-particle trap optimized for molecular Quantum Logic Spectroscopy (mQLS). This technique exploits the nice spectroscopic properties of a co-trapped atomic ion and the shared motional modes of the two ions to both translationally cool and read out the internal state of a molecular ion. This has been demonstrated with two atomic species to give the highest precision spectroscopy for atomic species to date[3]. Potentially, mQLS will allow discovery of (1) an expected breakdown of mirror symmetry in the intrinsic structure of stable matter, and (2) the hypothesized time-variation of fundamental constants.

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A versatile source of polarization-entangled photons.

A Maser[1], R Wiegner[1], U Schilling[1], C Thiel[1], and J von Zanthier[1]

[1] Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

We propose a method for the generation of a large variety of polarization-entangled photon states within the same experimental setup. Starting with N uncorrelated photons, emitted from N arbitrary single photon sources, and using linear optical tools only, we demonstrate the creation of all symmetric states, e.g., GHZ- and W-states, as well as all (symmetric and non-symmetric) total angular momentum eigenstates of the N qubit compound [1].

The proposed scheme consists of N uncorrelated single photon sources emitting photons of identical frequency (e.g., trapped ions, neutral atoms, quantum dots, molecules or photons produced via SPDC). In front of each source a polarization filter is installed, which projects the polarization vector of the emitted photon onto the polarizer's axis. Optical fibers guide the photons from the sources to N detectors such that a given detector, upon detection, cannot distinguish which single-photon source emitted the recorded photon, leading to a loss of Welcher-Weg information. By assuming that each detector registers exactly one photon, the correlated photon detection signal will display N-photon interferences. By changing the orientation of the polarization filters and/or the optical phases and by exploiting the N-photon interferences, a large variety of polarization-entangled photonic *N*-qubit states can be produced, amongst others all symmetric states, e.g., GHZ- and W-states, as well as all (symmetric and non-symmetric) total angular momentum eigenstates of the N qubit compound [1]. In particular, the scheme allows one to generate the canonical states representing all possible entanglement families of symmetric states inequivalent under SLOCC, as recently defined in [2,3]; to tune from one entanglement family of symmetric states to another, one just has to turn the orientation of the polarization filters in front of the sources. The scheme serves in this way as an optical switchboard which allows one to produce an extremely large variety of photonic multiqubit states from initially uncorrelated photons. The technique thus comes close to the ideal of a single apparatus "that tunes in any wanted multipartite entangled state by simply turning a knob" [4].

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Generation of all Symmetric and all Total Angular Momentum Eigenstates in Remote Qubits.

A Maser[1], U Schilling[1], T Bastin[2], E Solano[3], C Thiel[1] and J von Zanthier[1]

[1] Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
[2] Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège au Sart Tilman, 4000 Liège, Belgium
[3] Departamento de Química Física, Universidad del País Vasco–Euskal Herriko Unibertsitatea, 48080 Bilbao, Spain

We propose a scheme enabling the generation of all symmetric states [1] and all (symmetric and non-symmetric) total angular momentum eigenstates [2,3] of an N qubit compound using linear optical tools only. Hereby, an arbitrary number of single photon emitters with a Λ configuration can be entangled in their two long-lived ground states via the use of suitably designed projective measurements.

Our system consists of N indistinguishable single photon emitters with a Λ configuration, say trapped ions, trapped neutral atoms, quantum dots, or any other equivalent physical system with access to similar behavior. We assume that initially all N emitters are in the excited state and that the N photons subsequently emitted by spontaneous decay are collected by single-mode optical fibers transmitting the photons to different - but not necessarily all - N detectors equipped with polarization filters. In this way, it is impossible to determine after the measurement which atom emitted which photon so that quantum interferences of higher order can occur. Via the polarization sensitive measurement of the photons at the detectors it is possible to generate any symmetric state of an N qubit compound system. The generated state is hereby solely determined by the orientation of the polarization filters in front of the detectors.

By varying the length of the optical pathways and suppressing certain quantum paths it is moreover possible to generate all (symmetric and non symmetric) total angular momentum eigenstates of the N-qubit system. In reference to the algorithm describing the coupling of angular momentum of individual spin-1/2 particles, our method couples successively the remote qubit states to the coupled basis. Thereby, it offers access to all 2^N (symmetric and non symmetric) total angular momentum eigenstates.

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Trapped ytterbium ions for scalable quantum technology

J. J. McLoughlin, A. H. Nizamani, J. D. Siverns, R. C. Sterling, M. D. Hughes, B. Lekitsch, B. Stein, S. Weidt and W.K. Hensinger

Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK

Trapped ions provide a promising tool towards quantum information processing and quantum simulators. Their suitability has been well demonstrated with long coherence times, internal state manipulation for quantum algorithms and also transport within ion trap arrays. At Sussex, we are concentrating on scaling up ion trap architectures that can encompass all these features.

We present an ytterbium ion trap experiment with a setup offering versatile optical access and up to 90 electric inter-connects, allowing the operation and testing of advanced surface and multi-layer ion trap chips mounted on chip carriers [1]. The experiment was performed using a macroscopic ion trap, with ion-electrode distance of 310(10) μm, and we present its performance including secular frequencies on the order of 1 MHz, trap depth of 4.9(2) eV, and ion lifetimes of many hours without the need of optical cooling. The motional heating of our trap was measured using a fluorescence detection technique and we present our results including an electric field noise density of S_E(1 MHz) = 3.6(9)$\times$10^{-11} V^{2}m^{-2}Hz^{-1}. A result which is consistent with previous measurements of other ions in different ion traps of similar dimensions, and also demonstrates a $\langle \dot{n} \rangle \propto 1/\omega^2$ behavior [1]. We can selectively trap most of the stable Yb$^+$ isotopes, including ^{171}Yb$^+$, as well as ion crystals. Using a simple technique, based on atomic fluorescence, [2] the neutral atom $^1S_0 \leftrightarrow {}^1P_1$ transition frequencies have been measured to ± 60 MHz absolute accuracy, which are more accurate than previously reported results. Using the fluorescence from trapped ions the $^2S_{1/2} \leftrightarrow {}^2P_{1/2}$ and $^2D_{3/2} \leftrightarrow {}^3D[3/2]_{1/2}$ transition wavelengths are measured for the stable ^{170}Yb$^+$, ^{171}Yb$^+$, ^{172}Yb$^+$, ^{174}Yb$^+$ and ^{176}Yb$^+$ isotopes [1] which are more precise than previously published work.

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Micro-Structured Ion Traps for Optical Clocks

T.E. Mehlstäubler[1,2], K. Pyka[1], J. Keller[1], N. Herschbach[1]
[1] QUEST at PTB
[2] Department of Time and Frequency, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

In the cluster of excellence QUEST (center for Quantum Engineering and Space-Time research) atomic clocks are developed for a new kind of quantum sensors and tests of fundamental theories, like Einstein's General Relativity or modern unifying theories, that predict a temporal variation of fundamental constants. Our work is targeted on the development of new optical frequency standards with the potential of a short term stability of $y < 10^{-15}$ in 1s and long term stability of 10^{-18}, which will open up new applications in geodesy and navigation.

Today's best standards are defined by single-ion clocks and neutral atom optical lattice clocks, which have demonstrated the potential for ultra-high short term stability and ultra-high accuracy, respectively. Our group dedicates its work to the development of new trap geometries for the trapping, manipulation and spectroscopy of many ions to combine the advantages of both and overcome the problems of the current technologies.

We have set up a new experiment to trap ions in micro-fabricated trap structures. $^{172}Yb^{+}$-ions serve to test and characterize the new trap geometries as well as to sympathetically cool $^{115}In^{+}$-ions, that serve for the high-precision spectrocopy. As the clock transition in indium ions is free of quadrupole shift, chains of ions can be stored in linear ion trap configurations without ion number and position dependent frequency shifts. We conduct first tests with indium and ytterbium ions in an integrated chip-trap made out of Rogers4350 printed circuit board. In parallel, a high-precision ceramic chip trap is being developed, based on our FEM-simulations to minimize micromotion.

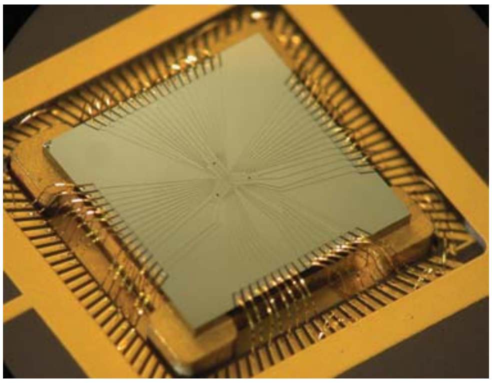
Microfabricated Surface Electrode Ion Traps: Junction Shuttling and Integrated Mirco-Optics

D. L. Moehring, M. G. Blain, G. R. Brady, R. D. Briggs, T. R. Carter, R. L. Cook, A. A. Cruz-Cabrera, A. R. Ellis, K. Fortier, R. A. Haltli, C. Highstrete, S. A. Kemme, S. Samora, D. Stick, C. Tigges, J. R. Wendt

Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

We present the design, modeling, and experimental testing of surface electrode ion traps fabricated in a heterostructure configuration comprising a silicon substrate, silicon dioxide insulators, and aluminum electrodes. Plasma enhanced chemical vapor deposition (PECVD) was used to grow silicon dioxide pillars to electrically separate overhung aluminum electrodes from an aluminum ground plane, and the top metal trap layer (comprising electrodes, their leads, and outside grounded regions) overhangs the supporting oxide pillars by a user defined $5\ \mu$m. The overhang also allows for vertical deposition of metal on top of the aluminum electrode layer without shorting DC control or RF electrodes. In addition to fabrication, we report techniques for modeling the control voltage solutions and the successful demonstration of trapping and shuttling ions in three identically constructed linear traps [1] and two different Y-junction traps.

