Book of Abstracts

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ORAL PRESENTATIONS

Quantum Information Science with Trapped Ions

Rainer Blatt[1,2]

[1] Institute for Experimental Physics, University of Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
[2] Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria

Rainer.Blatt@uibk.ac.at

In this talk, the basic toolbox of the Innsbruck quantum computer based on strings of trapped Ca^+ ions will be reviewed [1] and an overview will be given on our current experiments in the field of quantum information science. For quantum information processing, the toolbox operations are used to encode one logical qubit in entangled states distributed over seven trapped-ion qubits. We demonstrate the capability of the code to detect one bit flip, phase flip or a combined error of both, regardless on which of the qubits they occur. Furthermore, we apply combinations of the entire set of logical single-qubit Clifford gates on the encoded qubit to explore its computational capabilities [2]. With the quantum toolbox both analog and digital quantum simulations are carried out [3]. The basic simulation procedure will be presented and its application will be discussed for a variety of spin Hamiltonians. Including a carefully controlled dissipation mechanism, the toolbox even allows for the quantum simulation of open systems [4]. With long ion strings, the quantum toolbox is applied to investigate the propagation of entanglement in a quantum many-body system represented by the trapped-ion qubits [5].

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Dissipative state preparation and direct measurement of trapped-ion motion in an engineered harmonic oscillator basis

J. P. Home

Institute for Quantum Electronics, Otto Stern Weg 1, 8093 Zürich, Switzerland

E-mail: jhome@phys.ethz.ch

I will describe recent experiments demonstrating quantum superposition state generation and stabilization by reservoir engineering with trapped-atomic calcium ions [1,2]. These are produced by combining an engineered spin-motion coupling Hamiltonian with dissipation of the spin, with the latter realizing an effective zero temperature reservoir which results in cooling of the motion to a desired state. We demonstrate the generation of squeezed, displaced-squeezed and coherent states of the oscillator, which appear as steady-states protected indefinitely against noise. Additional engineered spin-motion couplings allow us to directly drive two-state correlated spin-motion Rabi oscillations starting from the prepared state, providing a simple diagnosis for the state fidelity which offers high signal-to-noise. These couplings allow us to climb a ladder of oscillator states which forms a generalized Fock state basis defined by our choice of Hamiltonian. We verify the sqrt(n) scaling of the matrix elements of this state ladder for the squeezed Fock states, and generate superpositions of these states. In addition to these results on quantum control, I will briefly give an overview of our experimental progress in other areas, including mixed-species ion chains, ion transport, and cryogenic trapping.

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Structural Phase Transitions and 2-D Spectroscopy in Ion Traps

M.B. Plenio

Institut für Theoretische Physik, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany

E-mail: martin.plenio@uni-ulm.de

In this talk I will present recent result that we have obtained concerning the dynamics of structural phase transitions in ion Coulomb crystals [1,2,3] and novel approach to the underlying theory of the Kibble-Zurek effect [4]. In a second part I will present a novel approach towards the spectroscopic examination of ion Coulomb crystals by meanss of multi-dimensional spectroscopy that we adapt and transfer from the field of nuclear magnetic resonance [5].

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

E. Peik

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

E-Mail: ekkehard.peik@ptb.de

Laser-cooled and trapped ions permit the study of strongly forbidden transitions with extremely small natural linewidths and long coherence times that find applications as references in highly accurate optical clocks. The frequency of the electric octupole (E3) transition $S_{1/2}$ - $F_{7/2}$ at 467 nm in $^{171}Yb^+$ with a natural linewidth in the nHz range is remarkably insensitive against external electric and magnetic fields [1]. The light shift induced by the higher laser intensity that is needed to drive this weak transition was regarded as problematic for a clock. We have shown that an optimized "Hyper-Ramsey" interrogation sequence actively compensates the light shift [2] so that it makes only a minor contribution to the total systematic uncertainty, which we presently evaluate as 3.9×10^{-18}.

The E3 transition frequency shows a strong sensitivity to the value of the fine structure constant α. Repeated measurements against Cs clocks and other optical clocks can be used to search for variations of α and the proton-to-electron mass ratio μ. Together with previous measurements of the $S_{1/2}$ - $D_{3/2}$ electric quadrupole transition in $^{171}Yb^+$ and with data from other elements, a least-squares analysis yields $(1/\alpha)(d\alpha/dt)=-0.20(20)\times10^{-16}$/yr and $(1/\mu)(d\mu/dt)=-0.5(1.6)\times10^{-16}$/yr, confirming a previous limit on $d\alpha/dt$ and providing the most stringent limit on $d\mu/dt$ from laboratory experiments [3].

An even better immunity against frequency shifts from external perturbations can be expected for the nuclear transition in $^{229}Th^{3+}$ at about 160 nm wavelength with a linewidth in the mHz range. In order to excite the so far only indirectly observed transition using a two-photon electronic bridge process, we have investigated the dense electronic level structure of Th^+ [4,5] and have started an experiment with trapped $^{229}Th^+$ ions.

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The NIST Al^+ quantum-logic clock*

S.M. Brewer[1,2], J.S. Chen[1], C.W. Chou[1], D.B. Hume[1],
D.R. Leibrandt[1], D.J. Wineland[1] and T. Rosenband[1,3]

[1] National Institute of Standards and Technology, Boulder, CO 80305, USA
[2] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3] Harvard University, Cambridge, MA 02138, USA

E-mail: david.leibrandt@nist.gov

Optical atomic clocks based on quantum-logic spectroscopy of the $^1S_0 \leftrightarrow {}^3P_0$ transition in $^{27}Al^+$ have reached an uncertainty of 8.0×10^{-18} [1], enabling table-top tests of fundamental physics [2] as well as measurements of gravitational potential differences and relativistic time dilation [3]. The clock transition in $^{27}Al^+$ has the lowest known sensitivity to blackbody radiation, and the largest contributions to the uncertainty of previous $^{27}Al^+$ clocks have been second order time dilation shifts due to the driven motion (i.e., micromotion) and thermal motion of the trapped ions.

We are developing a third-generation $^{27}Al^+$ quantum-logic clock with the goals of reduced uncertainty and portability. In order to suppress the time dilation shifts, we have designed and built a new ion trap based on a gold-plated, laser-machined diamond wafer with differential RF drive (see Fig. 1). In this talk, we present details of the trap design and operation as well as a preliminary characterization of ion motion in the trap.

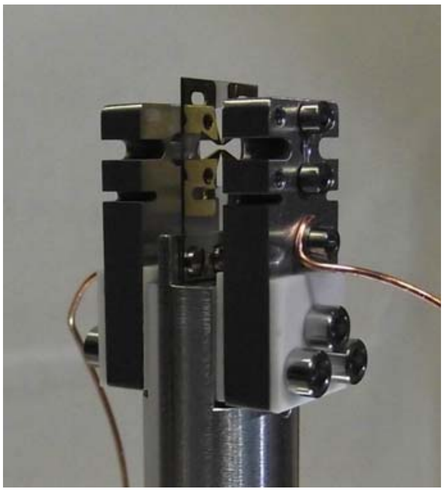

Figure 1

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Kibble Zurek experiments in linear ion crystals

K. Pyka[1], J. Keller[1], R. Nigmatullin[2], H.L. Partner[1], T. Burgermeister[1], A. Retzker[3], M.B. Plenio[2,4], W.H. Zurek[5], A. del Campo[5] and T.E.Mehlstäubler[1]

[1] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2] Institute for Theoretical Physics, Albert Einstein Allee 11, Ulm University, 89069 Ulm, Germany
[3] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Givat Ram, Israel
[4]Center for Integrated Quantum Science and Technology, Ulm University
[5]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, USA

E-mail: tanja.mehlstaeubler@ptb.de

Our experiment focuses on the realization of an optical clock based on a many-body ion system. This requires a high level of control of the dynamics of ion crystals. For this, $^{172}Yb^+$ ions are laser-cooled in a linear Paul trap with low axial micromotion [1], which allows for trapping of large Coulomb crystals. Depending on the aspect ratio of axial to radial trapping frequencies the Coulomb crystals take on different phases. In particular, the transition from the linear to zigzag phase, see upper part of fig.1, has been identified as a 2nd-order phase transition with well-defined critical exponents [2]. When such a symmetry breaking phase transition is crossed nonadiabatically and the finite speed of information prevents different regions from coordinating the choice of the symmetry broken state, structural defects can form. We have successfully stabilized two different types of defects, shown in fig. 1 (lower part). According to the Kibble-Zurek mechanism (KZM) the kink density is predicted to follow a power law scaling in the rate of the transition [3]. Owing to the universal laws of phase transitions, this theory applies to many other systems, ranging from solid-state systems to cosmology [3]. We demonstrate scaling of the number of topological defects with the transition rate – the central prediction of KZM - using ion Coulomb crystals in a harmonic trap [4]. We will discuss kink dynamics [5] and stability. Implementing mass defects and electric fields we demonstrate first steps towards a controlled kink preparation and manipulation for future studies of nonlinear physics in ion Coulomb crystal [6].

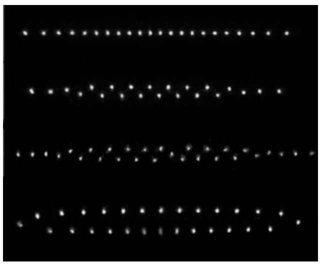

Figure 1. Linear and zigzag phase in ion Coulomb crystals. Two structural defects are shown in the lower part.

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Observation of the Kibble-Zurek scaling law and stability of defects in ion crystals

S. Ulm[1] , K. Groot-Berning[1], G. Jacob[1], J. Rossnagel [1], C. Degünther[1], S.T. Dawkins[1], U.G. Poschinger[1], O. Estrada[1], K. Singer[1], F. Schmidt-Kaler[1], R. Nigmatullin[2;3], A. Retzker[4], M.B. Plenio[2;3]

[1] QUANTUM, Institut für Physik, Universität Mainz
[2] Institut für Theoretische Physik & Center for Integrated Quantum Science and Technology Ulm University
[3] Department of Physics, Imperial College London
[4] Racah Institute of Physics, The Hebrew University of Jerusalem

E-mail: ulmst@uni-mainz.de

Recently it was demonstrated that the Kibble-Zurek mechanism can be observed in inhomogeneous ion crystals [1,2,3]. This mechanism describes the generation of structural defects during the phase transition from a linear crystal into a zigzag crystal. Structural defects are created at the boundaries of causally separated regions with incompatible symmetries (see Fig.1). The structural defect density depends on the speed at which the phase transition is traversed [4,5,6,7,8]. Image acquisition of these defects via a CCD camera relies on stable defects for several milliseconds. This stability is governed by the Peierls-Nabarro potential [9,10] which can be varied by changing the trapping parameters. We have additionally shown how the scaling behavior can be influenced by the charge distribution as we increased the homogeneity of the crystal by using a double well potential.

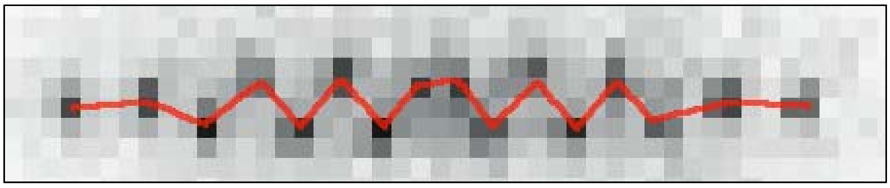

Figure 1. Fluorescence image of a trapped ion crystal with a defect, the red line indicates the structure

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Proposal for Verification of the Haldane Phase Using Trapped Ions

I. Cohen and A. Retzker

Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, 91904 Givat Ram, Israel

E-mail: retzker@phys.huji.ac.il

A proposal to use trapped ions to simulate spin-one XXZ antiferromagnetic (AFM) chains as an experimental tool to explore the Haldane phase is presented. I will explain how to reach the Haldane phase adiabatically, demonstrate the robustness of the ground states to noise in the magnetic field and Rabi frequencies, and propose a way to detect them using their characterizations: an excitation gap and exponentially decaying correlations, a nonvanishing nonlocal string order and a double degenerate entanglement spectrum. By scaling up to higher dimensions and more frustrated lattices, richer phase diagrams can be obtained. In specific cases the spin liquid phase can be reached, which can be detected by its entanglement entropy that obeys the boundary law. The talk is based on ref[1].

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Weak dipolar interactions in trapped ion chains

S. Kotler[1,2], N. Akerman[1,3,] N.Navon[1,4], Y. Glickman[1], Z. Meir[1], O. Schwartz[1], E. Shahmoon[1,3], D. Oron[1] and R. Ozeri[1]

[1] Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100 Israel
[2] Physical Measurement Laboratory, NIST, Boulder, Colorado 80305, USA
[3] Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100 Israel
[3] Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB30HE UK

E-mail: ozeri@weizmann.ac.il

In two recent experiments the weak magnetic and electric dipolar interactions, between laser-cooled ions at micrometer separation, were measured. In the first experiment, the magnetic spin-spin interaction between two trapped ions was observed to lead to the entanglement of their collective spin state. The measurement of this ultra-weak (mHz) interaction strength was made possible by restricting their spin evolution to a decoherence-free subspace [1]. In a second experiment, resonant electric dipole-dipole interactions were measured during photon scattering on an allowed optical dipole transition in chains of up to eight ions. The resonance frequency of the transition was shown to slightly (10' of kHz) shift whenever the separation between ions equaled an integer number of photon wavelength in what is known as a collective Lamb shift. This shift is due to emission and re-absorption of virtual photons between different ions in the chain, and is closely related to superradiance.

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Embedding Quantum Simulators for Measuring Entanglement Monotones and n-time Correlation Functions

J. S. Pedernales

Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain

E-mail: julensimon@gmail.com

I will present the concept of Embedding Quantum Simulations (EQS), a generalization of standard one-to-one quantum simulations (QS) that enables the access to quantities that otherwise would require full state reconstruction or the design of specific measurement apparatus. Among these quantities I consider, for example, entanglement monotones [1] and n-time correlation functions [2]. I will show how to use Embedding Quantum Simulators as an efficient method to access these quantities and I will further discuss experimental applications of these concepts in trapped ions [3].

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Shortcuts to adiabaticity in trapped ion manipulation

M. Palmero

Departamento de Química Física, Universidad del País Vasco-Euskal Herriko Unibertsitatea, Apdo 644, Bilbao Spain

E-mail: mikel.palmero@ehu.es.

Shortcuts to adiabaticity are techniques that mimic an adiabatic process, but without necessarily following an adiabatic evolution. The idea is to engineer the process such that, after the evolution (that could in principle be diabatic), we recover the same final state that would have been reached through an adiabatic process. The benefits of this are that one can in principle design the process to be as fast as wanted, since we are overcoming the adiabatic limits.
Here, we have used the invariant-based inverse engineering approach to design shortcut protocols to manipulate trapped ion chains such as transport [1], expansion/compression or splitting. Based on a normal mode approximation, we are able to apply the simple theory of 1 dimensional problems, and design the evolution of the driving potential for the different problems. These shortcut protocols are in principle designed for the approximate Hamiltonian, but our simulations show the validity range of it. The results show that this protocols work well in times relevant for quantum processing with trapped ion technology.

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High-precision Penning-trap mass spectrometry on radionuclide

J. Dilling[1,2]

[1] TRIUMF, Vancouver, Canada
[2] University of British Columbia, Department of Physics and Astronomy

E-mail JDilling@triumf.ca.

Accepted The field of mass spectrometry with radionuclide, or short-lived accelerator-based generated isotopes, is key to the discipline of fundamental nuclear physics, which strives to understand the inner working of nuclear many-body quantum systems. Mass spectrometry provide unique access, via a precise and accurate mass determination, and the use of the mass-energy equivalence principle, to all effective forces inside the isotopes. If one understands the effective forces, and is able to describe them theoretically, a major breakthrough is achieved. This has profound impact on our understanding of the limits of nuclear stability, helps understand symmetry principles in the Universe, and the distribution and abundances of the chemical elements in the Cosmos.

Ion traps, and in particular Penning traps [1] have revolutionized the field of mass spectrometry at accelerator facilities. Major accomplishments are based on technical developments for precision, accuracy, sensitivity, and speed; all important aspects when dealing with short-lived radionuclides. The talk will provide an overview, and gives perspectives and future directions.

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The *g*-factor of highly charged ions – Stress test for the Standard Model and access to fundamental constants

S.Sturm

Max-Planck Institut für Kernphysik, Heidelberg

E-mail: sven.sturm@mpi-hd.mpg.de

The ultra-precise measurement of the g-factor of highly-charged ions provides a unique possibility to probe the validity of the Standard Model under extreme conditions. The bound electron is exposed to electric fields of up to 10^{16} V/m, yielding a high sensitivity for higher-order contributions and hypothetical physics beyond the Standard Model. We have determined the *g*-factor of hydrogen- [1] and lithiumlike [2] silicon by measuring the Larmor- and cyclotron frequencies of single ions in a Penning trap with previously unprecedented precision [3]. The comparison of these values with the prediction of theory yields the most stringent test of quantum electrodynamics and relativistic inter-electron interaction in strong fields. Furthermore, the developed techniques open an access to fundamental constants. Recently [4], we have determined the atomic mass of the electron with a relative uncertainty of 30 parts-per-trillion, more than an order of magnitude better than the current CODATA literature value. This result enables future ultra-high precision tests of the Standard Model, *e.g.* the determination of the fine-structure constant and bound-state QED tests. Currently, we are setting up a next-generation apparatus which will be able to study even the heaviest highly-charged ions and thus explore the validity of the Standard Model at the strongest fields.

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ISOLTRAP's multi-reflection time-of-flight mass separator and spectrometer

R. Wolf[1,2]
for the ISOLTRAP collaboration

[1] Institut für Physik, Universität Greifswald, Felix-Hausdorff-Str. 6, 17489 Greifswald
[2] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg

E-mail: rwolf@mpi-hd.mpg.de

Precision mass measurements of radioactive nuclides give direct insight to one of the most fundamental properties of atomic nuclei, their binding energy. Investigating this property as a function of proton and neutron numbers is crucial for advancing theory in describing and predicting the structure of nuclei. Furthermore, knowledge of masses far from stability is necessary for the understanding of nucleosynthesis in supernovae and neutron stars.