Finally, we discuss the successful demonstration of an integrated optical system for collecting the fluorescence from a trapped ion [2]. The system has been introduced to the ion trapping chamber without negatively impacting the performance of the chip. Considerations such as our choice of epoxies, vacuum feedthrough, and optical components did not degrade the vacuum environment. We have demonstrated ion trapping and shuttling behavior similar to chips without integrated optics with no modifications to the control voltages of the chip.



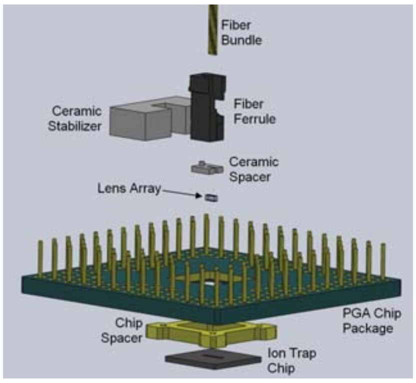


Figure 1: **Left:** Image of a surface Y-junction trap. **Right:** Exploded schematic view of packaged ion trap with integrated optics.

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Towards Cryogenic Surface Ion Traps

M Niedermayr[1], M Kumph[1], R Lechner[1], A Pauli[1], M Brownnutt[1] and R Blatt[1,2]

[1] Institut für Experimentalphysik, Uni. Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria

[2] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria

One promising approach for scalable quantum information processing (QIP) architectures is based on miniaturized surface ion traps. These traps, with dimensions in the sub-100 μm range, can be fabricated by photolithographic techniques. The ion-heating rate increases strongly with decreasing trap dimensions, though it can be reduced significantly when the trap electrodes are cooled from room temperature to 4 K.

The ultra-high vacuum necessary in ion trap experiments is accomplished by adsorbing of the background gases on the cold cryostat surfaces. By this method, lower pressures than in a standard room temperature vacuum setup can be reached. This leads to longer life times of the ions which can be limited by, among other things, background gas collisions. It also allows short turn-around times since no time-consuming bake out is required. Furthermore, the dramatic reduction of out-gassing at low temperature allows the use of some materials which would otherwise be non-vacuum-compatible.

We will present the characterisation of a microtrap system which has been developed for use at cryogenic temperatures. Within the new experiment we intend to investigate surface traps at low temperatures. These traps will be used for quantum simulations, for fundamental investigations of large-scale entanglement and for precision measurements enhanced by quantum metrology techniques employing entangled particles.

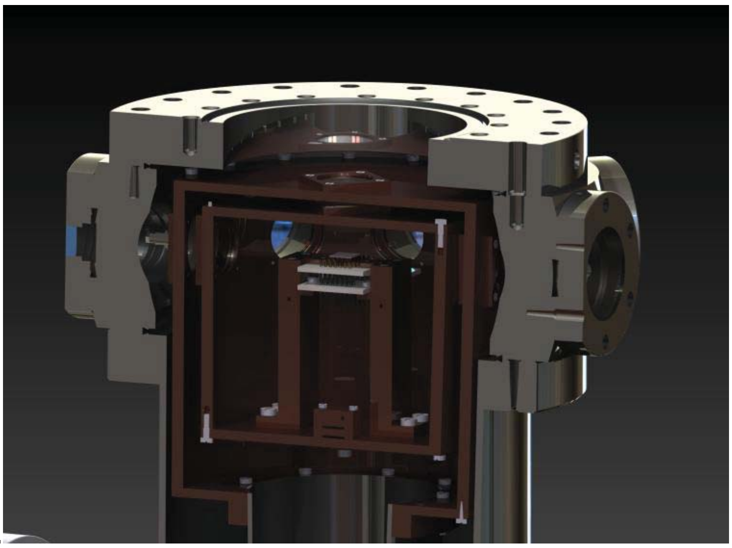

Figure 1. Cross section of the microtrap in the cryo-system.

Optimum surface trap geometries for fast ion separation and the development of junctions within ion trap arrays

A. H. Nizamani[1], B. Stein[1] and W. K. Hensinger[1]

[1] Department of Physics and Astronomy, University of Sussex,
Brighton, BN1 9QH, UK

Trapped ions in a radio frequency (rf) Paul trap can produce quantum logic gates which are the building blocks of a quantum computer. This application can be implemented with a pair of ions and can be extended to a few ions in a single trap. It would be useful if qubits can be stored in separate trapping regions, *memory zones* and only be brought together in a single trap *processor zone* when quantum operations are required. This scheme can be achieved by using ion trap arrays with the possibility of ion transportation between trapping regions.

For many quantum information implementations with trapped ions, effective shuttling operations are important. Here we discuss the efficient separation and recombination of ions in surface ion trap geometries. The maximum speed of separation and recombination of trapped ions for adiabatic shuttling operations depends on the secular frequencies the trapped ion experiences in the process. Higher secular frequencies during the transportation processes can be achieved by optimising trap geometries. We show how two different arrangements of segmented static potential electrodes in surface ion traps can be optimised for fast ion separation or recombination processes and carry out a comparison between them. We also show how to optimise the trap geometry to achieve maximum trap depth for a given ion height above the trap electrodes.

We also report on our studies for the development of optimal junctions within ion trap arrays. Potential barriers within the junction region make adiabatic transport of ions through a junction challenging. At the same time, large variations of the ion secular frequencies within the ion's shuttling path crossing a junction pose a problem for adiabatic transport. We relate the constraints involved in maintaining high secular frequencies whilst keeping the barrier height small to the low-order multipole expansion of the rf potential to particular junction designs and present results on the design of optimal junctions within surface ion traps.

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Toward Cavity-Assisted Cooling of a Single $^{40}\mathrm{Ca}^{+}$ Ion

T E Northup[1], A Stute[1,2], B Brandstätter[1], B Casabone[1], D Habicher[1], J Reichel[3], P O Schmidt[1,4] and R Blatt[1,2]

[1] Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
[2] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria
[3] Laboratoire Kastler Brossel de l'E.N.S., 24 rue Lhomond, 75231 Paris Cedex 05, France
[4] QUEST Institut für Experimentelle Quantenmetrologie, Physikalisch-Technische Bundesanstalt und Leibniz Universität Hannover, Bundesallee 100, 38116 Braunschweig, Germany

One advantage which trapped ions have to offer cavity QED experiments is a sophisticated toolbox for quantum state manipulation and readout. We have previously demonstrated Raman spectroscopy [1] and a deterministic single-photon source [2] using a single $^{40}\mathrm{Ca}^{+}$ ion trapped within an optical cavity; however, these experiments were carried out without the capability to address the the $4^2S_{1/2} - 3^2D_{5/2}$ qubit transition. Having now implemented ground-state cooling and state detection on this transition, we present improved Raman spectra and data on ion localization in the cavity standing wave. We discuss initial steps toward cavity cooling of a single ion as well as plans for atom-photon entanglement.

The requirements of ion-trap geometries also present constraints for cavity QED. Specifically, in ion-trap experiments, it has not yet been possible to integrate cavities with a small enough mode volume to access the strong coupling regime, in which the coherent ion-cavity interaction is the dominant process. We outline our efforts to access this regime with a new experiment using fiber-based mirrors. We present results from measurements in which we approach trapped ions with an optical fiber in order to explore the effects of surface charges, and we report on our characterization of high-finesse fiber cavities and their integration within a miniature Paul trap.

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Ion Dynamics in Linear RF Traps

J. Pedregosa Gutierrez[1], C. Champenois[1], M. Marciante[1],
M. Houssin[1], M Kajita[2], M Knoop[1]

[1]Physique des Interactions Ioniques et Moléculaires, CNRS-Aix-Marseille Université,
Centre de Saint Jérôme, Case C21, 13397 Marseille Cedex 20, France
[2] National Institute for Information and Communications Technology, 4-2-1,
Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan

The radiofrequency linear ion trap is a widely used device in physics and chemistry. The quadrupole linear trap is a widespread tool for many fundamental physics experiments (quantum computing, phase transition study, metrology, etc). Compared to quadrupole trap, higher order traps present the interesting feature to generate an almost flat potential well, which induces a small RF-driven motion and a low RF-heating, compared to quadrupole trap. These traps have been widely used in the ultra cold collisions community with buffer gas cooled samples and recently, to produce Coulomb crystals of a new kind thanks to laser cooling [1]. Moreover, multipole traps have been at the heart of a promising microwave ion clock based on a double trap, a quadrupole plus a 16-pole [2].

In this context, we are setting up a novel experiment which will be presented at the meeting. The purpose of this device is to study ion dynamics under laser cooling, in quadrupole and octupole RF traps, aiming at the confinement and transport of a wide panel of ion clouds from small chains to large samples (N>106). The set-up consists of three trapping regions of different storage potential: quadrupole-quadrupole-octupole. This configuration allows to separate the ion creation zone from the laser-cooling zone, in order to avoid perturbations of the potential created by atom deposition on the RF electrodes.

In the search for the least perturbed harmonic potential for the quadrupole zones, an extensive numerical work has been performed to optimise the geometry of the DC electrodes, which has an important impact on the trapping potential. This trap potential optimisation is crucial if large ion clouds are to be trapped. We have found an optimal geometry which presents some advantages with respect to other more complicated configurations [3].

Interpretation of the observed ion dynamics and the stable crystal structures will be carried out by comparing the experimental to the numerical results produced by ion dynamics simulation which can be pursued in different trapping potential using molecular dynamics. Thanks to these simulations, it has been found that few ions stored in an octupole trap and forming a ring crystal structure can be laser cooled to the Doppler limit along the symmetry axis of the trap. We propose the use of this ring for optical frequency metrology [4], in a tight confinement configuration which reduces the frequency sensitivity to the fluctuations of the number of trapped ions. The systematic shifts introduced by the non-null RF electric field are also evaluated for the optical clock transition of calcium ions, showing that a ring of 10 or 20 ions allows to reach a short term stability better than for a single ion without introducing limiting long term fluctuations.

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PENTATRAP: A high-precision Penning trap mass spectrometer for highly-charged ions

C Roux[1,2], C Böhm[1,2], J Crespo Lopez-Urrutia[1], A Dörr[1,2], S Eliseev[1], M Goncharov[1,4], Y Novikov[4], J Repp[1,2], S Sturm[3], S Ulmer[1,2,3] and K Blaum[1,2]

[1] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[2] Ruprecht-Karls-Universität Heidelberg, 69120 Heidelberg, Germany
[3] Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
[4] St. Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia

A novel cryogenic Penning trap setup called PENTATRAP is presently under construction at the Max-Planck-Institut für Kernphysik, Heidelberg, Germany. The project aims for high-precision mass measurements on single highly-charged and stable ions related to e.g. tests of non-perturbative QED in strong electric fields as well as neutrino oriented mass determinations.
In order to achieve the needed relative mass uncertainty of $\delta m/m \leq 10^{-11}$, a stack of five Penning traps will be used. Thereby, the two outer monitor traps will be used for real time monitoring of the magnetic field during the whole measurement cycle. The high-precision mass measurements will be performed in the three central traps. For relative mass measurements, the setup will enable a very fast ion-exchange of the ion of interest and a reference ion. Additionally, both ions can be measured at the same time in different traps, which should reduce the influence of magnetic field fluctuations compared to an alternating method. All measurements will be performed via a non-destructive image current detection technique. Therefore, all traps will be coupled to resonators with high quality factors *Q* followed by low-noise amplifiers with high input impedance. The apparatus is planned to be connected to the EBIT at MPIK and later to the HITRAP facility at GSI Darmstadt. The design studies of the traptower as well as the present status of the experimental setup will be presented.

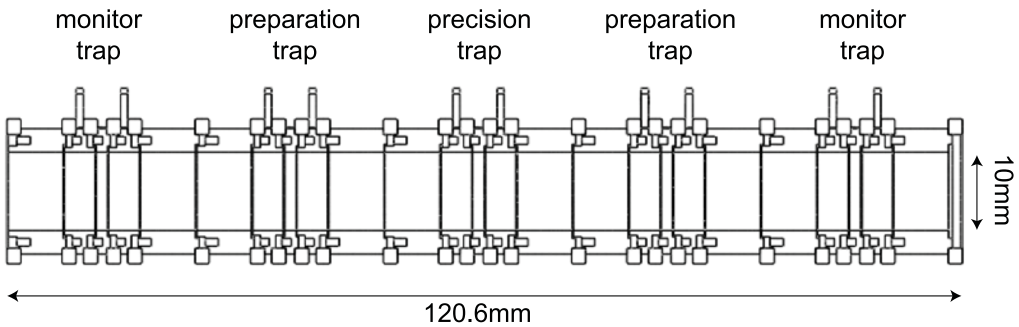

Figure 1: PENTATRAP tower consisting of five cylindrical 5-pole Penning traps.

Heralded entanglement of arbitrary degree in remote atoms by detection of emitted photons.

U Schilling[1], C Thiel[1], E Solano[2], T Bastin[3] and J von Zanthier[1]

[1] Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
[2] Departamento de Química Física, Universidad del País Vasco–Euskal Herriko Unibertsitatea, 48080 Bilbao, Spain
[3] Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège au Sart Tilman, 4000 Liège, Belgium

We propose a method how to generate two qubit states with an arbitrary degree of entanglement in remote atoms using polarization sensitive projective measurements.

Incoherent scattering of a photon off an atom can be described by a common state of the atom and the electric field [1]. A measurement of the electric field can thus project the atom into a specific state and vice versa. This rather simple idea may be extended to the case were multiple atoms scatter a single [2] or even multiple [3-5] photons, with the detectors unable to distinguish which photon was actually scattered by which atom. Through this principal indistinguishability, all possible quantum paths exist in a coherent superposition, and the detection of a photon projects the atoms into a potentially entangled state [2-5]. Here, we investigate a setup in which each of two Λ-level atoms scatters a photon subsequently registered with two detectors which are equipped with polarization filters [5]. One way to ensure the indistinguishability of the photon paths is to position the detectors in the far field of the atoms; other possibilities include using optical fibers to guide the photons to the detector or interferring the photons on a beam splitter. Each detection of a photon projects the state of the atoms into a coherent superposition of all pathways compatible with the measurement result. Analyzing the final state after two detection events, it turns out that the amount of entanglement between the two atoms (as measured by the concurrence) depends only on the difference of the optical path lengths from either atom to the detector (and thus their relative positions) and on the orientation of the two polarization filters. In this way, we are able to tune the entanglement between the two atoms to an arbitrary degree, simply by adjusting these two easily accessible experimental parameters. For certain detector positions, the concurrence between the two atoms can even be described by a “Malus law”, taking into account only the relative angle between the two polarization filter orientations. By exploiting the entanglement between the electromagnetic field and the atoms the arrival of the two photons at the two detectors heralds thus a certain amount of entanglement between the two atoms. We also investigate the experimental feasibility of our scheme.

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Repetitive quantum error correction with trapped ions

P. Schindler [1], T. Monz[1], J. T. Barreiro[1], M. Chwalla[1], D. Nigg[1], V. Nebendahl[2], M. Hennrich[1], and R. Blatt[1,3]

[1] Institut für Experimentalphysik, Universität, Innsbruck
[2] Institut für theoretische Physik, Universität, Innsbruck
[3] Institut für Quantenoptik und Quanteninformation, Innsbruck

Quantum error correction is a necessity for a large scale quantum computer. Implementations of a single correction step in various physical systems including trapped ions [1] have been shown. In order to perform multiple correction steps a technique to reset the auxiliary qubits is needed. This reset step is challenging as it should affect neither the electronic state of the ion carrying the information nor the motional state of the ion string.

We report on the first experimental realisation of a repeated quantum error-correcting code in a system of trapped $^{40}\mathrm{Ca}^{+}$ ions. The implemented algorithm detects and corrects a single-qubit phase error where the correction is performed without any classical measurement. The pulse sequence for this algorithm was compiled with the aid of an optimization technique resulting in a very compact sequence [2]. A novel technique is used to reset the ancilla qubits. The reset steps heats the ion string on average by 0.015 phonons. Therefore up to ten correction steps could be performed before re-cooling of the ion is necessary.

We fully analyze the single qubit process with quantum process tomography and achieve process fidelities of F=90.1(2)/79.8(4)/72.9(5)% for one/two/three correction steps. The performance of the algorithm for any error probability is reconstructed in the presence of uncorrelated and correlated phase noise.

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Towards trapping and cooling for quantum optics with massive clusters and molecules

Ph. Schmid, P. Geyer, N. Dörre, P. Haslinger and M. Arndt

Quantum optics, quantum nanophysics and quantum information,
Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna.

The generation of cold samples of neutral, large molecules and very massive metal clusters in the gas phase has recently become an important challenge for experiments on the foundations of physics such as matter wave interferometry [1], quantum metrology [2] and other quantum optics experiments.

While electrospray methods (ESI) [3], matrix assisted laser desorption (MALDI) [4] and cluster sources [5] have already been established over the last two decades for preparing gas-phase ions even in excess of 1 MDa, the preparation of neutral, mass selected particle beams still proves to be difficult, in particular if the molecule shall be internally cold, well collimated and slow ($T \approx 10$ K).

We discuss the options for using a buffer gas loaded ion trap and subsequent electron detachment of negatively charged cluster ions.

We present the current ideas for loading, trapping and detecting such particles – with an eye on minimized heating and high flexible enough to be coupled to various particle sources and quantum optics experiments.

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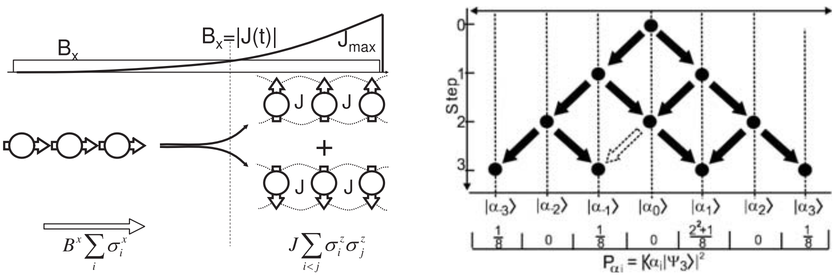
Quantum Simulations and Quantum Walks

C. Schneider[1], J. Stroehle[1], M. Enderlein[1], S. Duewel[1], T. Huber[1] and T. Schaetz[1]

[1] Max-Planck-Institut for Quantum Optics, Garching, Germany

We study the building blocks for quantum simulations based on trapped ions. Hereby we focus on the simulation on quantum spin-Hamiltonians and present our experimental results on the proof of principle for the quantum walk.