Laboratory experiments are often extremely challenging due to the short half-lives and low production rates of the nuclides of interest. At the same time, longer-lived or stable contaminations are produced by orders of magnitude more, demanding a high selectivity and resolving power of the mass spectrometer. ISOLTRAP at ISOLDE/CERN has already investigated over 500 isotopes on an uncertainty level down to dm/m=1x10-8 by use of Penning-trap techniques. To extend the range of accessible nuclides even further, the setup has been upgraded with a multi-reflection time-of-flight mass analyzer [1]. This device can be operated as a mass purifier or a mass spectrometer, which allowed mass measurements for nuclear astrophysics applications [2] and tests of valence-shell calculations based on 3N forces [3]. The talk will give an overview of these recent developments and further applications of the new MR-ToF device.

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Scaling up ion-trap-based quantum spin simulators and their excited state spectroscopy

J.K. Freericks[1], **B. Yoshimura**[1], **W. Campbell and Monroe experimental group at JQI/UMD**[3]

[1] Department of Physics, Georgetown University, Washington, DC 20057, USA
[2] UCLA Physics & Astronomy, 475 Portola Plaza, Los Angeles, CA 90095-1547, USA
[3] Joint Quantum Institute, Computer and Space Sciences Bldg., University of Maryland, College Park, MD 20742, USA

E-mail: freericks@physics.georgetown.edu.

I will discuss some recent experiments that have scaled up quantum simulations to 18 ions [1] and will discuss a number of ideas for measuring excited energy levels within the quantum simulators [2,3]. One of the initial motivations for quantum simulators was to employ the adiabatic theorem to generate complex quantum ground states from simple ones via adiabatic state preparation. Current experiments turn out to be quite far from the adiabatic limit and end up creating significant excitations into a number of different excited states. This opens the possibility of using the diabatic excitations to determine excited state energy levels and performing spectroscopy on the quantum simulator. I will discuss some of the recent experiments in this direction which measure excitations by modulating the magnetic field [2] and recent theory that describes how to perform similar experiments by examining the time evolution of expectation values and advanced signal processing [3].

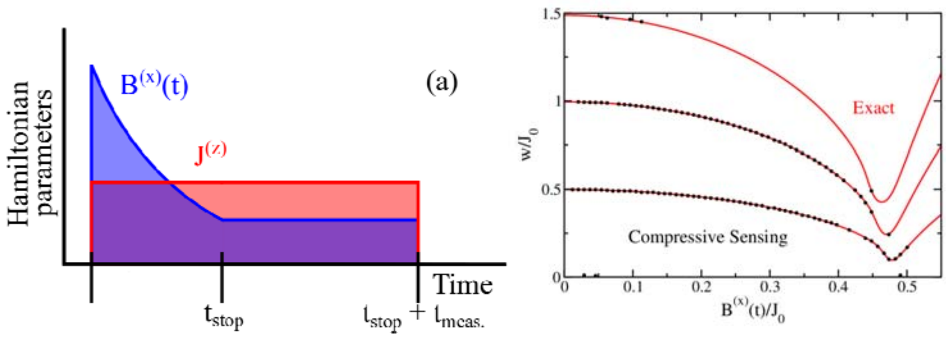

Figure 1. Example experimental protocol and output data for the diabatic ramping spectroscopy of many-body excited states in a trapped-ion quantum simulation

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Highly charged ions in Coulomb crystals

L. Schmöger[1,2], O.O. Versolato[1,2], M. Schwarz[1,2], S. Feuchtenbeiner[1], B. Piest[1], A. Windberger[1], T. Leopold[2], M. Kohnen[2], P. Micke[2], M. Drewsen[3], J. Ullrich[2], P.O. Schmidt[2], J.R. Crespo López-Urrutia[1]

[1] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[3] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

crespojr@mpi-hd.mpg.de

Sympathetic cooling of HCI has been achieved by combining an electron beam ion trap (EBIT) with a linear RF trap, CryPTEx (Cryogenic Paul Trap Experiment) [1,2]. This device was developed and built at the Max-Planck-Institut für Kernphysik in collaboration with Aarhus University, and brought there for commissioning experiments using laser cooled Mg^+ ions and sympathetically cooled MgH^+ ions [3,4]. CryPTEx, now back in Heidelberg, is used for preparing Coulomb crystals of Be^+ ions by laser cooling using their 313 nm transition. The Ar^{13+} ions were extracted from the EBIT, decelerated by means of a pulsed bunching drift tube, and injected into the Paul trap. In order to further reduce their residual kinetic energy, the ions are forced to bounce several times inside the linear RF trap, repeatedly interacting with the Coulomb crystal, until they finally are implanted in the crystal close to its axis. We obtain images of the crystal with and without HCI injection, and observe several different configurations indicating that the HCI can be trapped both in a liquid-phase Be^+ ensemble, building a tunnel around the trap axis, as well as in a crystalline phase. The re-trapped HCI dislodge a large number of Be^+ ions from their locations, leaving behind characteristically darker spaces of spherical shape. Imperfections of the trapping potential lead to small departures from perfect crystal symmetry.

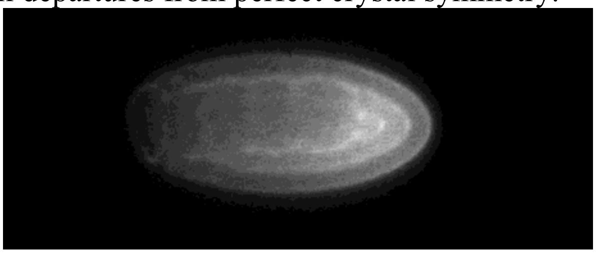

Figure 1. Image of a Coulomb crystal of Be^+ ions that contains sympathetically cooled HCI. The darker spots are caused by the strong electrostatic repulsion due to the presence of several Ar^{13+} ions close to the trap axis. The main axis of the crystal is approximately 500 μm long.

Ongoing measurements point to HCI temperatures below 0.1 K; this would correspond to a reduction of 4-orders of magnitude in the spectroscopic Doppler width in comparison with the values typically found in EBITs. We expect this cooling to be a great advantage for laser spectroscopy of forbidden transitions in HCI, and for their applications to, e. g., frequency metrology, and for searches of limits for the variation of the fine structure constant.

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Production of a cold antihydrogen beam with a cusp trap

S. Van Gorp[1], N. Kuroda[2], S. Ulmer[3], D.J. Murtagh[1], Y. Nagata[1], M. Diermaier[4], S. Federmann[4,5], M. Leali[6], C. Malbrunot[4], V. Mascagna[6], O. Massiczek[4], K. Michishio[7], T. Mizutani[3], A. Mohri[1], H. Nagahama[2], M. Ohtsuka[2], B. Radics[1], S. Sakurai[8], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[2], H.A. Torii[2], L. Venturelli[6], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[8], Y. Kanai[1], E. Lodi Rizzini[6], Y. Nagashima[7], Y. Matsuda[2], E. Widmann[4] and Y. Yamazaki[1,2]

[1] Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan
[2] Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo153-8902, Japan
[3] Ulmer Initiative Research Unit, RIKEN, Saitama 351-0198, Japan
[4] Stefan-Meyer-Institut für Subatomare Physik, Osterreichische Akademie der Wissenschaften, 1090 Wien, Austria
[5] CERN, 1211 Geneva, Switzerland
[6] Dipartimento di Ingegneria dell'Informazione, Universitá di Brescia & Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy
[7] Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
[8] Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

E-mail: simon.van.gorp@cern.ch

Antihydrogen is the simplest atomic system to perform precision measurements on the properties of antimatter. Comparing the ground-state hyperfine transition frequencies of hydrogen and antihydrogen is one of the most sensitive direct tests of CPT symmetry. Towards this goal the ASACUSA experiment had developed an antihydrogen beam apparatus that can be used for Rabi-like in-flight spectroscopy measurements. The production of antiatoms is performed in an anti-Helmholtz type magnetic configuration (cusp), which allows spin-dependent focusing and formation of a polarised beam. During mixing of antiprotons and positrons in the cusp field a total of 80 antihydrogen atoms have been successfully detected 2.7 meters away from the source [1], where residual magnetic fields are negligible. After correcting for detection efficiency the beam count rate for antiatoms with $n < 43$ principal quantum number was 40 mHz [1]. This result opens a new window to direct tests of fundamental symmetries in the Standard Model of elementary particle physics.

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ALPHA: Antihydrogen and Fundamental Physics

N. Madsen
for the ALPHA Collaboration

Department of Physics, College of Science, Swansea University, SA2 8PP Swansea, UK

E-mail: n.madsen@swansea.ac.uk

Detailed comparisons of antihydrogen with hydrogen promise to be a fruitful test bed of fundamental symmetries such as the CPT theorem for quantum field theory or studies of gravitational influence on antimatter. With a string of recent successes with trapped antiatoms [1,2], starting with the first measurement of a quantum transition in anti-hydrogen [3], and followed by proof-of-principle work on the gravitational influence [4] and the neutrality of antihydrogen [5], the ALPHA collaboration is well on its way to perform such precision comparisons.
We will discuss the key innovative steps that have made these feats possible and in particular focus on the detailed work on positron and antiproton preparation to achieve antihydrogen cold enough to trap as well as the unique features of the ALPHA apparatus that has allowed the first quantum transitions in anti-hydrogen to be measured with only a single trapped antihydrogen atom per experiment. We will also look at how ALPHA plans to step from here towards more precise comparisons of matter and antimatter [6].

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Direct High-Precision Measurement of the Magnetic Moment of the Proton

J. Walz[1,2], A. Mooser[3], K. Blaum[4], K. Franke[3,4], P. Koß[1,2], H. Kracke[1,2], N. Leefer[2], C. Leiteritz[2], W. Quint[5], G. Schneider[1,3], C. Smorra[3,6] and S. Ulmer[3]

[1] Johannes Gutenberg-Universität Mainz, Germany
[2] Helmholtz-Institut Mainz, Germany
[3] RIKEN, Ulmer Initiative Research Unit, Japan
[4] Max-Planck-Institut für Kernphysik, Germany
[5] GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Germany
[6] CERN, Switzerland

E-mail: andreas.mooser@cern.ch

Recent advances in quantum control of a single isolated nucleus enabled the first observation of spin flips [1], the resolution of single spin flips [2] and the first demonstration of the double Penning trap technique with a single proton. Based on these techniques, we performed the first direct high precision measurement of the magnetic moment of the proton μ_p in units of the nuclear magneton μ_N [3]:

$$\mu_p / \mu_N = 2.792\ 847\ 350(7)(6).$$

The achieved fractional precision of 3.3 parts in a billion improves the currently accepted literature value [4] by a factor of 2.5.
Our experiments are driven by the fascination and motivation to compare the properties of matter and antimatter at lowest energies and with greatest precision, to perform stringent tests of CPT invariance [5]. To apply our techniques to the antiproton, we were setting up the BASE experiment [6] at the antiproton decelerator of CERN, which is prepared to participate in the 2014 antiproton physics run.
In the talk the recent results are presented.

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Beta-decay of highly-charged ions

Y.A. Litvinov
for the FRS-ESR Collaboration

GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

E-mail: Y.Litvinov@gsi.de

Atomic charge states can significantly influence nuclear decay rates. An obvious example is the electron capture (EC) decay probability, which depends strongly on the number of bound electrons. A straightforward motivation for studying the beta-decay of highly charged ions (HCI) is that stellar nucleosynthesis proceeds at high temperatures where the involved atoms are highly ionized. Furthermore, HCIs offer the possibility to perform basic investigations of beta decay under clean conditions: The decaying nuclei can be prepared as well-defined quantum-mechanical systems, such as e.g. one-electron ions in which all interactions with other electrons are excluded, and thus the complicated corrections due to shake-off effects, electron screening etc can be removed.
Largest modifications of nuclear half-lives with respect to neutral atoms have been observed in beta decay of fully ionized nuclei. Presently, the ion-storage ring ESR at GSI in Darmstadt is the only tool in the world for addressing radioactive decays of HCIs. There, the radionuclides produced at high kinetic energies as HCIs and purified from unwanted contaminants can be stored in the cooler-storage ring ESR. Due to the ultra-high vacuum of about 10^{-10} mbar, the high atomic charge states of stored ions can be preserved for extensive periods of time (minutes, hours). The decay characteristics of electron cooled stored HCIs can accurately be measured by employing the highly sensitive non-destructive time-resolved Schottky spectrometry technique.
Recent experiments with stored exotic nuclei that have been performed at the ESR will be discussed in this contribution. A particular emphasis will be given to two-body beta decays, namely bound-state beta decay and orbital electron capture.
As an outlook, the perspectives of future experiments with HCIs at existing storage ring facilities (ESR in Darmstadt and CSRe in Lanzhou) as well as at the planned facilities (TSR@ISOLDE, FAIR, HIAF, RI-RING) will be outlined.

Physical Units Bases on Fundamental Constants – Changing With Time?

J. Ullrich

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

E-Mail: joachim.ullrich@ptb.de

In 2018, on the occasion of the 25th meeting of the General Conference on Weights and Measures, CGPM, of the Metre Convention founded in 1875, it is envisaged to redefine the International System of Units (SI). In the future, as outlined by Max-Planck in his famous paper of 1900 postulating the “Planck constant”, it shall be based on fundamental constants of nature, the “defining constants”: the velocity of light, the charge of the electron, the Boltzmann, Avogadro and the Planck constants, the Cs hyperfine clock transition and the luminous efficacy.
In the talk I will provide an overview on the progress, challenges and future perspectives of the new “Quantum SI”, illustrated in Fig. 1, and discuss the question on whether or not the fundamental constants are indeed constant in time. New experiments are presently being devised, one of them based on next-generation optical clocks using transitions in highly charged ions that are read out via quantum-logic schemes. They bear the potential to trace potential changes in the fine structure constant α on the level of $\Delta\alpha/\alpha \approx 10^{-20}$ per year.

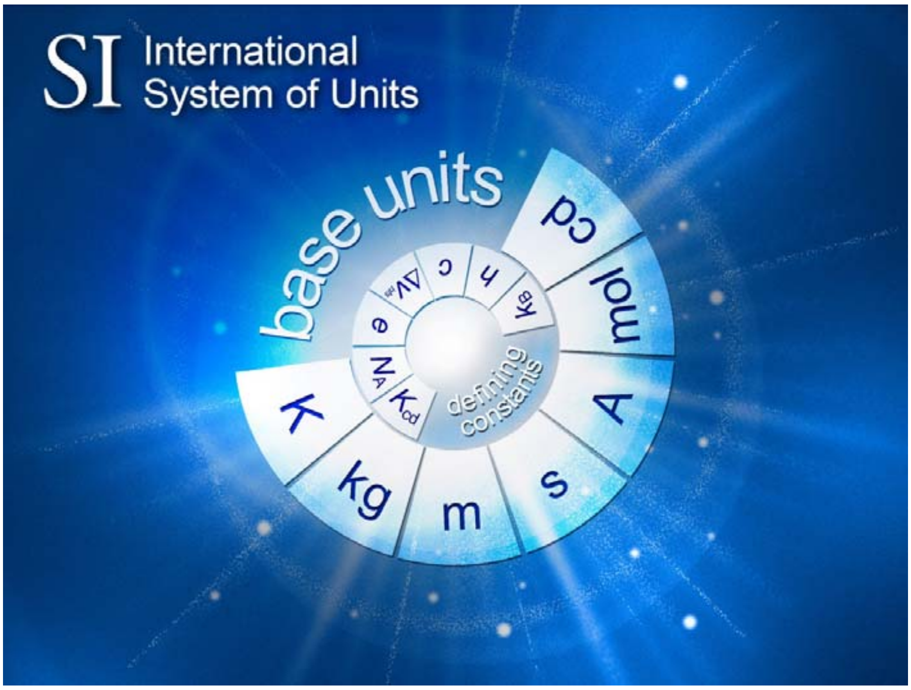

Figure 1. Logo of the New SI with the defining constants and the seven base units

Electric trapping and cooling of neutral polyatomic molecules

G. Rempe

Max Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

E-mail: gerhard.rempe@mpq.mpg.de

Molecules with their many degrees of freedom and their permanent electric dipole moment offer new perspectives for the exploration of fundamental physics and chemistry, ranging from the measurement of the electron electric dipole moment to the simulation of quantum many-body systems and the control of reactive collisions. Neutral polyatomic molecules are ideal workhorses for such investigations.

Towards this goal, generally applicable and sufficiently simple molecular control techniques including slowing, trapping and cooling as well as accumulation need to be developed. The talk will highlight achievements in this direction including the deceleration of molecules with a spinning centrifuge [1], their accumulation and trapping in tailor-made electrostatic fields [2], and their cooling via a Sisyphus effect which employs radio-frequency and microwave transitions between rotational states to decrease energy and spontaneous transitions between vibrational states to remove entropy [3].

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Doppler-broadened and Doppler-free spectroscopy of the HD^+ molecular hydrogen ion

J.C.J. Koelemeij

LaserLaB and Department of Physics & Astronomy, VU University Amsterdam, the Netherlands

E-mail: j.c.j.koelemeij@vu.nl

At VU University we have performed laser spectroscopy of the (v,L): (0,2) – (8,3) rovibrational overtone transition (782 nm) in the molecular hydrogen ion HD^+. Trapped HD^+ ions are sympathetically cooled to ~10 mK by storing them with laser-cooled Be^+ ions in a linear rf trap, and vibrational transitions are observed through state-selective photodissociation of HD^+ (v=8) by 532 nm laser radiation. Using a realistic line-shape model (which takes into account slow population recycling by blackbody radiation, Doppler effects due to secular motion and micromotion, signal nonlinearities, and saturation effects), we achieve an unprecedented resolution of 0.8 ppb [1]. Surprisingly, and contrary to the widespread view that the secular motion of laser-cooled ions follows Boltzmann statistics, our spectrum shows evidence of non-thermal velocity distributions with power-law tails, the occurrence of which is confirmed by molecular dynamics simulations. Such non-thermal velocity distributions appear to be a general feature of laser-cooled Coulomb crystals, which under specific conditions can lead to significant line shifts. The analysis of this and other systematic effects is nearing completion.
To overcome the first-order Doppler effect, we are currently implementing two-photon spectroscopy of HD^+ in the Lamb-Dicke regime using the nearly-degenerate transitions (v,L): (0,3) – (4,2) and (4,2) – (9,3) at 1.44 μm, following a recent proposal [2]. We expect to observe line widths in the 100-Hz range, and to achieve a relative uncertainty of the order of 10^{-14} for the two-photon transition [2]. A comparison of such experimental results with state-of-the-art HD^+ level structure calculations may provide a new stringent test of molecular QED at the level of 0.04 ppb [3], produce a new value of the proton-electron mass ratio with a relative uncertainty of 0.1 ppb, and enable searches for hypothetical 'fifth forces' ensuing from rolled-up higher dimensions with improved sensitivity [4].