(a) Quantum Magnet (b) Quantum Walk

Figure 1: a) By increasing the (simulated) magnetic field, the spins evolve from the initialised paramagnetic to a ferromagnetic arrangement. b) A superposition of coin states allows a state dependent optical force to step the walker to the left and the right simutaneously. Subsequent interferences allows for non-classical behaviour.

Recently, we explored the limits of quantum simulations based on linear chains of ions in conventional linear traps, extending the operations from the common axial- to the radial degree of freedom. For calibration purposes, we realized a two-qubit phase-gate on several radial modes simultaneously with a preliminary fidelity of 95% and achieved the cooling of five ions close to the motional ground state. We will address the differences to the attempt on universal quantum computation and our plans in the current system. 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).
Lately we were able to demonstrate experimentally a quantum walk of one ion in a linear ion trap. With a single-step fidelity exceeding 99%, we perform three steps of an asymmetric walk on the line. We clearly reveal the differences to its classical counterpart if we allow the walker/ion to take all classical paths simultaneously. Quantum interferences enforce asymmetric, non-classical distributions in the highly entangled degrees of freedom (of coin and position states). We theoretically study and experimentally observe the limitation in the number of steps of our approach that is imposed by motional squeezing. We propose an altered protocol based on methods of impulsive steps to overcome these restrictions, allowing to scale the quantum walk to many, in principal to several hundreds of steps.

Aiming to Lock a Local Oscillator Phase to the Atom Phase

N Shiga[1,2], M Takeuchi[2]

[1] Presto, Japan Science and Technology Agency (JST), Tokyo, Japan
[2] National Institute of Information and Communications Technology (NICT), 4-2-1 Nukuikita, Koganei, Tokyo, Japan

We are in process of proposing new method of locking local oscillator (LO) phase to the atom phase, aiming to improve the stability of the atomic clock beyond the limit due to the noise of the LO. We are also preparing the experiment for proof-of principle experiment using a cloud of Yb^+ atoms trapped in a liner Paul trap[1]. We will introduce the main idea and report the experimental progress toward this “Atom phase lock.”
Currently, the atomic clocks are limited by the stability of the Local Oscillator (LO) and the noise of the LO is reduced to the white frequency noise level at the best. As we aim to further reduce the noise level of the LO, we need to achieve the reduction of noise to white phase noise level. In order to achieve this white phase noise, we need to 1) compare the phase of LO and atom and 2) preserve the coherence of the atom spin. Traditional Ramsey method measure the phase difference of the LO and atom spin, but it destroys the coherence of the atom spin. This destruction of the coherence is the reason that the performance of the Ramsey method is limited to white frequency noise, even though it measures the phase difference.
We plan to preserve the coherence of the atom phase by replacing the projection measurement by the non-destructive measurement, using Faraday rotation for example[2]. Figure 1 describes this coherence preserved version of the Ramsey method using Bloch sphere. The difference from the traditional method is that measurement is performed via

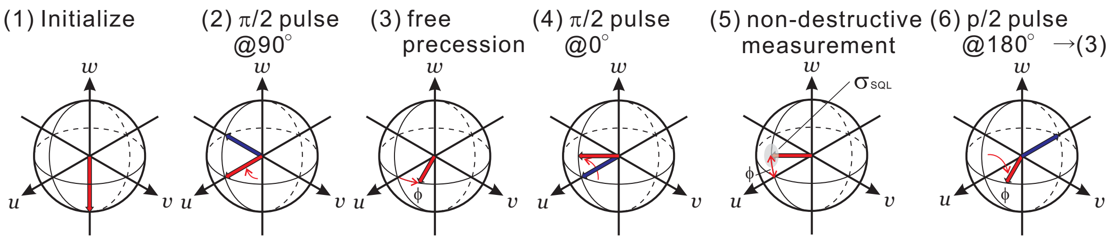


Figure 1: Coherence preserved Ramsey method described using the Bloch sphere. The difference is in (5) and (6) compared to traditional Ramsey method.

non-destructive measurement in (5), and spin is brought back to the original place in (6) and continued to (3) without initializing the atom spin.
We have estimated that we can perform the 100 cycles of Faraday rotation measurement, if we stop the measurement at Signal to Noise ratio (S/N) of 10. This S/N=10 is a sufficient level in order for the phase not to slip over 2π phase.

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Optimisation of a microfabricated surface trap geometry for use in quantum simulations

J.D. Siverns1, R.C. Sterling1 and W.K. Hensinger1

[1] Department of Physics and Astrophysics, University of Sussex, Brighton BN1 9QH, UK

Two-dimensional lattices of trapped ions have been proposed as a suitable system for performing quantum simulations of spins systems. With the requirement for long ion coherence times and strong ion-ion interaction, 2D ion trap arrays must be optimised if successful simulations are to take place. Using a Bio-Savart-like analytical field calculation [1], in the gapless plane approximation, we show how to optimise a 2D array of island electrodes, as shown in figure 1. Using this knowledge a 2D surface geometry is presented along with a method to determine the optimal diameter, D, and centre spacing, A and shape in order to create an optimal 2D ion lattice for use in quantum simulations.

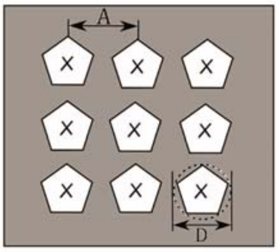

Figure 1: Diagram showing a three by three microtrap array consisting of 5 sided polygons with a circumscribed diameter, D, separated by a distance, A. The grey area represents RF electrodes, whilst the white polygon centres are DC.

We will also show how this design lends itself to be easily microfabricated using microelectromechanical (MEMS) fabrication technologies and we report our progress towards constructing such a device.

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On the Sympathetic Cooling of Atomic and Molecular Ions with Ultracold Atoms

W W Smith[1], D Goodman[1], I Sivarajah[1], J Wells[1] and F A Natducci[2]

[1] Physics Department, University of Connecticut, Storrs, CT 06269-3046, USA
[2] EO Sensors Division, Naval Air Systems Command, Patuxent River, MD 20670, USA

Ion collisions with ultracold neutral atoms are dominated by universal types of long-range polarization forces between charged particles and neutrals. For example, we have calculated the elastic scattering cross section in the mK range for Ca$^+$ ions on Na atoms to be 10^6 atomic units [1]. These collisions have potential applications, for example, to ion-molecule reactions in the interstellar medium, to decoherence effects in trapped-ion quantum computing and quantum information experiments, as well as precision spectroscopy. A hybrid cold ion-neutral trap has been built and is being put through its paces. Ultracold Na atoms are trapped in a vapor cell magneto-optic trap (MOT) and will be overlapped spatially with a small cloud of ^{40}Ca$^+$ or ^{23}Na$^+$ ions trapped in a co-located linear Paul radiofrequency trap, which we have constructed. We have indications that both traps can operate simultaneously without interference. We have been working on stabilizing the Na cooling laser for the MOT, improving the optics to ensure reliable operation, and developing the Paul trap apparatus and ion diagnostics. We hope to confirm theoretical predictions that trapped atomic and molecular ions can be cooled very efficiently by collisions with the ultracold atoms in a high vacuum environment. The method, if it works as expected, is very general and can be used in cases where direct laser translational cooling of molecular ions is impractical. Once cooled, precision Doppler free spectroscopy and studies of reactions of molecular ions and atomic clock ions with neutrals become possible. Potential measurements of internal state molecular-ion cooling due to collisions with ultracold atoms are also of great experimental and theoretical interest. Other international theoretical and experimental groups are beginning to initiate research in this area, including a breakthrough experiment at Cambridge University [2] in which a single Yb$^+$ ion was observed optically in its effect on de-trapping Rb atoms from a BEC. This general ion-cold neutral research area, which we were among the first to propose [3] (with theoretical help from Prof. R. Ct [4]), is proving to be of broad interest. We will present a progress report on our current hybrid trap experiments.

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Ultracold atom-ion collisions in mixed dimensionality

S. Srinivasan[1], A. Simoni[1]

[1] Insititut de Physique de Rennes, UMR UR1-CNRS 6251, Université de Rennes 1
F-35042 Rennes Cedex, Rennes, 35042, France

We study ultracold collisions in confined geometries. We consider in particular the system formed by an atom and an ion confined in a one dimensional waveguide, modeled by a transverse harmonic potential. The ion is confined in the longitudinal direction by an additional weaker harmonic trap whereas the neutral atom can move freely in the waveguide. We initially consider the case of a zero-range atom-ion interaction and of static trapping potentials. The collision energy is supposed to be less than the spacing of the transverse oscillation modes, such that the effect of the transverse coupling on the collision can be modeled by an effective 1D interaction.

We solve the scattering integral equation using a pseudospectral grid method adapted for treating the kernel singularity and compare with lower order discretizations. Coupling between center of mass and relative motion results in a nontrivial resonance behavior of the effective coupling constant (see Fig.1). The Fig.1 also shows the molecular states associated to resonances, identified based on numerical bound level calculations. We extend our time-independent model to a time-dependent Paul trap using a Floquet approach, and investigate atom and ion heating due to the collision process. Prospects for including in the model more realistic long-range interactions are discussed. Our results should be important to interpret current atom-ion collision experiments [1,2].

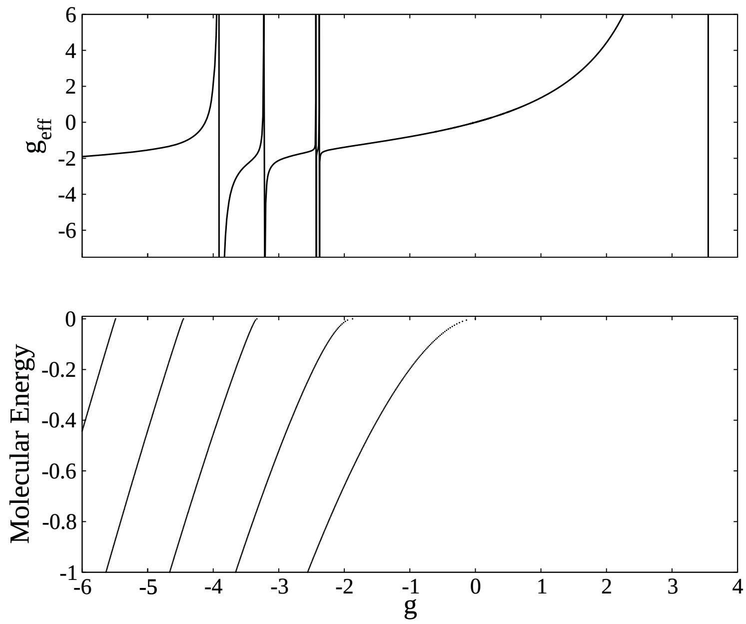

Figure 1: Upper panel : effective atom-ion 1D coupling constant g_{eff} as a function of the free space coupling constant g in the ultracold limit. Lower panel : evolution of the molecular levels associated to resonances with the free space coupling constant. All quantities are in natural harmonic oscillator units.

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Microfabrication of surface ion trap arrays

R. C. Sterling[1], P. Srinivasan[2], H. Rattanasonti[2], D. Brown[3], A. H. Nizamani[1], K. Schwab[3], M.Kraft[2] and W.K. Hensinger[1]

[1] Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK
[2] School of Electronics and Computer science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[3]Dept. of Applied Physics, 219 Steele, Caltech, 1200 E. California Blvd, Pasadena, CA 91125, USA

Microfabricated ion trap chips are of fundamental importance for the implementation of novel quantum technologies with trapped ions. Using micro-electromechanical (MEMS) fabrication technologies we report design and fabrication of multi-zone surface-electrode ion trap arrays. One such array consists of a silicon-on-insulator (SOI) wafer in which all dielectrics are optically and electrically shielded. This has been accomplished without the cost of additional complexity often associated with such designs and retains the scalability that makes surface architectures appealing.

Another design proposed consists of multi-layered gold electrodes resulting in a cantilever design which overlaps lower lying electrodes allowing the shielding of the dielectric layer from the ion. The fabrication process consists of gold layers built up on a quartz substrate via a series of photoresist and deposition layers. Additional features include the control of electrodes which are isolated from the surrounding of additional electrodes via buried wires.

The design of the ion trap arrays was performed with boundary element method simulations of the electric field. By adjusting the shape of the electrodes within the junction area the suppression of the rf barrier by a factor of 6 was achieved. The optimization of dc electrodes for ion separation was also incorporated into the trap design.

Keeping a Single Physical Qubit Alive by Experimental Dynamical Decoupling

D J Szwer, S C Webster, A M Steane, and D M Lucas

Department of Physics, University of Oxford, Oxford OX1 3PU, UK

We present experiments that demonstrate the use of Uhrig Dynamical Decoupling (UDD) to extend the T_2 coherence time of a (magnetic-field sensitive) hyperfine qubit in a single trapped $^{43}Ca^+$ ion [1, 2]. In a basic Ramsey experiment, we measured a T_2 time of 0.45 ms. Inserting a single spin-echo pi-pulse extends this to 2 ms, while a sequence of 20 pulses gives a T_2 of approximately 28 ms. The Carr-Purcell-Meiboom-Gill (CPMG) sequence was found to be equally effective in the ambient noise environment of our experiment. We also present a particularly simple derivation of the UDD sequence by treating the noise as an (unknown) polynomial in time, and showing how n correctly spaced pi-pulses cancel out the noise up to the $(n-1)$th power of t.

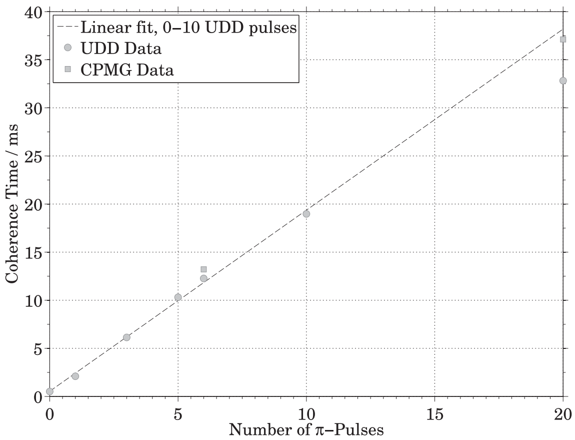

Figure 1: T_2 coherence time of the qubit, deduced by measuring the contrast of Ramsey fringes as a function of Ramsey gap time, with various dynamical decoupling sequences inserted in the Ramsey gap. T_2 rises as the number of pulses increases, approximately linearly.

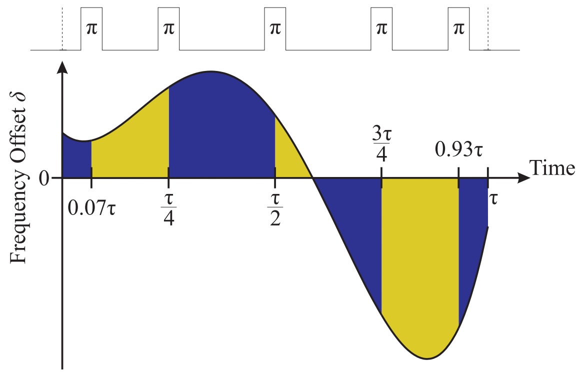

Figure 2: A qubit, whose precession frequency has a time-varying offset $\delta(t)$ relative to a reference oscillator, acquires unwanted phase of $\int \delta(t)\mathrm{d}t$. A spin-echo $\pi-$pulse effectively flips the sign of $\delta(t)$. Assuming that $\delta(t)$ is an $(n-1)$th-order polynomial in t, the n-pulse UDD sequence is designed so that the positive and negative phase contributions cancel out at exactly at time $t = \tau$. This is illustrated here for a 5-pulse UDD sequence and an (arbitrary) quartic polynomial; the area under the graph represents the acquired phase, and the two colours stand for positive and negative contributions. The total area of each colour is the same.

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Ytterbium Single-Ion Optical Frequency Standards at PTB

Chr. Tamm, N. Huntemann, B. Lipphardt, M. Okhapkin, I. Sherstov, E. Peik

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

A single laser-cooled ion in a radiofrequency trap is a nearly ideal reference for an optical frequency standard. The ion $^{171}Yb^{+}$ has two attractive reference transitions: an electric-quadrupole transition from the $^2S_{1/2}$ ground state to the $^2D_{3/2}$ state at 436 nm with a natural linewidth of 3.1 Hz, and an electric-octupole transition to the $^2F_{7/2}$ level at 467 nm. The latter transition has a negligible natural linewidth in the nanohertz range and its frequency is comparatively insensitive to external fields [1].

The absolute frequency of the $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ quadrupole transition was measured with a total uncertainty of $1.1\cdot10^{-15}$ which was dominated by the uncertainty of the employed caesium fountain reference. Using a differential measurement scheme, we determined the quadrupole shift of the transition frequency that is caused by the gradient of the static electric stray field in the trap [2]. The temporal variations in the shift and in the applied stray-field compensation voltages were observed over a time interval of 74 days after loading a new ion into the trap. These investigations point to potential causes of stray-field variation and allow to estimate the accuracy of averaging schemes that cancel the quadrupole shift.

In a first spectroscopic investigation of the $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ octupole transition, the transition was driven by a frequency-doubled diode laser system with a linewidth in the Hertz range and a minimum resonance width of 13 Hz was observed [3]. Since the oscillator strength of this transition is extremely small, the intensity required to obtain a π-pulse of 0.1 s length leads to a light shift of the transition frequency in the range of 100 Hz through coupling to other levels. The preliminary unperturbed transition frequency value which we obtained by extrapolation to zero excitation intensity is in good agreement with the value determined at NPL (Teddington) [4]. Our present work aims at the further development of the $^{171}Yb^{+}$ octupole frequency standard. This includes the use of a new efficient repumping scheme from the $^2F_{7/2}$ level using a transition at 760 nm, and the implementation of a Ramsey-type excitation scheme for the octupole transition which promises a strongly reduced light shift sensitivity [5].