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New Developments in Collisional and Spectroscopic Studies of Cold Molecular Ions in Traps

S. Willitsch

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

E-mail: stefan.willitsch@unibas.ch

We present new developments in the study of collisions and the spectroscopy of sympathetically cooled molecular ions in traps. We will briefly recapitulate recent results on cold collisions studied in a hybrid trap for atomic ions and neutral atoms, highlighting the salient features of ion-neutral reactive processes at very low energies [1, 2]. We will then discuss extensions of hybrid-trapping technology to study collisional processes of ultracold atoms with sympathetically cooled molecular ions [2] and the recent combination of a hybrid trap with a molecular-beam machine for the generation of quantum-state-selected, sympathetically cooled molecular species [3]. We will also present the development of a new "dynamic" hybrid trap for the study of cold ion-neutral collisions with a greatly improved energy resolution which aims at exploring the quantum nature of cold collisions.

In the second part of the talk, we will highlight the (to our knowledge) first observation of electric-quadrupole (E2) infrared spectroscopic transitions in a molecular ion [4]. Applications of these extremely weak spectral features (with natural linewidths in the nHz range) in quantum technology and precision spectroscopy will be discussed.

Lastly, we will present recent results on the sympathetic cooling of molecular ions in a surface-electrode ion trap [5] as a first step towards miniaturizing cold-molecular-ion experiments.

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Scalable quantum information processing with trapped ions at NIST

D. Leibfried

National Institute of Standards and Technology, 325 Broadway, Boulder CO 80305, USA

E-mail: dil@boulder.nist.gov

This talk will provide an overview of the progress in quantum information processing and quantum simulation with trapped ions at NIST.
Most basic requirements for quantum information processing and quantum simulation have been demonstrated for trapped ions, with two big challenges remaining: Improving operation fidelity and scaling up to larger numbers of qubits. In the last few years, operation fidelities have steadily increased with single qubit rotation errors per π-pulse close to 10^{-6} for microwave operations and 10^{-4} for laser-based Raman-transitions on hyperfine ground state qubits. Laser-based two-qubit entanglement schemes have demonstrated fidelities of deterministically produced Bell states of larger than 0.99. Entanglement operations with microwaves in miniaturized surface electrode traps have demonstrated Bell state fidelities of 0.76. At NIST, scaling towards larger systems is based on moving ion-qubits through a multi-zone trap array and sympathetically cooling them with a second ion species. Micro-fabrication approaches to ion-trap-arrays have yielded structures that should be capable of holding and manipulating large numbers of ions.
After a brief overview of the current status, one recent experiment where the internal states of ions held in separate trapping wells are entangled will be discussed in particular. The experiment demonstrates the basic building block of a potentially scalable approach to analog quantum simulation using two-dimensional surface trap arrays.

This work has been supported by IARPA, DARPA, ONR, and the NIST Quantum Information Program.

High-fidelity qubit operations with $^{40}Ca^+$ and $^{43}Ca^+$

D.M. Lucas

Department of Physics, Oxford University,
Clarendon Laboratory, Parks Road, Oxford OX1 3PU, U.K.

E-mail: d.lucas@physics.ox.ac.uk

Recent work on improving the fidelity of elementary qubit operations using calcium ions will be reported.
Using intermediate-field "atomic clock" states in calcium-43, we have demonstrated all single-qubit operations (preparation, memory, gates and readout) with 99.9% fidelity or better [1]. This was achieved in a room-temperature surface trap incorporating integrated microwave waveguides and resonators [2]. The trap was also designed to implement two-qubit gates driven by near-field microwaves [3], and progress towards this goal will be reported.
We have also designed and fabricated a separate surface trap to implement scalable independent qubit addressing using near-field microwaves [4]. In a pilot experiment, we drive qubit rotations with microwaves in one trap zone, while nulling the microwave field in a neighbouring zone (1mm distant), and achieve an addressing error below 0.01%. We also demonstrate control of the microwave polarization in a single zone.
In a third experiment using a macroscopic trap, we have studied the speed/fidelity trade-off for two-qubit gates driven by Raman laser beams [5]. Here we achieve gate fidelities between 97% (for a gate time 3.8us) and 99.9% (for a gate time 100us), after accounting for single-qubit errors [6].
The fidelity of all operations exceeds the minimum threshold (≈ 99%) required for fault-tolerant quantum computing by a significant margin. Maintaining these fidelity levels in a single system, while scaling to larger numbers of qubits, remains a significant challenge.
For more detail on these experiments, please refer to the posters of M. Sepiol, D. P. L. Aude Craik, and C. J. Ballance.

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Microwave quantum logic and architectures for quantum technology with ions

W.K. Hensinger

Department of Physics and Astronomy
University of Sussex
Falmer, Brighton, East Sussex, BN1 9QH
United Kingdom

E-mail: w.k.hensinger@sussex.ac.uk

To this point, entanglement operations on ion qubits have predominantly been performed using lasers. When scaling to larger qubit numbers however this becomes problematic due to the challenging engineering that might be required. The use of microwaves combined with a static magnetic field gradient overcomes this problem. I will present our work towards implementing entanglement gates using microwave radiation including the experimental demonstration of spin-motion entanglement and the first realisation of driving motional sideband transitions with microwave dressed states.

I will also discuss our approach at Sussex creating microfabricated ion trap architectures for quantum simulation, computation and sensing. At Sussex, we have developed a multitude of ion chips including superconducting ion chips with integrated microwave resonators (expected Q 10^6) featuring vertical interconnect (VIA) technology, multilayer ion chips with gold electrodes and VIA technology, Silicon-on-insulator ion chips as well as multilayer ion chips with gold electrodes and VIA technology featuring embedded current carrying wires. These chip technology platforms are used to produce X and Y junctions, 2D arrays, ion storage rings, vertical shuttling traps, and linear segmented architectures.

Paul trapping of charged particles in aqueous solution

W.Guan[1], S. Joseph[2], J. Hyun Park[2], P.S. Krstić[2], and M.A. Reed[1,3]

[1] Department of Electrical Engineering, Yale University, New Haven, CT 06520
[2] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[3] Department of Applied Physics, Yale University, New Haven, CT 06520

E-mail: mark.reed@yale.edu

We experimentally demonstrate [1] the feasibility of an aqueous Paul trap using a proof-of-principle microfabricated planar device. An oscillating quadrupole electric field generates a pseudopotential well and individual charged particles are dynamically confined to a nanometer scale region, whose size can be externally tuned by driving parameters (voltages and frequencies). Compared with conventional Paul traps working in frictionless vacuum, the aqueous environment associated with damping forces and thermally induced fluctuations (Brownian noise) exerts a fundamental influence on the underlying physics. We investigate the impact of these two effects on the confining dynamics, with the aim to reduce the rms value of the positional fluctuations. We find that the rms fluctuations can be modulated by adjusting the voltages and frequencies. We additionally elucidate [2] the interplay between AC electrophoretic (ACEP) or dielectrophoretic (DEP) (as well as electro-osmotic) effects in this systems, and determine the conditions for which effect will dominate the trapping dynamics. In contrast to DEP traps, ACEP traps favor the downscaling of the particle size. This technique provides an alternative for the localization and control of charged particles in an aqueous environment.

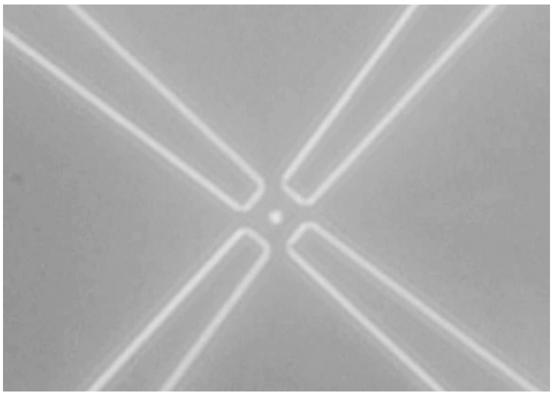

Figure 1

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Digital Ion Traps and the Production of Multiply Charged Cluster Anions

S. Bandelow[1], F. Martinez[1,2], G. Marx[1], L. Schweikhard[1] and A. Vass[1]

[1] Institute of Physics, University of Greifswald, Felix-Hausdorff-Str. 6, 17489 Greifswald, Germany
[2] Institute of Physics, University of Rostock, Universitäts-Platz 3, 18051 Rostock, Germany

E-mail: LSchweik@Physik.Uni-Greifswald.de

Simultaneous Penning-trap storage of electrons and singly charged cluster anions can be used to produce polyanionic clusters by sequential electron attachment. However, the Coulomb repulsion between electrons and anions and the "critical mass" constrain the achievable charge states. An improvement was made recently by upgrading the Penning-trap setup "ClusterTrap" with a 12-T magnet [1]. Paul traps offer an alternative approach for cluster-polyanion production. However, they do not allow simultaneous electron storage, and their radiofrequency (RF) field hinders a smooth passage of an electron beam through the trap volume. An auxiliary magnetic field can guide the electrons, but their energy is still modulated considerably. For well-defined interaction energies the digital ion trap (DIT) [2] version of Paul traps has been further developed.

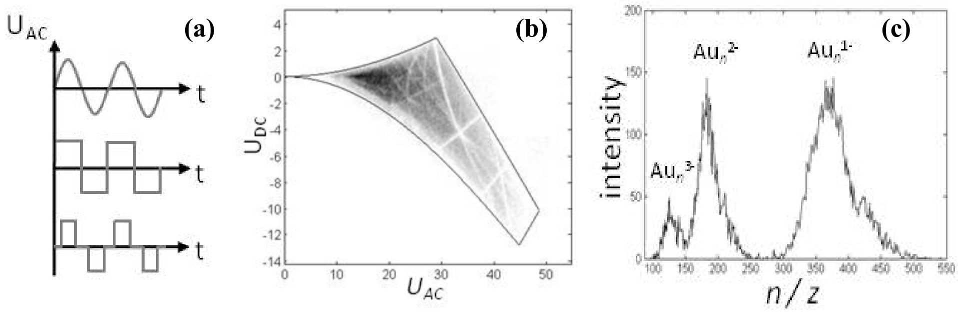

Figure 1. RF signals (a), stability diagram (b), cluster abundance spectrum (c). See text.

In the conventional DIT the harmonic RF signal (Fig. 1a, top) is replaced by a (2-state) square-well signal (Fig. 1a, center). The remaining problem described above is solved by introduction of a third level (3-state DIT, Fig. 1a, bottom). In the resulting field-free time slots the electron energy is not affected. Measurements have shown that both DIT versions have the same trapping conditions, i.e. stability diagram (Fig. 1b) [3], as the harmonic-signal trap (for RF amplitudes equaling the first harmonic of the DIT signal, as found by Fourier analysis). Our contribution will include results from electron-attachment experiments in a DIT (Fig. 1c) [4]. This work is supported by the Collaborative Research Centre SFB 652 of the DFG.

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Sideband cooling an ion to the quantum ground state in a Penning trap with very low heating rate.

J.F. Goodwin, G.Stutter, R.C. Thompso[1] and <u>D.M. Segal</u>

Blackett Laboratory, Imperial College, London SW72AZ

E-mail: d.segal@imperial.ac.uk

We are working towards applications in quantum information processing and simulation using laser cooled Ca^+ ions in a Penning trap [1-6]. We report the laser cooling of a single $^{40}Ca^+$ ion in a Penning trap to the motional ground state in one dimension. Cooling is performed in the strong binding limit on the 729nm electric quadrupole $S_{1/2}$-$D_{5/2}$ transition, broadened by a quench laser coupling the $D_{5/2}$ and $P_{3/2}$ levels. We find the final phonon number to be n=0.014 ± 0.009. We measure the heating rate of the trap to be very low with n =2.5 ±.3 s^{-1} and a scaled spectral noise density of $\omega S_E(\omega) \sim 1.6 \times 10^{-8}\ V^2m^{-2}Hz^{-1}s^{-1}$, which is consistent with the large ion-electrode distance. We perform Rabi oscillations on the sideband-cooled ion and observe a coherence time of 0.7±0.1ms, noting that the practical performance is currently limited by the intensity noise of the probe laser.

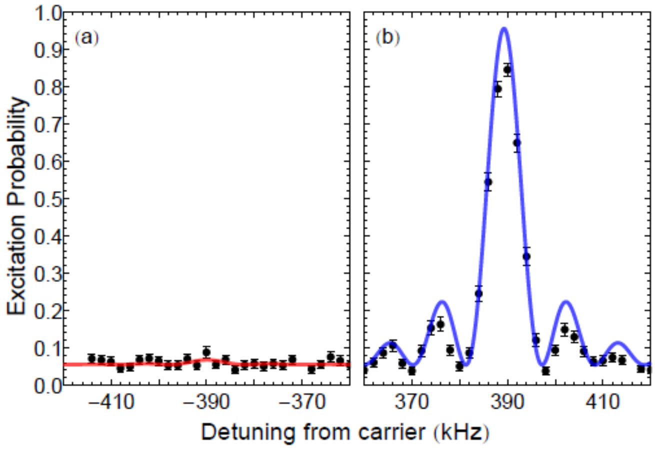

Figure 1. (a) First red and (b) blue sidebands after 21 ms of cooling on the first red sideband. The ratio of the sideband heights above the background shows that the average phonon number is n =0.014 ± 0.009

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Entanglement as a resource for a cavity-based quantum interface

B. Casabone[1], K. Friebe[1], B. Brandstätter[1], K. Schüppert[1], A. Stute[1], F. Ong[1], R. Blatt[1,2] and T.E. Northup[1]

[1] Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25/4, 6020 Innsbruck, Austria
[2] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

E-mail: tracy.northup@uibk.ac.at

Not only is entanglement between trapped ions a critical resource for quantum information processing, but it can also play a key role within future quantum networks. Here, the central concept is that entanglement can enhance the coherent interaction of light and matter at a quantum interface.
Our interface consists of a high-finesse optical cavity coupled to calcium ions in a linear Paul trap. I will describe how we transfer quantum information from a single ion onto a photon and analyze the fidelity and efficiency of this process [1]. Next, we replace the ion with a logical qubit composed of two ions in a maximally entangled state. The phase of the entangled state determines the collective interaction of the ions with the cavity mode, that is, whether the emission of a single photon into the cavity is suppressed or enhanced. The latter case corresponds to a superradiant state of the ion-cavity system, for which we demonstrate that quantum information transfer onto a single photon is improved [2]. This tunable interaction could be applied selectively to turn off and on the coupling of logical qubits to the cavity, providing addressable read-write operations in a quantum register.

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Sympathetic cooling of molecules in an ion trap

Eric R. Hudson

UCLA

E-mail: hudson@physics.ucla.edu

The combination of a magneto-optical trap (MOT) and an ion trap, dubbed the MOTION trap, represents a new experimental platform for the study of neutral-ion physics with implications ranging from fundamental physics to quantum information and simulation.

This talk will be divided into two parts. First, I will introduce the MOTION trap environment and related techniques, as well as present the results of several experimental 'detours' in quantum chemistry and plasma physics that had to be taken before the MOTION trap could be used for efficient sympathetic cooling. These experiments both raise important theoretical questions and point the way for future directions with hybrid atom-ion systems. In the second half of the talk, I will focus on efforts to use the MOTION trap to produce ultracold, ground state diatomic molecular ions. The low-energy internal structure of these diatomic molecules, *e.g.* the electric dipole moment and vibrational, rotational, and Ω-doublet levels, presents a host of opportunities for advances in quantum simulation, precision measurement, cold chemistry, and quantum information. Excitingly, a recent proof-of-principle experiment has demonstrated the MOTION trap is extremely efficient at cooling molecular ions.

Controlling strings of ions

M. Drewsen

Department of Physics and Astronomy
Aarhus University
Denmark

E-mail: drewsen@phys.au.dk

Spatial and motional control of strings of ions is essential for large range of experiments with trapped atomic and molecular ions. This includes strings of atomic ions being used for quantum information processing, quantum simulations, quantum memories for light, exploration of energy transport in finite systems and as starting point for studies of symmetry breaking in structural phase transitions. In addition, strings incorporating molecular ions have been exploited in investigations of molecular processes at the single particle level, and in the near future, spectroscopy of highly charged ions are expected to significantly improve the measurement precision through Coulomb crystallization into 1D structures.

In the talk, I will discuss partly new results regarding pinning of identical atomic ions in 1D-configurations within the periodic potential wells of optical lattices, and partly the outcome of a series of experiments focused on sorting two-species ion systems into specific ordered string structures. The latter, includes the nearly deterministically preparation of perfectly interleaved 1D-string with every second ion being of one specific type, and the formation of two parallel strings with each one composed exclusively of atomic and molecular ions, respectively.

Testing time-reversal symmetry using trapped molecular ions

K.C. Cossel, **W. Cairncross, M. Grau, D.N. Gresh, Y. Ni, J. Ye and E.A. Cornell**

JILA, National Institute of Standards and Technology and University of Colorado, and
Department of Physics University of Colorado, 440 UCB, Boulder, CO 80309, USA

E-mail: cossel@jilau1.colorado.edu

Molecular ions have several advantages over neutral molecules for high-resolution spectroscopy. In particular, they can be easily trapped and thus enable long interrogation times. While single ions have been used in several experiments, higher signal-to-noise is possible using many ions, as long as the coherence time is still long. Here we demonstrate precision spectroscopy using many trapped HfF^+ for a stringent test of time-reversal symmetry by measuring the permanent electric dipole moment of the electron (eEDM) [1]. In this experiment (Fig. 1a), we perform Ramsey spectroscopy (Fig. 1b) between spin states in the metastable $^3\Delta_1$ level with a coherence time of up to 400 ms (Fig 1c). The Fourier-limited linewidth of 300 mHz is – to our knowledge – the narrowest line observed in a molecular system. We discuss various aspects of the experiment including metastable state preparation, state detection, and application of rotating electric and magnetic bias fields. In addition, we discuss limits to the coherence time due to ion-ion collisions and field inhomogeneity. Finally, we demonstrate a preliminary eEDM measurement of $-1.5 \pm 3.0 \times 10^{-27}$ *e* cm.

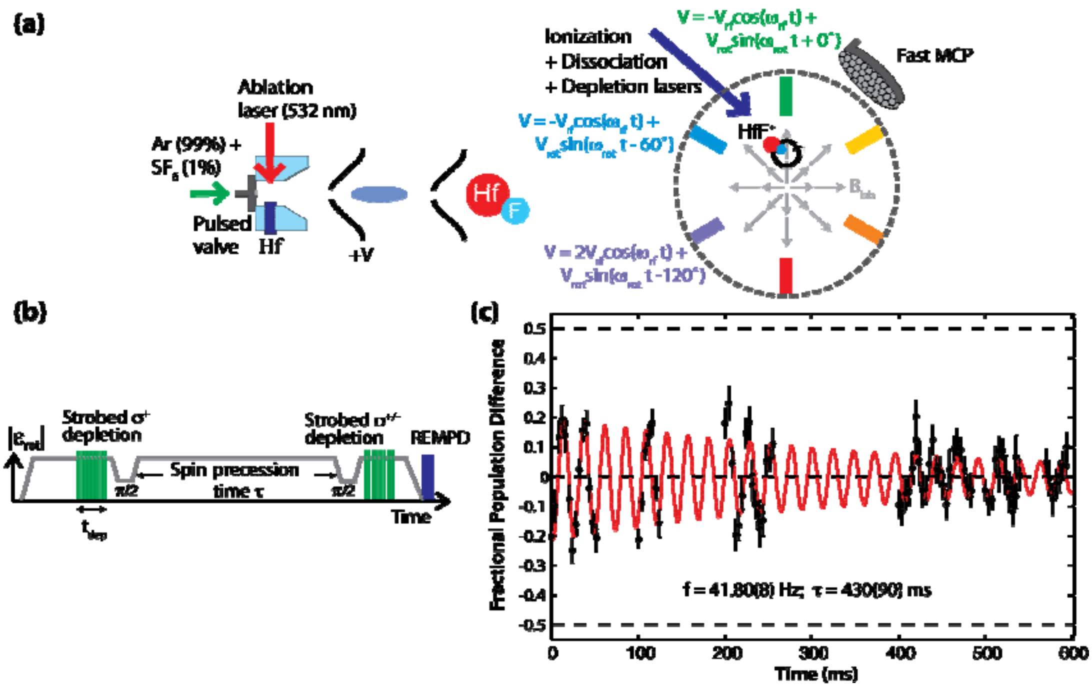

Figure 1

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Test of QED in extreme fields with highly charged ions confined in traps and rings

V.M. Shabaev

Department of Physics, St.Petersburg State University , Ulianovskaya 1, Petrodvorets, 198504, St.Petersburg, Russia

E-mail: shabaev@pcqnt1.phys.spbu.ru

The present status of tests of quantum electrodynamics in extreme fields with high-Z few-electron ions is reviewed. The calculations of the energy levels, hyperfine splittings, and the bound-electron g-factors are compared with available experimental data. Special attention is paid to the calculations of the isotope shifts of the energy levels and the g-factors of high-Z lithiumlike ions. Tests of QED in supercritical fields, that can be achieved in low-energy heavy-ion collisions, are also discussed.

Phase-Imaging Ion-Cyclotron-Resonance technique for high-precision measurements of nuclide masses

K. Blaum[1], M. Block[2], S. Chenmarev[1,3], A. Dörr[1], C. Droese[4,5], S. Eliseev[1], T. Eronen[1], P.E. Filyanin[1,3], M. Goncharov[1], M. Höcker[1], J. Ketter[1], E. Minaya Ramirez[1], D.A. Nesterenko[1,6], Yu.N. Novikov[1,3,6], L. Schweikhard[4] and V.V. Simon[2,5]

[1] Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[3] Physics Faculty of St. Petersburg State University, Petergof, Russia
[4] Institut für Physik, Ernst-Moritz-Arndt-Universität, Greifswald, Germany
[5] Helmholtzinstitut Mainz, Mainz, Germany
[6] Petersburg Nuclear Physics Institute, Gatchina, Russia

E-mail: sergey.eliseev@mpi-hd.mpg.de

A novel approach based on the projection of the Penning-trap ion motion onto a position-sensitive detector opens the door to very accurate mass measurements on the sub-ppb level even for short-lived nuclides with half-lives well below a second. In addition to the accuracy boost the new method provides a superior resolving power by which low-lying isomeric states with excitation energy on the 10-keV level can be separated from the ground state. Recent measurements of the mass differences of ^{132}Xe and ^{131}Xe, ^{187}Re and ^{187}Os and ^{48}Ca and ^{40}Ca with a relative uncertainty of a few parts in 10^{10} have demonstrated the great potential of the new approach.

Realizing a hybrid atom-ion trap for Li and Yb^+

J. Joger, H. Fürst, N. Ewald and R. Gerritsma

Johannes Gutenberg-Universität Mainz, Germany

E-mail: fuersth@uni-mainz.de

Systems comprised of ultracold atoms interacting with trapped ions are interesting for studying cold chemistry, ultra-cold collisions and quantum many-body physics [1]. The time-dependent trapping field of the Paul trap can however cause heating in hybrid atom-ion systems, preventing reaching deep into the quantum regime. One way to mitigate this problem is to employ ion-atom combinations with a large mass ratio [2]. In my talk I will present the design and development of a hybrid Yb^+/Li experiment. This combination has the highest convenient mass ratio - for species that still allow for straightforward laser cooling - of ~29. I analyze the prospects of using the system as a quantum simulator of crystalline solids, in which the fermionic Li atoms couple to the phonon modes of an Yb^+ ion crystal in analogy to electron phonon coupling [3]. I also introduce a two-ion-atom detector we plan to implement in the experiment. Here, a pair of ions is used to detect atoms or atom-ion interactions by making use of non-classical states [4].

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Ultracold atom-ion collisions

<u>Z. Idziaszek</u>[1] A. Simoni[2], T. Calarco[3], P.S. Julienne[4], K. Jachymski[1], M. Krych[1]

[1] Faculty of Physics, University of Warsaw, Warsaw, Poland
[2] Institut de Physique de Rennes, Université de Rennes 1, France
[3] Institut für Quanteninformationsverarbeitung, Universität Ulm, Germany
[4] Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, Maryland, USA

E-mail: idziaszek@fuw.edu.pl

Based on multichannel quantum defect method, we developed a formalism to describe atom-ion collisions in realistic systems including many scattering channels [1,2] and the effects of external fields inducing shape and Feshbach resonances. By including an imaginary term in the quantum-defect matrix describing short range part of the wave function, one can describe the effects of inelastic or reactive collisions, e.g. the charge transfer process or spin flipping collisions. In this way we extended the conventional Langevin capture model to include the non-universal case when the short-range reaction probability is smaller than one. Our model is valid from the ultracold up to the high-temperature limit, and in the limiting case of low and high temperatures it provides explicit analytical formulas for elastic and reactive collision rates [3].
In my talk I will discuss some basic properties of elastic, inelastic and charge-transfer collisions in ion-atom systems at low temperatures. I will show that in analogy to neutral atom collisions, atom-ion interactions can be controlled with magnetic Feshbach resonances. I will discuss the mechanism of charge exchange process, where both free-free and free-bound transitions can occur, and molecular ions can be created. As an illustration I will present results for some specific systems that are of experimental interest: Ba+ ion and Rb atom [4], and Yb+ ion and Li atom. The elastic, inelastic and charge transfer collision rates were obtained with the numerical close-coupled calculations using recent ab-initio potential energy curves, and the multichannel quantum defect model.
The ions trapped in radio-frequency traps experience the small-amplitude micromotion. We developed master equation formalism describing the dynamics of an ion in the radio-frequency trap immersed in cold Bose gas of atoms [5]. I will discuss how cold atomic reservoir modifies the stability diagram of the ion in the trap, creating regions where the ion is cooled or heated due to the energy quanta exchanged with the time-dependent potential [5].

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

M. Köhl

Physikalisches Institut, University of Bonn, Wegelerstrasse 8, 53115 Bonn
Germany

michael.koehl@uni-bonn.de

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

Quantum Simulation of the Jaynes-Cummings-Hubbard Model Using Trapped Ions

K. Toyoda, A. Noguchi and S. Urabe

Graduate School of Engineering Science, Osaka University, Japan

E-mail: toyoda@ee.es.osaka-u.ac.jp

Recent advances in quantum technology enabled us to simulate a certain quantum system with another well-controlled system (*quantum simulation* or *analog quantum computation*). Systems of trapped ions are among the best suited for that purpose. We report here an experiment on quantum simulation of the Jaynes-Cummings-Hubbard (JCH) model [1-3] using two ions in a linear Paul trap.
The JCH model was originally proposed for a system of coupled cavity arrays, each containing a two-level atom [1]. Photons naturally hop between adjacent cavity sites, while coupling with two-level atoms leads to effective photon-photon repulsion. The model has a similarity to the Bose-Hubbard model, which was introduced in relation to studies on strongly-correlated electron systems and later extensively studied with cold neutral atoms in optical lattices. Quantum phase transition between conducting and insulator phases, which is common in these systems, is also expected to be observed for the JCH model.
We performed quantum simulation of the JCH model using an ion chain based on a proposal by Ivanov et al. [2], where each ion in a linear ion crystal represents a cavity in the coupled cavity system, and the single-mode electric field in each cavity is simulated with radial phonons in each ion site. The Jaynes-Cummings (JC) interaction arising from radial red sideband excitation offers effective on-site repulsion, and inter-site hopping of radial phonons is naturally incorporated from the Coulomb coupling.
We observed quantum dynamics derived from the JCH Hamiltonian of a two-ion system, and adiabatic transfer of population from a localized state to a delocalized state (Fig. 1) [3]. Observation of a polaritonic Mott insulator ('frozen phonons') and the possibility of scaling up the system to several ions will be also discussed.

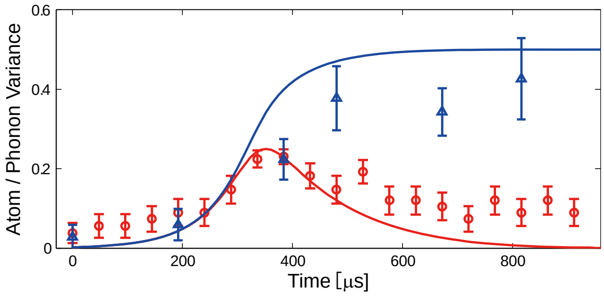

Figure 1. Atom and phonon variances (circles and triangles, respectively) indicating an insulator-to-superfluid quantum phase transition

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Engineering and observation of interacting quasiparticles in a trapped-ion many-body system

P. Jurcevic[1,2], B. Lanyon[1,2], P.Hauke[1,3], C. Maier[1,2],
C. Hempel[1,2], P. Zoller[1,3], R. Blatt[1,2] and C. Roos[1,2]

[1] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstr. 21a, 6020 Innsbruck, Austria
[2] Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
[3] Institut für Theoretische Physik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria

E-mail: cornelius.hempel@oeaw.ac.at

Quantum dynamics in many-body systems can be described by particle-like carriers of information that emerge in the collective behavior of the underlying system. Using spin-dependent forces and single-ion addressing, we engineer such quasiparticles in a linear chains of up to 20 ions and study their time evolution under a 1D transverse Ising Hamiltonian with a tunable interaction range.
I will report on our recent work [1] studying the propagation of entanglement in this system in different experimental regimes. In an extension to this work, we make use of a spin-wave description of the system's excitations and directly extract dispersion relations from the dynamics of superposition of quasiparticles. Using Fourier spectroscopy, we also observe energy shifts due to their interaction [2].
The entangled states, created at various times during the laser-driven dynamics, are no longer accessible to full state tomography nor can they easily be characterized by a simple entanglement witness. Based on tomographic measurements of subsets of the full chain, we are currently investigating the use of matrix product states and –operators [3,4] in the efficient representation of the system's full quantum state. I will report on early results that we have obtained in this manner.

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Modular Quantum Information Processing

D. Hucul, **C. Crocker, I.V. Inlek, G. Vittorini and C. Monroe**

[1] Joint Quantum Institute, University of Maryland Department of Physics and National Institute of Standards and Technology, College Park, MD 20742

E-mail: dhucul@umd.edu

Trapped ions are qubit standards in quantum information science because of their long coherence times and high fidelity entangling gates controlled with external fields. Scaling to very large dimensions may require the use of a modular architecture where trapped ions in separate modules are entangled using a photonic interface while ions in the same module are entangled using a phonon bus. We report the successful combination of these types of entanglement within and between two modules [1]. We use fast optics to generate heralded remote entanglement between modules at rates exceeding 4 per second, faster than the experimentally measured decoherence rate of the remote entangled state. The resource scaling in such a modular architecture is super-exponential in the ratio of the mean remote entanglement time to the entangled qubit coherence time, and trapped ions are the only experimental system to date where this ratio is small and the overhead is not forbidding.

When scaling up such a system, it will become necessary to track the phases associated with successive coherent rotations and entangling operations between and within modules at different times. We report the experimental demonstration of such a system where the phases of entangling Coulomb gates as well as qubit rotations are mutually locked to a common, high-quality master oscillator without the need for optical phase stability within or between modules [2]. In addition, we have implemented several pulse shaping schemes to reduce errors during phonon-based entangling gates within a module [3]. Appropriate phase modulation of phonon-based gates reduces sensitivity to detuning and timing errors. Amplitude modulation of these gates can be used for fast, high-fidelity gates in the presence of spectral crowding of the phonon bus modes. To account for different qubit environments between modules, we demonstrate a control scheme to create heralded entanglement between distinguishable qubits in separate modules using interference of non-identical photons without significant loss of remote entanglement rate or fidelity [4].

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POSTER SESSION I

PI-1
Observation and theory of electric-dipole-forbidden infrared transitions in cold molecular ions

M. Germann[1], **X. Tong**[1,2] **and S. Willitsch**[1]

[1] Department of Chemistry, University of Basel, Klingelbergstrasse 80, 4056 Basel, Switzerland
[2] State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China

E-mail: matthias.germann@unibas.ch

Homonuclear diatomic molecules do not show a rotational-vibrational spectrum within the electric-dipole approximation. However, higher order terms in the multipole-expansion of their charge distribution give rise to weak lines in their rovibrational spectrum, so called dipole-forbidden transitions.
For molecular ions, the low intensity of these transitions has so far precluded their detection. Here we report the – to our knowledge – first observation of such transitions in molecular ions. More specifically, we have observed the electric-quadrupole infrared fundamental transition in N_2^+ ions [1]. For these observations the ions were produced in a selected internal quantum state, sympathetically cooled to millikelvin temperatures and stored in a linear Paul trap [2, 3]. The ions were vibrationally excited with a quantum cascade laser and the excitation was detected using a state-selective charge transfer reaction with argon atoms [4] that allows us to monitor absorption events on the single-molecule level. To understand the measured spectra, we have also developed the theory of hyperfine-resolved quadrupole infrared transitions in Hund's case b molecules. The weakness of these dipole-forbidden transitions is associated with an extremely narrow linewidth. Thus their observation may open up new applications in precision spectroscopy and metrology such as highly accurate molecular clocks [5] and the investigation of possible variations of fundamental constants [6].

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PI-2
Sympathetically cooled hydrogen molecular ions for precision measurements

J.-Ph. Karr[1,2], A. Douillet[1,2], V.I. Korobov[3], N. Sillitoe[1] and L. Hilico[1,2]

[1] Laboratoire Kastler Brossel, UEVE, UPMC, CNRS, ENS, CDF, 4 place Jussieu, 75252 Paris cedex 05
[2] Dpt de physique, Université d'Evry Val d'Essonne, Bd F. Mitterrand, 91000 EVRY
[3] Joint Institute for Nuclear Research, 141980 Dubna, Russia

E-mail:hilico@spectro.jussieu.fr.

Cold hydrogen molecular ions H_2^+ or HD^+ allows for direct optical determination of the proton to electron mass ratio m_p/m_e using high resolution laser spectroscopy. The expected relative accuracy is limited by theoretical predictions. Recently published calculations reach the 6. 10^{-11} level [1]. We present new calculations reducing the uncertainty by a factor of 4, allowing a determination improved by more than one order of magnitude with respect to the present CODATA and more precise than the value recently deduced from bound-electron g-factor measurements [2].
Some selected rovibrational transitions have extremely high quality factors [3,4], making hydrogen molecular ions extremely good candidates for m_p/m_e time variation analysis. We first discuss the best Doppler-free transitions in H_2^+ and HD^+ towards these metrological goals (counter propagating two-photon transitions versus dipole allowed/quadrupole transitions in the Lamb-Dicke regime), taking into account initial molecular state preparation, ion trapping and sympathetic cooling as well as transition detection.
We present the experimental set-up we are setting up in Paris, including a REMPI state selected H_2^+ ion source, a linear trap for light molecular ions sympathetic cooling by laser cooled Be^+ ions, as well as the laser sources.
Sympathetic cooling of light ions produced in an external source and injected in a linear trap is an experimental issue that deserves intense numerical simulations to determine optimal trapping and injection conditions. Beyond hydrogen molecular ions, they are useful for highly charged ion or antimatter ion cooling [5,6]. We report on our recent progress in implementing a highly efficient (5.5 TFlops) multi-GPU simulation code taking into account the exact N-body dynamics in the time dependant RF fields of the trap, and the cooling laser interaction.