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Smooth composite pulses in coherent atomic excitation

B Torosov[1,2] and N V Vitanov[1]

[1] Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria
[2] Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR CNRS 5209, BP 47870, F-21078 Dijon, France

Excitation by composite pulses is routinely used in nuclear-magnetic-resonance experiments, in order to achieve excitation profiles with prescribed shapes [1,2]. The method consists of applying several consecutive pulses with appropriate relative phases. In such way one can achieve a robust analog of the traditional resonance pulses. This technique is, however, mainly developed for pulses with rectangular temporal shape.

In this work we show that composite pulses with smooth temporal shape can be used to obtain analogues of the π-pulses with arbitrarily flat excitation profile. The transition probability can be made robust against variations in the pulse area and/or the detuning. As the number of pulses increases, the excitation profile becomes increasingly insensitive (flat) to small deviations. In order to achieve this, we use the well-known analytic solution of the Rosen-Zener model [3], which assumes a hyperbolic-secant pulse shape and a constant detuning:

$$\Omega(t) = \Omega_0 \text{sech}(t/T), \quad \Delta(t) = \Delta_0, \tag{1}$$

where $\Omega(t)$ is the Rabi frequency, and Ω_0, Δ_0 and T are constant parameters. We calculate the total propagator by multiplying the phased propagators for each pulse. Then we take the Taylor expansion of the full propagator and nullify the first few terms in the respective series (vs. the pulse area deviation or vs. the detuning). The more composite pulses we use, the more terms we are able to nullify, and the more flat the profile will be.

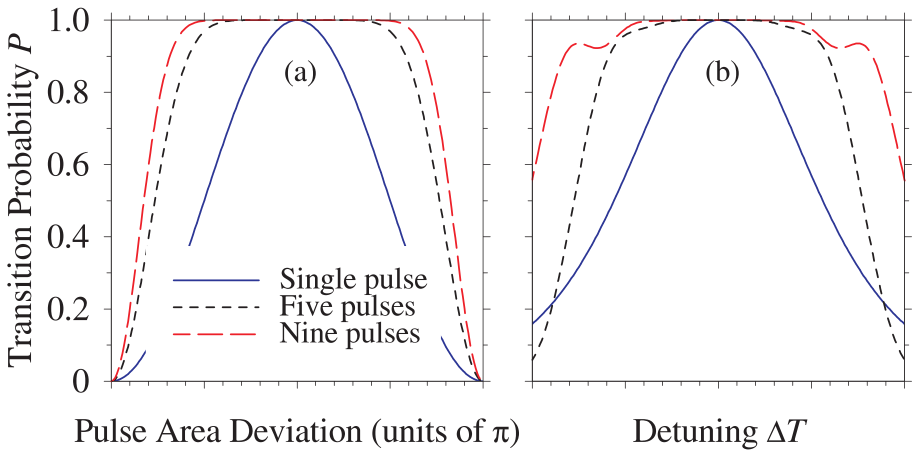

Figure 1: Transition probability for a single hyperbolic-secant pulse and for a sequence of five and nine pulses versus (a) pulse area deviation and (b) detuning.

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The CPW-cavity planar Penning trap

J Verdu[1]

[1] School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9RH, UK

Originally motivated by the requirement of scalability for quantum computation applications, novel planar Penning traps have been designed with flat electrodes and integrated on the surface of a chip. Trapping of electrons has been experimentally demonstrated using those designs, both at room temperature and using cryogenic set-ups. However, the experiments show that some technical difficulties remain unsolved [1], especially due to trapping-potential imperfections that unavoidably appear when using flat electrodes. We present our novel planar Penning trap design, based upon the coplanar waveguide (CPW) transmission-line which aims at solving those difficulties. The novel trap results simply from the projection of the well-known 3D cylindrical trap on the surface of a chip. Moreover, it behaves as an elliptical Penning trap [2], where the ellipticity, ϵ, can be controlled by the applied dc-voltages. In particular, ϵ can tuned very high, thereby almost eliminating the magnetron motion. In the latter case the electron is captured in a "quasi" 2D-trap and the anharmonicities of the electric potential can be very efficiently compensated. We discuss the future applications of the new trap to circuit-QED [3] and the physics of 2D electron gases.

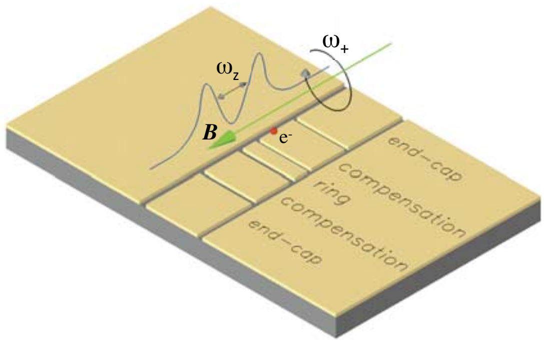

Figure 1: **Figure 1.** The CPW-cavity planar Penning trap.

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Towards Direct Frequency Comb Spectroscopy of Metal Ions

Yong Wan, Börge Hemmerling, Florian Gebert, Ivan Sherstov, Piet O. Schmidt

Leibniz University, Hannover, Germany
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Quantum computing based on trapped ions has flourished over the past decade, demonstrating exquisite control of the internal and external degrees of freedom of the atoms. Only now, first applications of the developed techniques start to emerge. One of these applications is the so-called quantum logic spectroscopy [1] in which a logic ion is used for laser cooling, internal state preparation, and detection of the internal state of a spectroscopy ion. This opens the door to perform precision spectroscopy on atomic and molecular ions with a complex level structure. We will present quantum logic spectroscopy schemes for metal ions using direct frequency comb spectroscopy. For this, an optical frequency comb is used to excite the spectroscopy transitions, while cooling and detection is performed using quantum logic via a simultaneously trapped logic ion.

The investigated atoms are relevant for the search of a possible temporal variation of the fine-structure constant on cosmological timescales. Laboratory experiments that compare ultra-precise clocks to probe the variation of the fine-structure constant are within their errors compatible with $\dot{\alpha}/\alpha \sim 0$. However, experiments on astronomical time scales that compare quasar absorption spectra with today's spectra of metal ions yield contradictory results reaching from no variation to $\Delta\alpha/\alpha \sim 10^{-5}$. The latter observations are amongst other obstacles limited by inaccurate spectroscopy data on certain transition lines in complex ions such as Ca^{+}, Ti^{+} and Fe^{+} [2]. Furthermore, the technique might allow cooling of molecular ions to their internal ground state.

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Development of monolithic 3D ion traps microfabricated using Si-on-SiO_2.

G Wilpers, P See, P Gill and A G Sinclair

National Physical Laboratory, Teddington, TW11 0LW, UK

We have developed a microfabrication process to create ion trap chips based on gold-coated, silica-on-silicon technology. These linear segmented ion traps are a 3D monolithic structure, with the electrodes in a unit aspect ratio configuration. The trap electrodes are formed by gold-coated SiO_2, and are spaced by highly-doped Si [1] (fig1a). Firstly, a thermal oxide is grown (to 15 μm thickness) on the surfaces of a Si wafer (350 μm thick). The SiO_2 is metallised with gold to form the electrode pattern, and is etched to define the gold-coated electrodes. The Si is etched to create the trap aperture and thus realise a 3D trap structure (fig1b). A shadow evaporation technique metallises the internal surfaces of the SiO_2, and electroplating enhances the electrodes' gold thickness to ~5 μm; the ion-electrode distance is 245 μm. Trap chips are mounted in a ceramic leadless chip carrier for incorporation into UHV (fig 1c).

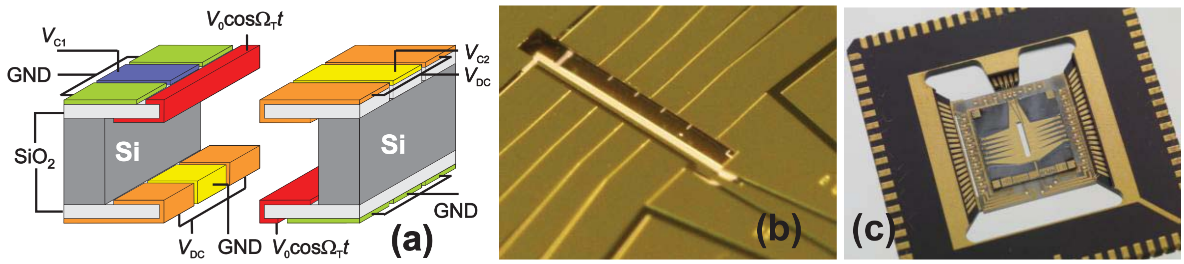

Figure 1. a) Trap concept: electrodes of Au on SiO_2 and separated by Si. b) Detail of electrodes in a fully processed 3D trap. b) Trap chip packaged in a CLCC.

When tested under the application of a drive voltage (U_{RF} ~250 V at Ω_{RF} ~15 MHz), RF loss is low and device temperature rises by only ~10 K. The resistance of the ohmic contacts to the Si is < 0.5 ohm, which ensures that the Si can be grounded effectively. The trap structure is mechanically sound; traps with all electrodes intact can be achieved with a high yield. The 3D structure is expected to exhibit a deep trapping potential, with motional frequencies in the range $\omega_r \leq 4$ MHz and $\omega_z \leq 2$ MHz at practical operating parameters. Traps that are very close to our ideal design [1] have been made and are now under test for trapping of $^{88}Sr^+$ ions. The current batch is limited to U_{RF} ~60 V, primarily due to surface flashover and/or field emission from the RF electrode to the grounded Si, inside the trap aperture.