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PI-3
Prospects for quantum logic spectroscopy of molecular ions

Y. Wan[1], F. Wolf[1], F. Gebert[1], J.C. Heip[1] and P.O. Schmidt[1,2]

[1] QUEST Institut, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Institut für Quantenoptik, Leibniz Universität Hannover, Germany

E-mail: Piet.Schmidt@quantummetrology.de

The rapid development in laser cooling and coherent state manipulation over the past decades has enabled exquisite control over the internal and external degrees of freedom of various species of atomic ions. The same techniques cannot be easily applied to molecular ions because of their rich internal level structure, typically lacking closed cycling transitions for laser cooling and state detection. On the other hand, ultra-cold molecular ions lend themselves for a number of novel applications, ranging from cold chemistry to tests of fundamental theories.
We propose to prepare a translationally cold molecular ion in a specific ro-vibrational state by employing the quantum logic technique [1] in which a laser-cooled atomic ion is simultaneously trapped with a single molecular ion. The cooling of the external degrees of freedom of the molecular ion is achieved via sympathetic cooling by the sideband-cooled atomic ion, while the preparation of its internal state will be achieved via a quantum-non-demolition measurement.
The investigated molecules MgH^+/CaH^+ are relevant for the search of a possible temporal variation of the electron-to-proton mass ratio $\mu = me/mp$ [2]. The transition frequency of ro-vibrational overtone transitions in the molecule depend on μ and can be compared to another optical reference, such as the Al^+ clock to obtain an improved upper bound for the time variation of μ.

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PI-4
Precision isotope shift measurements of Ca^+ ions using photon recoil amplification schemes

F. Gebert[1], **Y.Wan**[1], **F.Wolf**[1], **J. Berengut**[2] **and P.O. Schmidt**[1,3]

[1] QUEST Institut, Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[2] School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
[3] Institut für Quantenoptik, Leibniz Universität Hannover, Germany

E-mail: florian.gebert@quantummetrology.de.

We present isotope shift measurements of the $^2D_{3/2}$-$^2P_{1/2}$ and $^2S_{1/2}$-$^2P_{1/2}$ transitions in Ca^+ ions by extending the photon recoil spectroscopy (PRS) technique [1] to non-closed transitions. In PRS, a spectroscopy ion is trapped and sympathetically cooled by a cooling ion. Photon recoil from absorption on a spectroscopy transition results in motional excitation probed by the cooling ion using quantum logic techniques. In the new approach single-photon repumping of a meta-stable state enables motional excitation on an auxiliary transition. Before ground state cooling the two ion crystal via the logic ion, the Ca^+ spectroscopy ion is initialized in the $^2D_{3/2}$ state. The detuning dependent population transfer from the $^2D_{3/2}$ to the $^2S_{1/2}$ state via the $^2D_{3/2}$-$^2P_{1/2}$ transition serves as the spectroscopy signal which is efficiently translated into motion of the two ion crystal through recoil from absorption of photons resonant with the $^2S_{1/2}$-$^2P_{1/2}$ transition. The excitation laser is applied in 125ns long pulses synchronized to the motion of the ions in the trap. This assures the excitation along the momentum axis in phase space and provides an efficient way to minimize the overlap of the final motional state with the groundstate [2]. The $^2P_{1/2}$ state decays with a branching ratio of 1:14.5 into the $^2D_{3/2}$ and the $^2S_{1/2}$-state, respectively. Therefore, the ion is reinitialized in the $^2D_{3/2}$ state after 70 excitation pulses. The repetition of spectroscopy/excitation cycles efficiently enhances the motion of the two ion crystal and after three cycles maximum excitation was reached for our experimental parameters. The residual motional ground state population serves as the inverse spectroscopy signal and is probed using a motional sideband pulse on the $^{25}Mg^+$ logic ion. We present isotope shift measurements using the new technique with an accuracy improved by up to two orders of magnitude.
Combining the data with measurements of the isotope shift of the $^2S_{1/2}$-$^2P_{1/2}$ transition using the PRS technique, we were able to perform a King plot analysis to extract the relative field and mass shift constants. The improved accuracy enables us to extract and refine nuclear calculations by comparing these measurements with theoretical predictions.

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PI-5
Quantum Logic Spectroscopy of Highly Charged Ions

P. Micke[1,2], T. Leopold[1], L. Schmöger[1,2], M. Schwarz[1,2], O. Versolato[1,2], M. Kohnen[1,3], J. Ullrich[1,2], J. Crespo López-Urrutia[2] and P. Schmidt[1,3]

[1] Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[2] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[3] Leibniz Universität Hannover, 30167 Hannover, Germany

E-mail: peter.micke@ptb.de

Highly charged ions (HCIs) offer forbidden optical transitions near level crossings due to reordering of the electronic level structure as the charge state grows. Some of these transitions have an enhanced sensitivity to a possible time variation of the fine-structure constant [1]. Furthermore, HCIs are insensitive to external fields because of their strong internal Coulomb field. This can be exploited for building optical clocks with small systematic shifts.

Generally, HCIs do not have transitions appropriate for direct laser cooling. However, they can be sympathetically cooled with another ion species – in our case Be^+. Then, spectroscopic measurements can be carried out by using quantum logic: A single HCI (spectroscopy ion) is co-trapped together with a Be^+ logic ion, which provides not only cooling, but also both state preparation and readout.

For this purpose an electron beam ion trap (EBIT) breeds HCIs. Next, the HCIs are extracted, decelerated and injected into a linear cryogenic Paul trap. The cryogenic environment provides extremely high vacuum for preventing HCIs from capturing electrons from residual atoms. Thereby, long storage times can be achieved. Recently, the collaborative experiment CryPTEx (Cryogenic Paul Trap Experiment [2]) at the Max-Planck-Insitut für Kernphysik has already proven the successful deceleration and injection of HCIs into a liquid of trapped Be^+ ions (see figure 1).

We are currently setting up an experiment for the Physikalisch-Technische Bundesanstalt aiming at quantum logic spectroscopy of HCIs. For this experiment we combine a novel low-maintenance EBIT based on permanent magnets as well as a novel low-vibration cryogenic Paul trap.

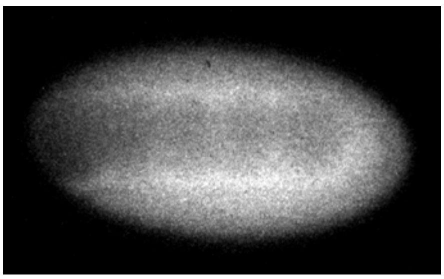

Figure 1. Five highly charged ions are trapped within a liquid of Be^+ ions.

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PI-6
The high-precision Penning-trap mass spectrometer PENTATRAP

H. Bekker[1,2], K. Blaum[1,2], Ch. Böhm[1,2,3], J.R. Crespo López-Urrutia[1], A. Dörr[1,2], S. Eliseev[1], M. Goncharov[1,2], A. Rischka[1,2], R. Schüssler[1,2], S. Sturm[1], S. Ulmer[4]

[1] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2] Universität Heidelberg, Fakultät für Physik und Astronomie, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[3] ExtreMe Matter Institute EMMI, Helmholtz Gemeinschaft, Planckstraße 1, 64291 Darmstadt, Germany
[4] RIKEN, Ulmer Initiative Research Unit, Wako, Saitama 351-0198, Japan

Rima.Schuessler@mpi-hd.mpg.de

The high-precision Penning-trap mass spectrometer PENTATRAP [1] has been set up and is currently being commissioned at the Max-Planck-Institut für Kernphysik, Heidelberg. It aims at mass-ratio measurements with a relative uncertainty of a few 10^{-12}, a precision so far only achieved for a few relatively light elements [2].
With mass-ratio measurements at this precision level, PENTATRAP will, for instance, contribute to electron-neutrino mass related measurements, e.g. with the determination of the Q-value of the electron capture transition from ^{163}Ho to ^{163}Dy. This work will be carried out within the ECHo collaboration [3], which investigates the de-excitation spectrum following the electron capture in ^{163}Ho to obtain information on the electron neutrino mass.

PENTATRAP will determine the mass ratios of ion species under investigation through measurements of their respective cyclotron frequencies in the strong magnetic field of a Penning trap. The experimental setup consists of five cylindrical Penning traps [4], making simultaneous storage of several ion species possible. Dedicated image current detection systems [5] with single ion sensitivity enable simultaneous determinations of the cyclotron frequencies in all traps. This allows for measurement schemes resulting in the cancellation of magnetic field fluctuations in the determination of mass ratios to first order.
Long storage times of highly-charged ions, delivered from the Heidelberg Electron Beam Ion Trap [6], are provided by a very good vacuum in the trap region due to direct immersion of the trap housing in a bath of liquid helium.
The current status and outlook of the experiment will be presented in the poster.

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PI-7
Towards quantum logic assisted cooling and detection of single (anti-)protons

M. Niemann[1], A.-G. Paschke[1], A. Bautista-Salvador[1,2], K. Voges[1], T. Feld[1], M. Borchert[1], S. Ulmer[3] and C. Ospelkaus[1,2]

[1] Insitut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
[2] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[3] RIKEN Advanced Science Institute, Hirosawa, Wako, Saitama 351-0198, Japan

E-mail: christian.ospelkaus@iqo.uni-hannover.de

We discuss quantum logic inspired methods amenable to cooling and state detection of single (anti-)protons in the context of g-factor measurements for testing CPT invariance. In the scheme proposed by Heinzen and Wineland [1,2] cooling and state detection of single (anti-)protons is accomplished by means of an atomic ion trapped in close vicinity.
For antiprotons, one must ensure that the atomic ion can be trapped in a way which allows for a significant Coulomb interaction between the antiproton and the atomic ion. Towards this end, it was proposed in [2] to store the antiproton and the atomic ion each in a separate well of a double-well potential. This technique has already been shown to work using pairs of atomic ions [3,4]. For spin state readout, an additional interaction is required which allows transfer of the antiproton spin state into its motional state as discussed in [5,6] in the context of quantum logic.
In order to adapt these ideas for a precision measurement, we have designed a Penning trap stack consisting of individual zones for (anti-)proton spectroscopy, spin-motional coupling, Coulomb coupling between the (anti-)proton and the $^9Be^+$ atomic ion and laser manipulation of $^9Be^+$. Particles will be moved between zones during the cooling and readout procedure as in the double Penning trap technique [7]. The present design for the Coulomb coupling zone features two potential wells at a distance of 300 μm from each other with a trap frequency of 4 MHz and a motional state exchange time of 3.7 ms. At the anticipated magnetic field of 5 Tesla, the control of $^9Be^+$ with laser beams will be challenging because of the large energy splitting between the qubit levels. We discuss techniques and recent experimental results for a stimulated-Raman laser system at 313 nm allowing to bridge more than 100 GHz in frequency splitting. We conclude with a discussion of techniques for loading $^9Be^+$ and of the optical setup for bringing in the control laser beams.

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PI-8
First Penning trap mass measurements of ^{163}Ho and ^{163}Dy

F. Schneider[1,2], T. Beyer[1,3], K. Blaum[3], S. Chenmarev[3,4], Ch. E. Düllmann[1,5,6,7], K. Eberhardt[1,7], M. Eibach[1,3], J. Grund[1,2], D. Renisch[1], Sz. Nagy[3] and K. Wendt[2]

[1]Institut für Kernchemie, Johannes Gutenberg-Universität, Mainz
[2]Institut für Physik, Johannes Gutenberg-Universität, Mainz
[3]Max-Planck-Institut für Kernphysik, Heidelberg
[4]Physical Faculty, St. Petersburg State University, St. Petersburg
[5]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt
[6]PRISMA Cluster of Excellence, Mainz
[7]Helmholtz-Institut Mainz, Mainz

E-mail: Fabian.Schneider@uni-mainz.de

The ECHo-Collaboration aims to determine the mass of the electron neutrino ν_e by analyzing the calorimetric spectrum of the ^{163}Ho → ^{163}Dy electron capture. The energy difference between its Q-value and the endpoint of the decay radiation spectrum reflects the neutrino rest mass. To reach the desired sensitivity below 1 eV, similarly precise measurements of these values are required. The currently recommended Q_{EC} value of 2.55 ± 0.016 keV [1] is based on several calorimetric measurements. A further gain in precision - independent of the neutrino mass – is only possible using high-precision mass spectrometry techniques.
Preparatory measurements were performed at the double Penning trap mass spectrometer TRIGA-TRAP. $^{163}Ho^{16}O^+$ or $^{163}Dy^{16}O^+$ molecules were created via laser ablation and cooled to room temperature in a gas filled Paul trap. These ion bunches were transported to the first, purification Penning trap to clean the bunch from any contaminations. In the second Penning trap the precision measurement of the free space cyclotron frequency is performed with the ToF-ICR method. From the ratio of the determined frequencies we obtained $Q_{EC} = 2.6 \pm 0.5$ keV which agrees with the calorimetric measurements. By using $^{12}C_{15}^+$ clusters as reference, we were also able to improve the uncertainty of the absolute masses of the two nuclides from 1.9 keV to 0.7 keV.
The measurements proved that the sample purity and ion preparation techniques allow Penning trap mass measurements with about 10^{15}-10^{16} atoms in the sample. Future measurements at SHIPTRAP (GSI, Darmstadt) will enhance the precision tenfold and finally measurements at PENTATRAP (MPI-K, Heidelberg) aim to reach the desired precision of 1 eV.

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PI-9
Optical clock based on the octupole transition of $^{171}Yb^{+}$

Chr. Tamm, **N. Huntemann, C. Sanner, B. Lipphardt and E. Peik**

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

E-mail: christian.tamm@ptb.de

We investigate an optical clock that uses the 467 nm electric octupole transition $^2S_{1/2}(F=0)$ – $^2F_{7/2}(F=3)$ of $^{171}Yb^{+}$ as the reference. This transition has a negligible natural linewidth in the nHz range and a low sensitivity to frequency shifts induced by electric and magnetic fields [1]. Both characteristics are advantageous for the realization of a single-ion optical clock. However, the extremely small oscillator strength of the reference transition requires excitation with high spectral power density. This leads to a significant light shift of the transition frequency due to nonresonant coupling to higher-lying levels.

To avoid the light shift, we have implemented the so-called Hyper-Ramsey spectroscopy (HRS) scheme, a pulsed excitation scheme tailored to produce a resonance signal that is immune to frequency shifts that appear during the interrogation pulses [2]. In the HRS scheme, the light shift of the excitation spectrum is compensated by phase-coherent switching of the probe light frequency during the excitation pulses. An additional pulse cancels the linear dependence of the resonance center frequency on the compensation frequency step. Our experiments demonstrate a suppression of the light shift by four orders of magnitude and immunity against its fluctuations [3]. For operation as a frequency standard, we use a servo system that controls the size of the HRS compensation frequency step by comparison with interleaved single-pulse Rabi excitation at the same intensity. Under these conditions the estimated light shift contribution to the fractional systematic uncertainty of the frequency standard is below $2\cdot10^{-18}$.

The differential polarizability of the octupole transition at infrared and lower frequencies has been determined with an uncertainty of less than 5 % through light shift measurements with lasers at various near-infrared wavelengths. Together with improved knowledge of the thermal radiation emitted by the ion trap and its mounting structure [4], the blackbody radiation shift of the transition frequency standard can now be corrected with a fractional uncertainty of less than $3\cdot10^{-18}$, which reduces the total systematic uncertainty of the $^{171}Yb^{+}$ octupole frequency standard to $3.9\cdot10^{-18}$.

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PI-10
Search for optical excitation of the low-energy nuclear isomer of Th-229

D.-M. Meier[1], O.A. Herrera-Sancho*, N. Nemitz[+], A. Yamaguchi[+], M.V. Okhapkin[1] and E. Peik[1]

[1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

E-mail: david-marcel.meier@ptb.de

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

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*present address: Universidad de Costa Rica, San José, Costa Rica
[+] present address: RIKEN, Quantum Metrology Laboratory, Saitama, Japan

PI-11
Building a Portable Aluminium-Ion Frequency Standard

I.D. Leroux[1], **J. Wübbena**[1], **S. Amairi**[1], **N. Scharnhorst**[1], **S. Hannig**[1] **and P.O. Schmidt**[1,2]

[1] QUEST Institute for Experimental Quantum Metrology, Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[2] Leibniz University of Hannover, 30167 Hannover, Germany

E-mail: idleroux@quantummetrology.de

We report on the development of an $^{27}Al^{+}$ frequency standard intended to demonstrate portable high-accuracy time-keeping and chronometric levelling. As part of this effort, we have developed a scheme for phase-locking lasers of widely differing wavelengths with sufficient bandwidth to avoid the need for pre-stabilisation of the free-running lasers. We have used such a multi-wavelength battery of phase-locked lasers to implement fast EIT cooling of $^{40}Ca^{+}$ to the motional ground state. We discuss the prospects of using these techniques to control motional shifts, currently the dominant systematic uncertainty in $^{27}Al^{+}$ clocks, at the level of parts in 10^{18}.