The microfabrication techniques used here are suitable for scaling up to devices containing a more complex array of a larger number of electrodes. We have also developed a compact arrangement for UHV packaging, including a straightforward solution for the many electrical feedthrough connections required.

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Laser spectroscopy of Be-like krypton ions

Danyal Winters[1,2], Th. Kühl[1,3], D. Schneider[4], P. Indelicato[5],

R. Reuschl[5], R. Schuch[6], E. Lindroth[6] and Th. Stöhlker[1,2,7]

[1] GSI Darmstadt, Germany
[2] Heidelberg University, Germany
[3] Mainz University, Germany
[4] Lawrence Livermore National Laboratory, USA
[5] Laboratoire Kastler Brossel, Paris, France
[6] Stockholm University, Sweden
[7] Helmholtz Institute Jena, Germany

Heavy few-electron ions, such as He-, Li-, and Be-like ions, are ideal atomic systems to study effects of correlation, relativity and quantum electrodynamics [1-4]. Very recently, theoretical and experimental studies of these species achieved a considerable improvement in accuracy. The Be-like ions are interesting because their first excited state, *i.e.* the $(1s^2 2s2p)\ ^3P_0$, has an almost infinite lifetime in the absence of nuclear spin (I), as it can only decay by a two-photon *E1M1* transition to the $(1s^2 2s^2)\ ^1S_0$ ground state [5]. If there is nuclear spin, the corresponding hyperfine structure will reduce this lifetime by orders of magnitude. In addition, the energy difference between the $^3P_0$ and the $^3P_1$ states is expected to be almost completely unaffected by QED effects, and is therefore dominated by the effects of correlation and relativity [6]. We want to determine the $(1s^2 2s2p)\ ^3P_0$ - $^3P_1$ level splitting in Be-like krypton ($^{84}Kr^{32+}$), which has I=0, by means of laser spectroscopy at the experimental storage ring (ESR) at GSI, Darmstadt. In such an experiment, the energy splitting can be obtained with very good accuracy, *i.e.* of the order of $\sim 10^{-5}$, and be compared with recent calculations [6]. These ESR experiments will most likely be carried out next year (2011). Similar experiments, albeit with lighter ions, are currently being set up at the Electron Beam Ion Trap (EBIT) in Stockholm.

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(a MultiConfiguration Dirac Fock and General Matrix Elements program,
http://dirac.spectro.jussieu.fr/mcdf)

Implementation of a MR-ToF isobar separator at the on-line mass spectrometer ISOLTRAP

R N Wolf[1], K Blaum[2], Ch Borgmann[2], M Breitenfeldt[5], D Fink[2], A Herlert[3], M Kowalska[3], S Kreim[2], D Lunney[4], G Marx[1], S Naimi[4], M Rosenbusch[1] and L Schweikhard[1]

[1] Institute of Physics, University of Greifswald, 17489 Greifswald, Germany
[2] MPI for Nuclear Physics, 69117 Heidelberg, Germany
[3] CERN, 1211 Geneva 23, Switzerland
[4] CSNSM, Orsay, France
[5] Instituut voor Kern- en Stralingsfysica, K.U. Leuven, 3001 Leuven, Belgium

Precision mass measurements are performed by the mass spectrometer ISOLTRAP at the isotope separator ISOLDE/CERN with a relative mass uncertainty routinely reaching to $1*10^{-8}$. The time-of-flight detection technique is employed to determine the frequency of an ion stored in a Penning trap, from which the mass can be extracted. The system has studied nuclides with half-lives below 100ms and production yields of less than 1000 ions per second. They range from light systems - such as 17Ne - to heavy ones - such as 229Rn, thus giving insight into numerous physics topics. In the period from 2007-2010, ISOLTRAP has delivered data for nuclear structure studies concerning shell closures and residual interaction e.g. in the regions of closed shells around N=50, N=82, N=126. Valuable input has also been provided for neutron and proton rapid capture processes in stellar environments with isotopes of Se, Br, Ag, Rb, Kr, Cd, Xe, Rn. In addition, new mass values improved the examination of the electroweak interaction based on super-allowed beta emitters such as 22Mg, 26mAl, 38Ca, and 74Rb.

To enhance the isobaric purification of rare-isotope ensembles as a preparation for precision mass determinations, a multi-reflection time-of-flight mass separator (MR-ToF-MS) has been built at Greifswald and implemented at the ISOLTRAP setup. The MR-ToF-MS consists of two ion optical mirrors between which ions are oscillating and are separated according to their different mass-over-charge ratios m/q [1]. Preliminary tests resulted in a mass resolving power of up to $m/\Delta m \approx 10^5$ and the separation was demonstrated for the isobaric ions CO^+ and N_2^+. In combination with a Bradbury-Nielsen beamgate [2,3], a selection of the separated species can be achieved.

The status of this project as well as the results of recent mass measurements will be presented.

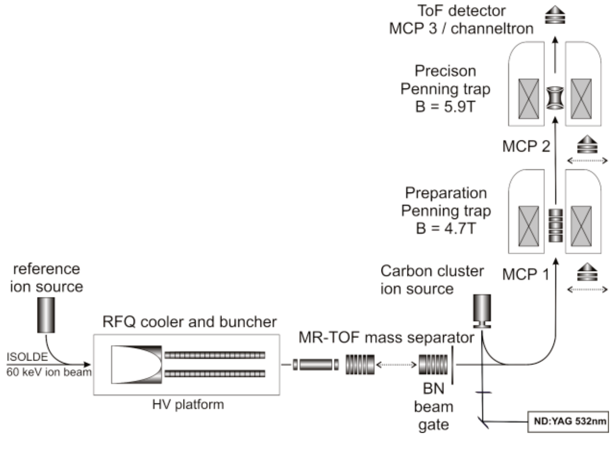

Figure 1 Overview of the ISOLTRAP setup.

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Cryogenic micro ion trap with integrated fiber cavity

F Ziesel[1,2], M Hettrich[1,2], D Heinrich[1] and F Schmidt-Kaler[1,2]

[1] Physics department, University of Mainz, 55122 Mainz, GE
[2] Physics department, University of Ulm, 89069 Ulm, GE

Our highly segmented ion trap allows the transport of ions from a 'large' trapping region (0.5 mm slit) to a narrow processing region (0.25 mm slit). So the ions is transferred into a very small radial confinement in which it is highly shielded from the environment by the surrounding electrodes. In this kind of trap we demonstrated coherent single and two qubit operations as well as shuttling of a single ion through the whole trap [1,2].

For the next generation of this kind of quantum processor we implemented a micro cavity in the narrow region in the trap. In addition we assembled the trap in a flow through cryostat to reduce the temperature of the trap electrodes and the cavity fibers. Cryogenic cooling has already shown a reduction in heating rate for multiple orders of magnitude [3].

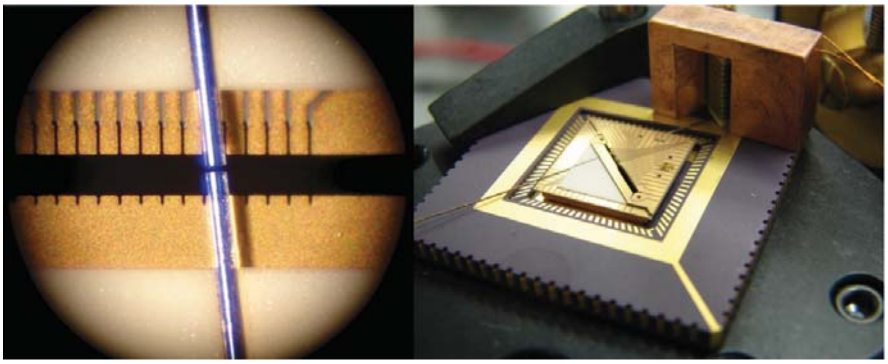

Figure 1: **Figure 1.** (left) Image of the fiber cavity on the bottom layer of the trap. Fiber alignment is achieved due to the alumina spacer material. (right) assembled trap setup with cavity fibers and shear piezo for scanning and stabilization.

The small radial trap geometry allows to bring micro cavity mirrors very close to the ion without disturbing the trapping potential too much. The cavity mirrors consist of curved and coated fiber tips, which achieves a finesse of 30 000. The actual setup can reach strong coupling of a light field with a single ion. The cavity will be used for non demolition measurements and as photon ion interface to determine or transport the quantum information of the ion.