PI-12
Frequency locking of an optical system for cooling $^{138}Ba^{+}$ ions

B.M. Mihalcea[1], **D. Sporea**[1], **M. Selagea**[2], **G. Vișan**[1], **A. Stăncălie**[1], **L. Mihai**[1] **and M. Ganciu**[1]

[1] Natl. Inst. for Laser, Plasma and Radiation Phys., Atomiștilor Str. Nr. 409, 077125 Măgurele, Romania
[2] Apel Laser SRL, Bucharest, Romania

E-mail: bogdan.mihalcea@infim.ro

Within the Photonic Investigations Department at CETAL (Integrated Centre for Advanced Laser Technologies) in Măgurele, we are developing an optical system intended for trapping and cooling $^{138}Ba^{+}$ ions at 493 nm. In order to achieve accurate frequency control of the system, the laser diode used to cool the ions is controlled and stabilized by means a frequency comb synthesizer. The optical frequency comb includes a dedicated LLE-SYNCRO module in order to lock the 493 nm radiation. This module generates an error signal whose value lies in the -10..+10 V range, that can be fed to the laser diode modulation input. The bandwidth of the modulation input and the unstabilized laser linewidth determine the bandwidth of the beat signal, which results at the output of the Beat Detection Unit – BDU. The BDU module is tuned on the LD wavelength (986 nm). When the frequency synthesizer operates in the monomode regime, the output power of the control signal is rated around hundreds of nW, a value which enables accurate locking of the frequency generated by the CW pump laser diode. The 650 nm radiation used to pump the $^{138}Ba^{+}$ ions out of the $D_{3/2}$ metastable level (see Fig. 1), is generated using a dedicated module within the frequency comb synthesizer.

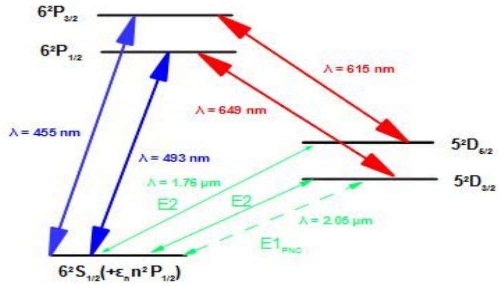

Figure 1. Scheme of the electronic levels of the $^{138}Ba^{+}$ ion

The frequency comb synthesizer we have used was purchased in the frame of the CETAL project, contract 8PM/2010, with financial support from UEFISCDI Romania. The authors acknowledge financial support from the Romanian Ministry of National Education (MEN-CDI), contract PN09.39.03.01.

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PI-13
Recent Progress on the MIKES $^{88}Sr^+$ Ion Clock

T. Lindvall, T. Fordell, A.E. Wallin and M. Merimaa

Centre for Metrology and Accreditation (MIKES), P.O. Box 9, Tekniikantie 1, FI-02151 Espoo, Finland

E-mail: thomas.lindvall@mikes.fi.

The next generation primary frequency standards are based on probing ultra-narrow optical transitions in trapped cold atoms or ions. We present the MIKES $^{88}Sr^+$ single-ion optical clock with emphasis on recent progress.

Our endcap-type Paul trap is based on an NRC (National Research Council of Canada) design [1]. The trap is loaded from a resistively heated Sr dispenser using doubly resonant photoionization (461 nm and 405 nm). In addition to the existing trap, a new compact and transportable physics package is currently under construction.

With the goal of making a robust transportable optical clock, several novel light sources were developed. The 461-nm photoionization laser is based on a frequency-doubled 922-nm DFB laser, which is frequency stabilized to a Sr atomic beam. The cooling light is produced by an 844-nm DFB seed laser, amplified, and frequency doubled to 422 nm. A rubidium vapor cell provides an absolute frequency reference for the 422-nm laser. Laser cooling of $^{88}Sr^+$ also requires a 1092-nm repumper light source to prevent decay into the $4d^2D_{3/2}$ state [2]. A novel unpolarized, incoherent light source [3] based on amplified spontaneous emission in an ytterbium-doped optical fiber pumped at 980 nm was developed [4]. A similar approach is used for state clearout at 1033 nm.

The clock laser (not transportable) is a DFB laser at 1348 nm, which is amplified and then frequency doubled to 674 nm. It is pre-stabilized using a fiber-based Michelson interferometer at 1348 nm, and then PDH locked to a high-finesse Fabry-Perot reference cavity at 674 nm. The cavity has a 300-mm ULE spacer and is housed in a vacuum chamber inside three heat shields, the outermost of which is actively temperature controlled. Several stages of vibration isolation are utilized for the cavity chamber. All light sources are coupled to the ion via an endlessly single-mode photonic crystal fiber.

Our preliminary results show that we can repeatedly and robustly photoionize and trap single $^{88}Sr^+$ ions. The loading times using the commercially available Sr dispenser are similar to previously reported values. Stable trapping for up to several hours is achieved. We are currently investigating methods for measuring and minimizing the excess micromotion of the ion.

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PI-14
Laser Spectroscopy Determination of the Hyperfine Splitting in H-Like and Li-Like Bismuth

S. Schmidt[1,2], J. Ullmann[1,3], J. Vollbrecht[4], Z. Andelkovic[5], A. Dax[6], W. Geithner[5], Ch. Geppert[1,2], Ch. Gorges[1], M. Hammen[2,7], V. Hannen[4], K. König[1], S. Kaufmann[1], Y. Litvinov[5], M. Lochmann[1], B. Maaß[1], J. Meisner[8], T. Murböck[9], W. Nörtershäuser[1], R.M. Sánchez[5], M. Schmidt[8], M. Steck[5], Th. Stöhlker[3,5], R. Thompson[10] and Ch. Weinheimer[4]

[1] Institut für Kernphysik, Technische Universität Darmstadt, Germany
[2] Institut für Kernchemie, Johannes Gutenberg-Universität Mainz, Germany
[3] Helmholtz Institut Jena, Germany
[4] Institut für Angewandte Physik, Westfälische Wilhelms Universität, Germany
[5] GSI Helmholtzzentrum für Schwerionenforschung, Germany
[6] Paul Scherrer Institut, Villingen, Switzerland
[7] Helmholtz Institut Mainz, Germany
[8] PTB Braunschweig, Elektrische Energiemesstechnik, Braunschweig, Germany
[9] Institut für Angewandte Physik, Technische Universität Darmstadt, Germany
[10] Department of Physics, Imperial College London, United Kingdom

E-mail: st.schmidt@gsi.de

An experimental comparison between the hyperfine structure (HFS) splitting in hydrogen- and lithium-like bismuth ions allows fundamental tests of the bound-state quantum electrodynamics in the strongest electromagnetic fields by determination of the so-called specific HFS splitting difference [1]. Even though the ground state hyperfine transition in H-like bismuth was found in 1994 [2], the transition in Li-like bismuth could not be observed until recently [3].

The experiment was performed in 2011 at the Experimental Storage Ring (ESR) at the GSI Helmholtz-Center for heavy ion research. Here, Li-like bismuth ions were stored at relativistic energies and the HFS transition was excited by means of collinear laser spectroscopy. Additionally the HFS splitting in H-like bismuth was remeasured. Even though the accuracy of our results are limited by the calibration of the electron cooler voltage, a significant deviation from the previous measurements of H-like Bi was found. The combination of both HFS splittings agrees with the theoretical prediction within the experimental uncertainty.

With the aim to improve the accuracy of our measurement, we repeated this experiment in 2014. This time, we were able to reduce the uncertainties in nearly all relevant parameters. Particularly, the voltage of 214 kV at the ESR electron-cooler was monitored in situ using a high-precision high-voltage divider provided by the Physikalisch-Technische Bundesanstalt. Results from 2011 and preliminary data from 2014 will be presented.

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PI-15
High-precision near-infrared spectroscopy of the molecular hydrogen ion HD^+

J. Biesheuvel[1], K.S.E. Eikema[1], W. Ubachs[1], J.-Ph. Karr[2,3], L. Hilico[2,3] and J.C.J. Koelemeij[1]

[1]LaserLaB and Department of Physics and Astronomy, VU University, Amsterdam
[2]Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Paris, France
[3]Département de Physique, Université Val d'Essonne, Evry, France

E-mail: j.biesheuvel@vu.nl

The uncertainty of theoretical (QED) energy level calculations of the molecular HD^+ ion is significantly limited by the uncertainty in fundamental constants, such as the proton-electron mass ratio. Therefore, comparison with highly accurate experimental data can both produce improved values of fundamental constants and lead to stringent tests of QED. We have performed high-precision spectroscopy of finite samples of trapped HD^+ ions, sympathetically cooled to 10 mK by laser-cooled Be^+ ions. Using resonance-enhanced multiphoton dissociation we obtained high-resolution optical spectra of the (v, J): (0,2)-(8,3) overtone at 782 nm with an unprecedented spectroscopic precision of 0.8 ppb. Remarkably, the lineshape of the spectrum shows evidence of a non-Boltzmann (secular) velocity distribution, in spite of the widespread view that Doppler laser cooling leads to thermal distributions. Realistic molecular dynamics simulations support our observation, which is of importance for spectroscopic studies of trapped ions. The analysis of this and other systematic effects is nearing completion. A comparison of our experimental results with state-of-the-art HD^+ level structure calculations [1] may ultimately lead to the most stringent test of QED in molecules so far performed, a new determination of the proton-electron mass ratio, and improved constraints on hypothetical 'fifth forces' between hadrons due to rolled-up higher dimensions [2].

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PI-16
Stopping and sympathetic cooling of highly charged ions in Coulomb crystals

L. Schmöger[1,2], O.O. Versolato[1,2], M. Schwarz[1,2], M. Kohnen[1], T. Leopold[1], A. Windberger[2], J. Ullrich[1], P.O. Schmidt[1,3] and J.R. Crespo López-Urrutia[2]

[1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[3]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany

E-mail: lisa.schmoeger@mpi-hd.mpg.de

Cold highly charged ions (HCI) are particularly interesting systems both for fundamental physics studies, such as testing the time stability of the fine structure constant α [1], and for technological applications such as high accuracy frequency references. Optical clocks based on forbidden optical transitions in HCI will benefit from the low polarizability of the deeply bound optically active electron, which largely suppresses systematic shifts due to external fields. Additionally, strong relativistic effects enhance the sensitivity of such transitions to possible drifts of α.
We have recently succeeded in re-trapping and sympathetically cooling HCIs produced with an electron beam ion trap (EBIT) in our cryogenic radiofrequency linear Paul trap CryPTEx. Fast (9 keV) HCIs extracted from the EBIT are decelerated by two pulsed drift tubes with time-focusing properties before they are injected into CryPTEx [2]. Here they are forced to interact multiple times with the laser-cooled Be^+ one component plasma in the liquid or crystalline phase by means of two switchable electrostatic mirrors until they finally become crystallized near the trap axis [Fig. 1]. The HCI temperature can currently be estimated to be in the 100 mK range, six orders of magnitude lower than typical translational temperatures of HCIs trapped in an EBIT. This is of great advantage for high precision laser spectroscopy with HCI ensembles. Ongoing experiments aim at the production of Be^+/HCI ion strings which are needed for quantum logic spectroscopy.

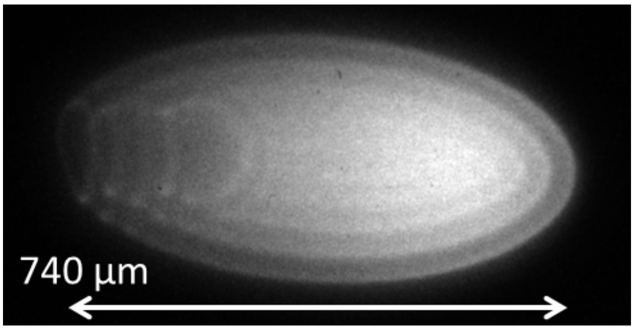

Figure 1. Image of three sympathetically cooled HCIs (visible as large dark spots) in a Be^+ Coulomb crystal.

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PI-17
The magnetic moments of the proton and the antiproton

A. Mooser[1], K. Blaum[2], K. Franke[1,2], T. Higuchi[1,3], P. Koß[4], H. Kracke[4,5], N. Leefer[5], C. Leiteritz[4], Y. Matsuda[3], H. Nagahama[1,3], W. Quint[6], G. Schneider[4], C. Smorra[1,7], J. Walz[4,5], Y. Yamazaki[8] and S. Ulmer[1]

[1] RIKEN, Ulmer Initiative Research Unit, Japan
[2] Max-Planck-Institut für Kernphysik, Germany
[3] University of Tokyo, Japan
[4] Johannes Gutenberg-Universität Mainz, Germany
[5] Helmholtz-Institut Mainz, Germany
[6] GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Germany
[7] CERN, Switzerland
[8] RIKEN, Atomic Physics Laboratory, Japan.

E-mail: andreas.mooser@cern.ch

One of the fundamental properties of the proton/antiproton is the spin magnetic moment $\mu_{p,pbar}$. In case of the proton the most precise value of μ_p was based on spectroscopy of atomic hydrogen conducted 42 years ago. Significant theoretical bound-state corrections had to be applied to indirectly determine μ_p with a relative precision of 9 ppb [1]. Very recently, we improved this value by a factor of 2.5 by directly measuring μ_p with a single proton in a Penning trap [2]. In case of the antiproton μ_{pbar} is known with a relative precision at the ppm level [3]. By applying our methods to the antiproton, we aim at a thousandfold improved measurement of the particle's magnetic moment. To this end, we are setting up the BASE experiment at the antiproton decelerator of CERN [4], to eventually provide a stringent test of CPT-invariance with baryons.
In a Penning trap the measurement of $\mu_{p,pbar}$ is based on the determination of the two frequencies of a single proton/antiproton, the Larmor and the cyclotron frequency. Based on a statistical detection of spin transitions we measured the Larmor frequency of a single proton for the first time [5], which resulted in a direct determination of μ_p with a fractional precision at the ppm level [6]. The precision was improved significantly by using a double Penning-trap technique. This required the detection of single spin flips, which was achieved with an improved apparatus and by using Bayesian data analysis [7]. Our developments ultimately culminated in the most precise and first direct measurement of μ_p.
For BASE a significantly improved setup using a state of the art trapping system has been developed. After a construction phase of about 1.5 years, we successfully commissioned our four-Penning trap system using single protons. A detailed status update will be presented.

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PI-18
Doppler-free two-photon spectroscopy of trapped HD^+ ions

S. Patra[1], J. Biesheuvel[1], T.J. Pinkert[1], K.S.E. Eikema[1], W. Ubachs[1], J.C.J. Koelemeij[1], V.Q. Tran[2], J.-Ph. Karr[2,3], A. Douillet[2,3] and L. Hilico[2,3]

[1]LaserLaB and Department of Physics and Astronomy, VU University, Amsterdam
[2]Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Paris, France
3Département de Physique, Université Val d'Essonne, Evry, France

E-mail: s.patra@vu.nl

High-precision spectroscopy using resonance-enhanced multi-photon dissociation (REMPD) of the (v,L): (0,2) – (8,3) overtone of trapped, laser-cooled HD^+ molecular ions has been demonstrated with an unprecedented resolution of 0.8 ppb [1]. The resolution achieved is largely limited by Doppler broadening. To overcome this in the present setup at VU Amsterdam, our target is to implement Doppler-free two-photon spectroscopy for HD^+ ion in the Lamb-Dicke regime. For this purpose, we have chosen the nearly degenerate (v,L): (0,3) – (4,2) and (4,2) – (9,3) rovibrational transitions of the molecule at 1.44 μm. We have performed realistic simulations of the spectroscopic signal taking into account saturation effects, ion trajectories, laser frequency noise, and redistribution of population by blackbody radiation. Sub-Doppler lines having widths in the 100-Hz range seem well feasible, allowing a relative uncertainty of the order of 10^{-14} for the two-photon transition [2]. A comparison of such experimental results with state-of-the-art HD^+ level structure calculations may provide the most stringent test of molecular QED at the level of 4×10^{-11} [3], provide a new value of the proton-electron mass ratio with a relative uncertainty of $\sim1\times10^{-10}$, and enable searches for possible fifth forces ensuing from rolled-up higher dimensions with improved sensitivity [4].

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PI-19
Controlling anti-ions to determine the gravitational behavior of antimatter

S. Wolf[1], **J.-P. Karr**[2], **A. Douillet**[2], **L. Hilico**[2], **N. Sillitoe**[2] **and F. Schmidt-Kaler**[1]

[1] QUANTUM, Institut für Physik, Universität Mainz
[2] UEVE CNRS UPMC ENS CDG, 4 place Jussieu, Paris, Dpt de physique, Université d'Evry Val d'Essone, Evry

E-mail: wolfs@uni-mainz.de

The symmetry of matter and antimatter is among the most urgent questions in physics. Gravitational interaction of antimatter and matter is mostly unknown. For charged particles gravitational forces are masked by order-of-magnitude stronger Coulomb forces. On the other hand, neutral antimatter cannot sufficiently be cooled for free-fall experiments [1]. The GBAR collaboration [2,3] is working on a free-fall experiment using anti-Hydrogen. In a first step positively charged anti-Hydrogen ions ($p^- + 2e^+$) are produced at the ELENA/AD at CERN. These ions are trapped in a Paul trap and sympathetically cooled in the motional ground state using laser cooled Beryllium ions [4]. The photo-detachment of the additional positron triggers the free-fall experiment. The accuracy of about 1000 measurement events will be about 1% [5,6]. We report of the current status of the experimental setup.

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PI-20
Investigation of a ring electrode ion trap to produce multiply-charged cluster anions

S. Knauer, G. Marx and L. Schweikhard

Institute of Physics, University of Greifswald, Felix-Hausdorff-Str. 6, 17489 Greifswald, Germany

Knauer@physik.uni-greifswald.de

The Coulomb barriers and electron binding energies of multiply-charged metal clusters are experimentally largely uninvestigated. Because metal clusters in general and with higher charge states in particular do not exist in nature, they have to be produced in laboratories by cluster-electron collision. This can be achieved with combinations of different cluster sources and ion traps [1]. A method to investigate the Coulomb barriers is the production of negative charge states with precise electron energies. To do so, one needs a field-free environment, which allows the interaction with electrons and simultaneously the storage of clusters.

For this purpose a multipole trap was built at Greifswald, a so-called ring electrode trap [2]. A magnetron sputter source [3] is used to produce singly-charged anionic metal clusters, which are guided into the trap. The clusters will be brought to higher charge states by electron attachment in the almost field-free center region of the ring-electrode trap. The reaction products will be investigated by time-of-flight spectroscopy. In the future, the experiment will provide higher charge states for laser interaction experiments, such as photoelectron spectroscopy. The contribution will discuss the principle and design of the ring electrode trap and present first characterization measurements.

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PI-21
Lifetimes of the hyperfine states in H-like and Li-like Bismuth

V. Hannen[1], Z. Andelkovic[2], A. Dax[3], W. Geithner[2], Ch. Geppert[4], Ch. Gorges[4], M. Hammen[5], S. Kaufmann[4], K. König[4], Y. Litvinov[2], M. Lochmann[4], B. Maaß[4], J. Meisner[6], T. Murböck[4], W. Nörtershäuser[4], R.M. Sánchez[2], M. Schmidt[6], S. Schmidt[4,7], M. Steck[2], Th. Stöhlker[2,8], R. Thompson[9], J. Ullmann[4,8], J. Vollbrecht[1] and Ch. Weinheimer[1]

[1] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, Germany
[3] Paul Scherrer Institut, Villingen, Switzerland
[4] Institut für Kernphysik, Technische Universität Darmstadt, Germany
[5] Helmholtz Institut Mainz, Germany
[6] PTB Braunschweig, Elektrische Energiemesstechnik, Braunschweig, Germany
[7] Institut für Kernchemie, Johannes Gutenberg Universität Mainz, Germany
[8] Helmholtz Institut Jena, Germany
[9] Department of Physics, Imperial College London, United Kingdom

E-mail: hannen@uni-muenster.de

An experimental comparison between hyperfine transitions in H- and Li-like heavy ions of the same isotope permits precise tests of QED in extremely strong electromagnetic fields [1]. A suitable candidate for such an experiment is ^{209}Bi, where both transitions are accessible to laser spectroscopy. While the transition energy of $^{209}Bi^{82+}$ has been determined already in 1994 [2], the transition in $^{209}Bi^{80+}$ was not observed until recently [3]. The experiment was performed at the Experimental Storage Ring (ESR) at the Helmholtz-Center for heavy ion research (GSI). Here Li-like bismuth ions were stored at relativistic energies and the HFS transition was excited by means of collinear laser spectroscopy. To collect the forward emitted fluorescence photons a movable parabolic mirror was placed around the ion beam. With this setup we were able for the first time to perform a laser spectroscopy determination of the 2s hyperfine splitting of Li-like $^{209}Bi^{80+}$. Besides the Li-like state also the HFS splitting in H-like $^{209}Bi^{82+}$ was remeasured. While the detection of the resonances was successful, the accuracy of the determination of the transition energies in the ions rest frame in the 2011 experiment suffered from uncertainties in the velocity determination of the ions on the 10^{-3} level. To resolve this problem, a 2nd beam time was performed in 2014 with special emphasis on the voltage calibration of the electron cooler of the ESR. Besides the transition energy, the experiments also allowed to determine the lifetimes of the excited states. Preliminary results on the experimentally determined lifetimes of the HFS states in H-like and Li-like Bismuth will be presented in this contribution.

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PI-22
Towards Precision Spectroscopy of Argon XIV in the SpecTrap Penning Trap

T. Murböck[1], S. Schmidt[2,3], Z. Andelkovic[4], G. Birkl[1], V. Hannen[5], K. König[2], A. Martin[1], W. Nörtershäuser[2], J. Ullmann[2,6], M. Vogel[4], J. Vollbrecht[5], R. Sanchez[4], D.M. Segal[7] and R.C. Thompson[7]

[1] Institut für Angewandte Physik, Technische Universität Darmstadt, Germany
[2]Institut für Kernphysik, Technische Universität Darmstadt, Germany
[3] Institut für Kernchemie, Johannes Gutenberg-Universität Mainz, Germany
[4] GSI Helmholtzzentrum für Schwerionenforschung, Germany
[5] Institut für Angewandte Physik, Westfälische Wilhelms Universität, Germany
[6] Helmholtz-Institut Jena, Germay
[7] Department of Physics, Imperial College London, United Kingdom

E-mail: t.murboeck@gsi.de

In few-electron ions, the strong electric and magnetic fields in the vicinity of the ionic nucleus significantly influence the remaining electronic system with respect to the neutral species. By means of laser spectroscopy, the transition energies and lifetimes of fine structure and hyperfine structure transitions in Highly Charged Ions (HCI) can be determined with an accuracy that reveals the contributions of bound-state quantum electrodynamics in strong fields.
We present the SpecTrap experiment [1] located at the HITRAP facility at GSI and the associated low-energy beamline, which is currently being operated with an electron beam ion source to produce mid-Z HCI such as Ar^{13+} and a second ion source for singly charged magnesium. Laser cooling on Mg+ ions to the mK regime and other functionalities of the trap have already been demonstrated. By use of resistive and sympathetic cooling with Mg+, the HCI can be cooled to cryogenic temperatures to prolong the storage time of the HCI and reduce Doppler broadening to some 10 MHz.
Here, we discuss the scientific outline, the experimental apparatus and first results of the detection and manipulation of HCI inside the Penning trap.

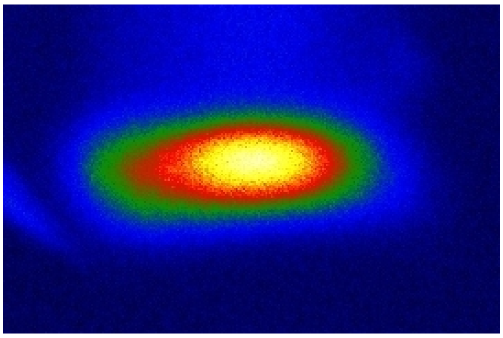

Figure 1. A cloud of laser cooled Mg+ ions.

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PI-23
Spectroscopy of the $^2S_{1/2}$-$^2D_{3/2}$ transition in single $^{171}Yb^+$ towards search for temporal variation of the fine structure constant

Y. Imai, K. Sugiyama, S. Higashitani and M. Kitano

Graduate School of Electronic Science and Engineering, Kyoto University, Kyoto 615-8510, Japan

E-mail: imai@giga.kuee.kyoto-u.ac.jp

Frequency comparison between two optical clocks which are referenced to different transitions enables us to explore a temporal variation of the fine structure constant α. A provisional constraint on it is estimated to be $(1.6\pm2.3)\times10^{-17}$/yr from the frequency ratio measurement between $^{27}Al^+$ and $^{199}Hg^+$ optical clocks [1].

Yb^+ has three clock transitions: $^2S_{1/2}$-$^2D_{3/2}$, $^2S_{1/2}$-$^2D_{5/2}$ and $^2S_{1/2}$-$^2F_{7/2}$ [2,3,4]. Comparison between the $^2S_{1/2}$-$^2F_{7/2}$ and the $^2S_{1/2}$-$^2D_{3/2}$ (or $^2D_{5/2}$) transitions has a large sensitivity [5]. Comparison between the $^2S_{1/2}$-$^2D_{3/2}$ and the $^2S_{1/2}$-$^2D_{5/2}$ transitions cancels the sensitivity, and is used for explorations of other effects which cause temporal variations. We can measure the frequency ratios by using the same ions in one trap. This eliminates common-mode frequency shifts such as gravitational shifts, and enables us to evaluate the uncertainties more closely. We so far detected a spectrum of the $^2S_{1/2}$-$^2D_{5/2}$ transition in single $^{174}Yb^+$ of a width of 5 kHz, and observed driving of the $^2S_{1/2}$-$^2D_{3/2}$ transition in single $^{171}Yb^+$ [6]. We present improvement in single-ion spectroscopy of the $^2S_{1/2}$-$^2D_{3/2}$ transition.

$^{171}Yb^+$ is laser-cooled by a cycle of the $^2S_{1/2}(F=1)$-$^2P_{1/2}(F=0)$ main cooling and $^2D_{3/2}(F=1)$-$^3[3/2]_{1/2}(F=0)$ main repumping transitions at 370 nm and 935 nm respectively. In order to avoid optical pumping, we need to drive the $^2S_{1/2}(F=0)$-$^2P_{1/2}(F=1)$ sub cooling and the $^2D_{3/2}(F=2)$-$^3[3/2]_{1/2}(F=1)$ sub repumping transitions. Main cooling radiation is generated by sum-frequency mixing of radiation from two ECLDs [7]. The lasers for sub cooling, and main- and sub-repumping are ECLDs. The laser for the $^2S_{1/2}$-$^2D_{3/2}$ clock transition is linenarrowed to the resonance of the same high-finesse cavity used for the laser for the $^2S_{1/2}$-$^2D_{5/2}$ clock transition. This is aimed at cancellation of common-mode frequency fluctuation caused by the cavity in the frequency ratio measurement.

In order to detect the $^2S_{1/2}(F=0)$-$^2D_{3/2}(F=2)$ clock transition, we initialize a single $^{171}Yb^+$ to the $^2S_{1/2}(F=0)$ state. Figure 1 shows the pumping rate to the $^2S_{1/2}(F=0)$ state after we block the laser for driving of the sub cooling transition. We set 10 ms for the initialization. Figure 2 shows a result of the single-ion spectroscopy by frequency sweep of the clock laser by 10-kHz intervals. The motional sidebands are clearly observed.

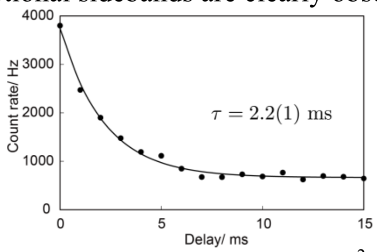

Fig. 1. Measurement of pumping rate to $^2S_{1/2}(F=0)$ state in $^{171}Yb^+$

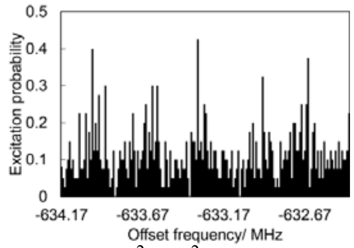

Fig. 2. Spectrum of $^2S_{1/2}$-$^2D_{3/2}$ clock transition in single $^{171}Yb^+$

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PI-24
Accumulation of single isotope ions into ion trap from ICPMS for isotope analysis

S. Hasegawa, **K. Jung, Y. Yamamoto and M. Kitaoka**

School of Engineering, The University of Tokyo, Tokyo 1138656, Japan

E-mail: hasegawa@n.t.u-tokyo.ac.jp

Thanks to the high resolution of lasers to resolve isotope shifts of elements of interest, laser spectroscopy is one of the most powerful tools for isotope analysis [1]. Technique of laser cooling is beneficial for decreasing widths of Doppler broadening to resolve isotope shifts and increasing absorption efficiencies of the isotope of interest. Atom Trap Trace Analysis (ATTA) is using the technique [1]. However, elements to which the laser cooling of neutral atoms is applicable are basically limited to alkaline elements and noble gases because of cooling efficiencies.
We proposed to apply ion trap and laser cooling techniques to isotope analysis because they can laser cool alkaline earth elements and controlling ions of interest can be performed by electromagnetic fields [2]. The controllability of ions enables one to use additional apparatuses to enhance isotope selectivity. We have developed the apparatus of an ion trap combined with an inductively coupled plasma mass spectrometer (ICPMS) as ion source [3, 4]. ICPMS, itself, has a quadrupole mass filter but a mass spectrometer using electromagnetic fields cannot distinguish isobars. Laser cooling spectroscopy serves as detector which can avoid the isobaric interferences. Calibration curves of isotope ratios were obtained through rate equation models [4]. However, buffer gas to enhance trap efficiencies thermalizes laser cooled trapped ions. We successfully observed accumulation of single isotope ions without buffer gas injected from an ICPMS. We will report the present status of the experiments.

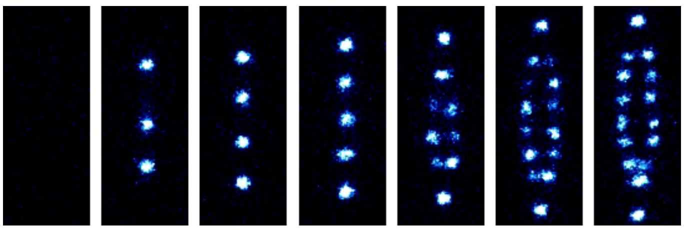

Figure 1. Accumulation of single isotope ions into a trap from ICPMS

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PI-25
Testing time-reversal symmetry using trapped molecular ions

K.C. Cossel, W. Cairncross, M. Grau, D.N. Gresh, Y. Ni, J. Ye, and E.A. Cornell

JILA, National Institute of Standards and Technology and University of Colorado, and Department of Physics University of Colorado, 440 UCB, Boulder, CO 80309, USA

E-mail: cossel@jilau1.colorado.edu

Molecular ions have several advantages over neutral molecules for high-resolution spectroscopy. In particular, they can be easily trapped and thus enable long interrogation times. While single ions have been used in several experiments, higher signal-to-noise is possible using many ions, as long as the coherence time is still long. Here we demonstrate precision spectroscopy using many trapped HfF^+ for a stringent test of time-reversal symmetry by measuring the permanent electric dipole moment of the electron (eEDM) [1]. In this experiment (Fig. 1a), we perform Ramsey spectroscopy (Fig. 1b) between spin states in the metastable $^3\Delta_1$ level with a coherence time of up to 400 ms (Fig 1c). The Fourier-limited linewidth of 300 mHz is – to our knowledge – the narrowest line observed in a molecular system. We discuss various aspects of the experiment including metastable state preparation, state detection, and application of rotating electric and magnetic bias fields. In addition, we discuss limits to the coherence time due to ion-ion collisions and field inhomogeneity. Finally, we demonstrate a preliminary eEDM measurement of -1.5 ± 3.0 x 10^{-27} *e* cm.

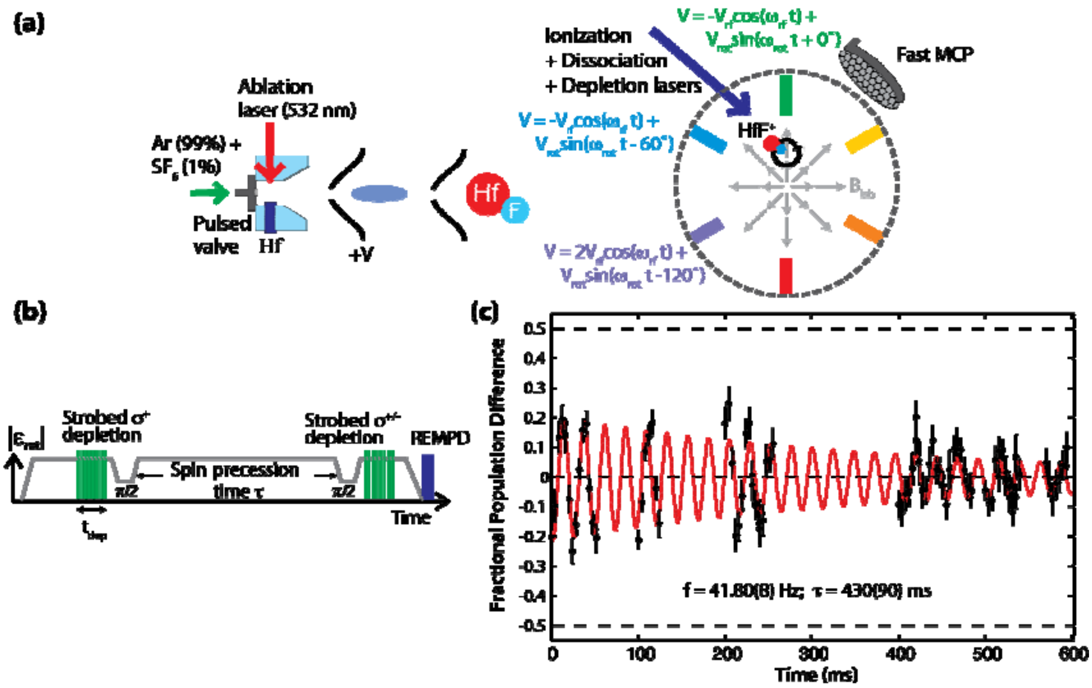

Figure 1

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PI-26
Diode-laser-based system for $^9Be^+$ cooling and manipulation at 313 nm

F.M.J. Cozijn[1], **G. Blume**[2], **K. Paschke**[2] **and J.C.J. Koelemeij**[1]

[1] LaserLaB, Department of Physics and Astronomy, VU University Amsterdam
[2] Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin

E-mail: f.m.j.cozijn@vu.nl

Laser-cooled $^9Be^+$ ions have been the workhorse in many experiments for quantum information processing and sympathetic cooling of light ionic species. Yet, simple and cost-effective laser systems for manipulation of $^9Be^+$ at 313 nm have so far been lacking. We present a diode-based 626 nm laser system, which is frequency doubled to 313 nm. A narrowband (sub-MHz) 626 nm DBR diode laser is used to slave a second diode through injection locking. In order to tune the band gap of the second diode downwards to 626 nm, we cool it to -32 °C inside a hermitically sealed enclosure. The DBR diode offers good insensitivity to mechanical vibrations and ease of operation. The system produces up to 200 mW of 626 nm light while preserving the spectral purity of the master diode. Using second harmonic generation in BBO inside an external enhancement cavity, over 1 mW of 313 nm is obtained, sufficient for cooling of $^9Be^+$.

PI-27
Quantum mechanical calculation of the C^+ ion mobility in a cooled He gas at 4.3 K

L. Aissaoui

Physics Department - Badji Mokhtar University

CANCELLED

PI-28
Non-destructive State Detection and Identification of Molecular Ions

A. Gardner, **W. Groom and M. Keller**

ITCM Group, Department of Physics and Astronomy, University of Sussex, Falmer, BN1 9QH, UK

E-mail: Amy.Gardner@sussex.ac.uk

The nature of ion traps allow for extremely well localised atomic and sympathetically cooled molecular species; leading to a variety of applications - most notably cold chemistry, testing fundamental theories [1,2,3], searching for changes in fundamental constants [4,5] and, potentially, the development of methods for quantum computing [6]. Prerequisite for these applications is also the cooling of the molecule's motion and its non-invasive identification. Furthermore, the internal quantum state of the molecule needs to be prepared and, at readout, non-destructively detected.
While blackbody assisted laser cooling was recently demonstrated [7,8], the non-destructive state detection of trapped molecules is still beyond current experiments. Employing state selective laser induced dipole forces we aim to detect the internal state of molecular ions by mapping the state information onto the ions' motion.
We can also identify different ionic species within a coulomb crystal by measuring the average charge-to-mass ratio of trapped ions with high precision [9]. This is a tool that can be used to investigate chemical reactions between neutral molecules/atoms and trapped molecular ions. The same means can also be achieved by using only laser forces [10].