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List of Participants

Surname	Name	Email
Alexandrov Ivanov	Peter	pivanov@phys.uni-sofia.bg
Allcock	David	d.allcock@physics.ox.ac.uk
Ballance	Christopher	chris@ballance.eu
Beige	Almut	a.beige@leeds.ac.uk
Best	Thorston	thorsten.best@physik.uni-freiburg.de
Blatt	Rainer	rainer.blatt@uibk.ac.at
Bollinger	John	john.bollinger@boulder.nist.gov
Brownnutt	Michael	michael.brownnutt@uibk.ac.at
Burrell	Alice	a.myerson1@physics.ox.ac.uk
Campbell	Wesley	wes3000@umd.edu
Cerrillo	Javier	j.cerrillo@imperial.ac.uk
Champenois	Caroline	caroline.champenois@univ-provence.fr
Charlton	Michael	M.Charlton@swansea.ac.uk
Cormick	Cecilia	cecilia.cormick@physik.uni-saarland.de
Crick	Daniel	daniel.crick05@imperial.ac.uk
Donnellan	Sean	s.donnellan07@imperial.ac.uk
Douglas Barrett	Murray	phybmd@nus.edu.sg
Drewsen	Michael	drewsen@phys.au.dk
Duewel	Stephan	stephan.duewel@mpq.mpg.de
Edwards	Emily	seroosa@umd.edu
Georgescu	Iulia	iulia.georgescu@unibas.ch
Gerlich	Dieter	gerlich@physik.tu-chemnitz.de
Germann	Matthias	matthias.germann@unibas.ch
Gill	Partrick	patrick.gill@npl.co.uk
Goodwin	Joe	joseph.goodwin09@imperial.ac.uk
Goold	John	quantumgoold@gmail.com
Guibal	Samuel	samuel.guibal@univ-paris-diderot.fr
Hall	Felix	felix.hall@unibas.ch
Harlander	Max	Max.Harlander@uibk.ac.at
Harty	Thomas	thomas.harty@balliol.ox.ac.uk
Hasegawa	Shiuchi	hasegawa@sys.t.u-tokyo.ac.jp
Hayasaka	Kazuhiro	hayasaka@nict.go.jp
Hempel	Cornelius	Cornelius.Hempel@uibk.ac.at
Hensinger	Winfred	w.k.hensinger@sussex.ac.uk
Herschbach	Norbert	norbert.herschbach@ptb.de
Hilico	Laurent	hilico@spectro.jussieu.fr
Huber	Thomas	thomas.huber@mpq.mpg.de
Huwer	Jan	jan.huwer@icfo.es
Ivanov	Svetoslav	svetljo@gmail.com
Jacob	Georg	jacobge@uni-mainz.de
Janacek	Hugo	hugo.janacek@chch.ox.ac.uk
Julienne	Paul	psj@umd.edu
Keller	Matthias	m.k.keller@sussex.ac.uk
Kenny	Daniel	daniel_kenny@waters.com
Knoop	Martina	Martina.Knoop@univ-provence.fr
Koehl	Michael	mk540@cam.ac.uk
Koelemeij	Jeroen	koel@few.vu.nl
Kumph	Muir	Muir.Kumph@uibk.ac.at
Kyoseva	Elica	cqtesk@nus.edu.sg
Landa	Haggai	haggaila@gmail.com

Lange	Wolfgang	W.Lange@sussex.ac.uk
Lanyon	Ben	Ben.Lanyon@uibk.ac.at
Leibfried	Dietrich	dietrich.leibfried@nist.gov
Lekic	Bjoern	B.Lekitsch@sussex.ac.uk
Leng Chuah	Boon	cqtcbl@nus.edu.sg
Li	Weibin	weibin.li@nottingham.ac.uk
Linke	Norbert	n.linke1@physics.ox.ac.uk
Lucas	David	d.lucas@physics.ox.ac.uk
Luis Verdu Galiana	Jose	J.L.Verdu-Galiana@sussex.ac.uk
Machnes	Shai	shai.machnes@uni-ulm.de
Marler	Joan	j-marler@northwestern.edu
Maser	Andreas	andreas.maser@physik.uni-erlangen.de
Mavadia	Sandeep	sm1004@ic.ac.uk
Mcloughlin	Jim	j.j.mcloughlin@sussex.ac.uk
Mehlstäubler	Tanja	Tanja.Mehlstaeubler@ptb.de
Meijer	Frans	frans.meijer@ucd.ie
Moehring	David	dlmoehr@sandia.gov
Monroe	Christopher	monroe@umd.edu
Morigi	Giovanna	Giovanna.Morigi@physik.uni-saarland.de
Morizot	Oliver	olivier.morizot@univ-provence.fr
Neidermayr	Michael	Michael.Niedermayr@uibk.ac.at
Nizamani	Altaf	a.h.nizamani@sussex.ac.uk
Northup	Tracy	Tracy.Northup@uibk.ac.at
Ozeri	Roee	ozeri@weizmann.ac.il
Pedregosa Gutierrez	Jofre	jofre.pedregosa@univ-provence.fr
Peik	Ekkehard	ekkehard.peik@ptb.de
Pello	Emily	samuel.guibal@univ-paris-diderot.fr
Porras	Diego	diego.porras@fis.ucm.es
Pyka	Karsten	Karsten.Pyka@ptb.de
Quint	Wolfgang	w.quint@gsi.de
Retzker	Alex	alex.retzker@uni-ulm.de
Roux	Christian	christian.roux@mpi-hd.mpg.de
Schaetz	Tobias	tobias.schaetz@mpq.mpg.de
Scharfenberger	Benedikt	scharfenberger@physik.uni-siegen.de
Schindler	Philipp	Philipp.Schindler@uibk.ac.at
Schmid	Philipp	philipp.schmid@univie.ac.at
Schmidt	Piet	Piet.Schmidt@ptb.de
Schmidt-Kaler	Ferdinand	fsk@uni-mainz.de
Schneider	Christian	christian.schneider@mpq.mpg.de
Schweikhard	Lutz	LSchweik@Physik.Uni-Greifswald.de
Segal	Danny	d.segal@ic.ac.uk
Shiga	Nobuyasu	shiga@nict.go.jp
Sinclair	Alistair	alastair.sinclair@npl.co.uk
Smith	Anne	winthrop.smith@uconn.edu
Smith	Winthrop	winthrop.smith@uconn.edu
Soderberg	Kathy-Anne	soderberg_kathyanne@bah.com
Srinivasari	Srihari	srihari.srinivasan@univ-rennes1.fr
Stachowska	Ewa	ewa.stachowska@put.poznan.pl
Sterling	Robin	r.c.sterling@sussex.ac.uk
Stroehle	Johannes	johannes.stroehle@mpq.mpg.de
Szwer	David	d.szwer1@physics.ox.ac.uk
Tamm	Christian	Christian.Tamm@ptb.de
Thompson	Richard	r.thompson@imperial.ac.uk
Tomas Barreiro Guerrero	Julio	julio.barreiro@gmail.com

Tong	Xin	xin.tong@unibas.ch
Torosov	Boyan	torosov@phys.uni-sofia.bg
Ulm	Stephan	stefan.ulm@uni-ulm.de
Vedel	Fernande	fernande.vedel@univ-provence.fr
Vitanov	Nikolay	vitanov@phys.uni-sofia.bg
von Hahn	Robert	robert.von.hahn@mpi-hd.mpg.de
von Zanthier	Joachim	joachim.vonzanthier@physik.uni-erlangen.de
Wada	Michiharu	mw@riken.jp
Wan	Yong	yong.wan@quantummetrology.de
Webster	Simon	s.webster3@physics.ox.ac.uk
Weidt	Seb	S.Weidt@sussex.ac.uk
Willitsch	Stephan	stefan.willitsch@unibas.ch
Wilpers	Guido	guido.wilpers@npl.co.uk
Wineland	David	djw@boulder.nist.gov
Winters	Danyal	D.Winters@gsi.de
Wunderlich	Christof	wunderlich@physik.uni-siegen.de
Youziel	Diana	diana.youziel09@imperial.ac.uk
Ziesel	Frank	ziesel@uni-mainz.de

Time	Sunday 19 Sept	Monday 20 Sept	Tuesday 21 Sept	Wednesday 22 Sept	Thursday 23 Sept	Friday 24 Sept
08:45 to 09:00		Welcome (WH, DS, RT)				
		Chair: Segal	Chair: Lucas	Chair: Blatt	Chair: Knoop	Chair: Porras
09:00 to 09:30		Lucas	Leibfried	Schmidt	Schaetz	Gerlich
09:30 to 10:00		(Tutorial)	(Tutorial)	(Tutorial)	(Tutorial)	(Tutorial)
10:00 to 10:30		Vitanov	Schmidt-K	Charlton	Peik	Schweikhard
10:30 to 11:00		Coffee	Coffee	Coffee	Coffee	Coffee
		Chair: Thompson	Chair: Monroe	Chair: Wunderlich	Chair: Bollinger	Chair: Schaetz
11:00 to 11:30		Bollinger	Wunderlich	Wineland	Campbell	Ozeri, Edwards
11:30 to 12:00		Knoop	Morigi	Drewsen	Guibal	Lanyon, Hilico
12:00 to 12:30		Blatt	Porras	von Hahn	Retzker	Huber, Machnes
12:30 to 13:00						
13:00 to 13:30		Lunch	Lunch	Lunch	Lunch	Lunch
13:30 to 14:00						
14:00 to 14:30			COST		Poster	
14:30 to 15:00			Round table		Session	
15:00 to 15:30	Registration				&	
		Chair: Drewsen	Chair: Willitsch		Exhibition	
15:30 to 16:00		Webster	Koehl	Free		Depart
16:00 to 16:30		Hayasaka	Julienne			
16:30 to 17:00		Tea	Tea	for		
		Chair: Peik	Chair: Vitanov			
17:00 to 17:30		Quint	Lange, Tong			Colour codes:
17:30 to 18:00		Wada	Nizamani, Huwer	Trip		Tutorials
18:00 to 18:30	Reception					Invited
18:30 to 19:00			Dinner			Hot Topic
19:00 to 19:30		Dinner		Dinner	Conference	Contributed
19:30 to 20:00	Dinner				Dinner	
20:00 to 20:30		Poster				
		Session	Chair: Hensinger			
20:30 to 21:00		&	Big Cheese			
21:00 to 22:00		Exhibition	Night			
22:00 to 22:30						
22:30 to 23:00						