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PI-29
Cold molecular ions in a surface-electrode trap

A. Mokhberi and **S. Willitsch**

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

E-mail: arezoo.mokhberi@unibas.ch

We present the sympathetic cooling and Coulomb crystallization of molecular ions [1] above the surface of an ion-trap chip. N_2^+ and CaH^+ ions were confined in a surface-electrode radio-frequency ion trap [2-4] and cooled by the interaction with laser-cooled Ca^+ ions to secular translational temperatures in the millikelvin range. The configuration of trapping potentials generated by the surface electrodes enabled the formation of planar bicomponent Coulomb crystals [5] and the spatial separation of the molecular from the atomic ions on the chip. The structural and thermal properties of the Coulomb crystals were characterized using molecular dynamics simulations [6]. The present study extends chip-based trapping techniques to cold molecular ions with potential applications in mass spectrometry, chemistry, quantum information science, and spectroscopy [7-10].

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PI-30
Detection-enhanced steady state entanglement with ions

<u>C.D.B. Bentley</u>[1], A.R.R. Carvalho[1,2], D. Kielpinski[3] and J.J. Hope[1]

[1] Department of Quantum Science, Research School of Physics and Engineering, Australian National University, Canberra, Australia
[2] ARC Centre for Quantum Computation and Communication Technology, The Australian National University, Canberra, Australia
[3] Centre for Quantum Dynamics, Griffith University, Brisbane, Australia

E-mail: christopher.bentley@anu.edu.au

Typically, decoherence drives a quantum system towards states with no traces of quantum behaviour. However, by combining decoherent dynamics with suitably chosen Hamiltonian evolution, the system can be steered to the desired steady states.
The steady-state fidelities achieved in recent trapped ion experiments [1,2] are far below the high fidelities achieved with more traditional time-dependent entangling gates [3] and still much lower than the fidelities required for a quantum information processing (QIP) system [3].
We propose a two ion steady-state scheme with fidelity above 0.99 [4]. Driven dissipation continuously pumps the system towards an asymmetric Bell steady-state, which is dark to the system dynamics. The dominant loss mechanism is anomalous heating of the motional modes, reducing our fidelity by less than 0.01 for current experimental rates. Our scheme jointly addresses the ions and does not use sympathetic cooling. We enhance our scheme by combining the dissipative state preparation with the detection of photons, and obtain a significant fidelity enhancement.

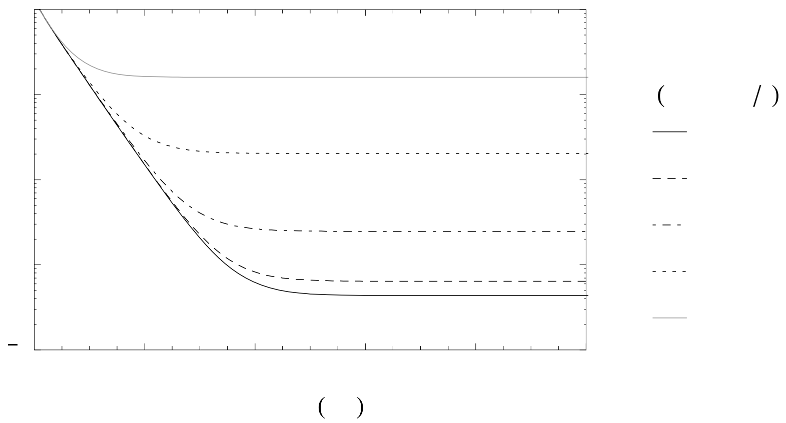

Figure 1 shows our scheme's asymptotic error (infidelity) with respect to the target Bell antisymmetric state, with anomalous heating h_r. The plot is before detection gains.

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PI-31
Experimental studies of interaction of negative ions with molecular hydrogen and deuterium at interstellar-relevant temperatures

D.Mulin[1], **Š. Roučka[1], P. Jusko[1], S. Rednyk[1], R. Plašil[1], D. Gerlich[1,2], and J. Glosík[1]**

[1] Department of Surface and Plasma Science, Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, 182 00, Prague, Czech Republic
[2] Department of Physics, Technische Universität Chemnitz, D-09107 Chemnitz, Germany

E-mail: dimamulin@gmail.com

We present a study of two anion-hydrogen reaction complexes and their deuterated variants at low temperatures. Measurements of reaction rate coefficients were conducted in a 22-pole ion trap apparatus, described in [1]. The first experiment is the study of H_2O formation in associative detachment reaction of O^- with H_2. The rate coefficients of reaction channels

$$O^- + H_2 \rightarrow H_2O + e^- \quad (1)$$
$$O^- + H_2 \rightarrow OH^- + H \quad (2)$$

are reported in the range of temperatures from 10 K to 250 K. The isotope effect in reaction with D_2 was observed.The other experiment consisted in the study of isotope exchange reactions

$$OH^- + D_2 \rightarrow OD^- + HD, \quad (3)$$
$$OD^- + H_2 \rightarrow OH^- + HD. \quad (4)$$

Reaction (3) is reported to be exothermic, whereas (4) is endothermic. However, the uncertainties of the enthalpies are large and the reported results vary [2], [3]. Our study indicates that reaction (3) is hindered by rotational excitation of D_2, because the measured reaction rate coefficient is proportional to the population of D_2 in rotational ground state ($J = 0$). We measured the enthalpy of the endothermic reaction (4) as ΔH = 8 meV. Taking into account that we used normal hydrogen, where 75% of molecules were rotationally excited ($J \geq 1$), the approximate endothermicity of the reaction (4) between ground state reactants is 23 meV, which is close to the value given in [2].

We thank the Chemnitz University of Technology and the DFG for lending the AB-22PT instruments to the Charles University. The work was partly supported by GACR (205/09/1183, P209/12/0233), by SV 267 302, by GAUK 388811, GAUK 406011, GAUK 659112.

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PI-32
Ion trap setup for core-level photoelectron spectroscopy of metal clusters at FLASH

F. Martinez, **P. Oelßner, M. Köther, J. Tiggesbäumker and K.H. Meiwes-Broer**

Institut für Physik, Universität Rostock

E-mail: franklin.martinez@uni-rostock.de

XUV radiation of high brilliance from the free electron laser facility FLASH (Hamburg) allows to access electronic core levels of free metallic clusters by photo-electron spectroscopy (PES). Recent experiments on lead cluster anions revealed a systematic shift of 5d and of 4f level energies as a function of cluster size [1,2]. For small clusters, a variation of the electron binding energy from the metallic sphere model is observed. It results from a reduced screening of the core-hole by the electrons, thus indicating a transition from a metallic to a non-metallic binding character in the cluster [2]. Moreover, a considerable contribution of low-energetic electrons in the PE-spectrum is due to electronic relaxation processes of the residual, highly excited cluster.
With increasing photon energies, but also with decreasing cluster size, the photoionization cross sections decrease rapidly, thus limiting the photo-electron yield. To increase the target density of size-selected clusters, and hence the electron yield, a new apparatus with a cryogenic, linear radiofrequency ion trap is currently being constructed (Fig.1). Additionally, such an ultra cold environment will prepare target clusters, which are close to their electronic and geometric ground states. With this setup many-electron dynamics due to x-ray photon absorption and highly-correlated phenomena on ultrashort timescales in clusters will be addressed in future experiments.
In this contribution, recent results on correlation effects in the photoemission of core-excited, mass selected metal clusters will be discussed, and the new ion trap setup will be introduced. The work is funded by the bmbf, and supported by the DFG (SFB 652).

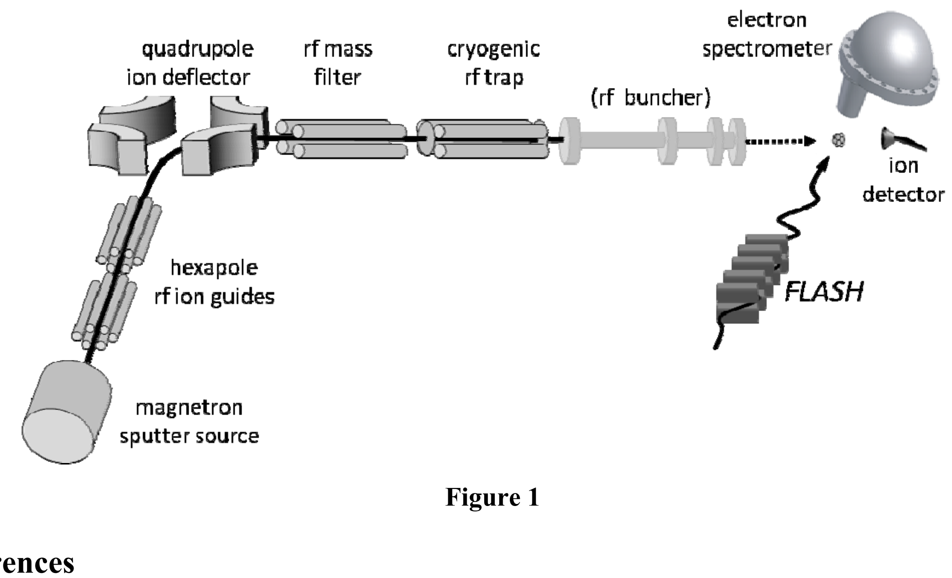

Figure 1

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PI-33
Preparation of cold ions and its application to gas-phase NMR spectroscopy

K. Fuke[1,2] and Y. Oshima[1]

[1] Institute for Molecular Science, Myodaiji, Okazaki, Japan.
[2] Graduate School of Science, Kobe University, Rokkodai, Kobe, Japan

E-mail: fuke@ims.ac.jp.

Recently, ultracold molecular ions attract much attention in physics and chemistry, because they allow precision measurements of molecular transitions, and also the study of cold chemistry such as the reactive collisions in the quantum regime and the formation of interstellar clouds. For these reasons, the preparation of ultracold molecular ions are the subject of intensive studies. In the present study, we are developing the methods to prepare and control cold molecular ions in a strong magnetic field and apply it to nuclear magnetic resonance (NMR) detection for mass-selected ions. NMR technique is a powerful tool to study the physical and chemical properties of materials in wide area. However, this technique is limited for the materials in condensed phase. Although this technique is also highly expected to use for mass selected gas-phase ions in both fundamental and applied sciences, the method to extend to the gas-phase ions is not reported yet. Recently, we presented a principle of the NMR detection for the gas phase ions based on a Stern-Gerlach experiment in a Penning-type trap and described the apparatus, which we are developing.[1] Here, we discuss the experimental techniques and the results on the formation and manipulate of cold ions with a kinetic energy of less than 5 meV, which are prepared through bunching and slicing of the ions generated by the photoionization of supersonically cooled molecules. We also discuss the subjects on the NMR detection for cold mass-selected ions.

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PI-34
A new measurement of the electron mass

J. Hou[1], **F. Köhler**[1,2], **S. Sturm**[1], **A. Wagner**[1], **G. Werth**[3], **W. Quint**[2] **and K. Blaum**[1]

[1]Max-Planck-Institut für Kernphysik, D-69117, Heidelberg
[2]GSI Helmholtzzentrum für Schwerionenforschung, D-64291, Darmstadt
[3]Johannes Gutenberg-Universität, D-55122, Mainz

E-mail: jiamin.hou@mpi-hd.mpg.de

Being one of the elementary particles in the Standard Model of physics, the atomic mass of the electron is closely linked to other fundamental constants, such as Rydberg constant and fine structure constant. A high-precision value of the electron mass is fundamental for the structure of matter on atomic and molecular scales and is also an important ingredient for the most stringent tests of quantum electrodynamics (QED) [1,2,3].

Here an indirect method similar to [4,5] is applied to determine the atomic mass of the electron, based on a determination of the electron's magnetic moment and consequently the spin-precession frequency. In our experiment, a single hydrogen-like carbon ion is trapped for several months in a Penning-trap apparatus, with magnetic field of 3.76 T at a cryogenic temperature of 4K and an ultra-low pressure of $p \leq 10^{-16}$ mbar.

The electron mass is extracted from the ratio of the electron spin-precession frequency and the ion's cyclotron frequency. The spin-precession frequency is determined using the continuous Stern-Gerlach effect in a quantum non-demolition manner, while the ion's cyclotron frequency is measured with a phase-sensitive detection technique, PnA (Pulse and Amplify [6]), which allows to determine the cyclotron frequency to an extremely high accuracy.

Combining a state-of-the-art QED calculation and our experimental result, we have derived the electron mass with a relative uncertainty of $3 \cdot 10^{-11}$ [7], with an improvement by a factor of 13 with respect to the previous CODATA value [8].

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PI-35
Generation of vacuum ultraviolet radiation for quantum state detection of single trapped ions

K. Wakui[1], T. Ido[1,2] and K. Hayasaka[1]

[1] National Institute of Information and Communications Technology, 4-2-1 Nukui-kitamachi, Koganei, Tokyo 184-8795, Japan
[2] PRESTO, Japan Science and Technology Agency, Honcho, Saitama, 223-0012, Japan

E-mail: hayasaka@nict.go.jp

Optical clocks based on trapped ions with two outer electrons supply frequency accuracy in the order of 10^{-18} level. Difficulty of the present implementation with quantum logic spectroscopy might be overcome if vacuum ultraviolet (VUV) radiation is available for detecting the ions by direct excitation of their electronic transitions in the VUV region. This alternative quantum state detection method might lead to a new ion clock with enhanced stability based on simultaneous detection of multiple ions.
We report generation of VUV radiation at around 159 nm toward the goal by intracavity high-harmonic generation (HHG). We assume In^+ as our initial target, but the same technique might be applicable to Al^+ probe transition at 167 nm. The radiation is generated as the fifth harmonic of a femtosecond Ti:S oscillator in a xenon gas jet placed at the beam waist of a passive femtosecond enhancement cavity. A fluoride-multilayer-coated output-coupler was designed for this wavelength, and we experimentally confirmed its reflectance in the VUV region. Using this coupler, an average power reaching 6.4 μW at around 159 nm is coupled out from a modest fundamental power of 650 mW. Although continuous generation is limited by unexpected decay of the fifth harmonic associated with non-permanent loss of the coupler at the fundamental wavelength, radiation more than 4 μW is generated over a few hundred seconds by adjusting the coupler position as shown in Fig.1.
Under a realistic experimental condition hundreds of fluorescence photons per second will be detectable by resonant excitation of a single In^+ with a single component out of the 1.9×10^5 VUV-comb teeth. When the decay problem is properly addressed, our method would supply an alternative detection method of ion clocks.

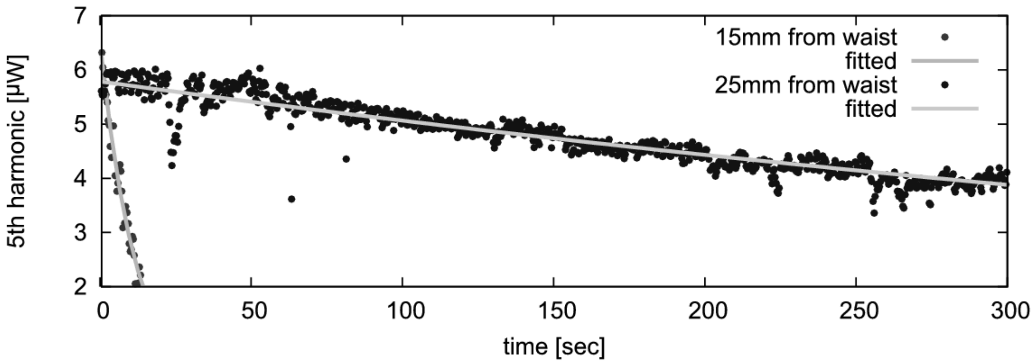

Figure 1. Time evolution of the generated 159 nm radiation

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PI-36
Interaction of D^- with H atoms in a cryogenic 22-pole trap

Š. Roučka, **D. Mulin, P. Jusko, R. Plašil, D. Gerlich and J. Glosík**

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

E-mail: stepan.roucka@mff.cuni.cz

We studied the reaction of D^- ions with atomic hydrogen using the AB-22PT instrument, a combination of an H atom beam with a 22-pole trap. Collisions without isotopic labeling, H^- + H, have been studied recently with the same experimental setup [1]. In the presented experiment, the D- ions were stored in the variable-temperature 22-pole trap. For interaction with the ions, a beam of atomic hydrogen with variable temperature was passing through the ion cloud. It was inferred from our measurements that the product channels are H^- + D as well HD + e^-. The branching ratios and the relative reaction rate coefficients have been measured at temperatures down to 10 K. Chemical probing with CO_2^+ was used to obtain the effective number density of H atoms inside the trap. This allows us to obtain absolute rate coefficients for both reaction channels. The preliminary results are in a good agreement with a recently published theory [2] and will be presented on a poster.

Acknowledgments: We thank the Technische Universität Chemnitz and the DFG for lending the AB-22PT instruments to the Charles University. This work was partly supported by the Czech Grant Agency (GACR 14-14715P, GACR P209/12/0233) and by the Charles University (UNCE 204020/2012, GAUK 659112).

PI-37
Weak dipolar interactions in trapped ion chains

S. Kotler[1,2], N. Akerman[1,3,] N.Navon[1,4], Y. Glickman[1], Z. Meir[1], O. Schwartz[1], E. Shahmoon[1,3], D. Oron[1] and R. Ozeri[1]

[1] Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100 Israel
[2] Physical Measurement Laboratory, NIST, Boulder, Colorado 80305, USA
[3] Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100 Israel
[3] Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB30HE UK

E-mail: ozeri@weizmann.ac.il

In two recent experiments the weak magnetic and electric dipolar interactions, between laser-cooled ions at micrometer separation, were measured. In the first experiment, the magnetic spin-spin interaction between two trapped ions was observed to lead to the entanglement of their collective spin state. The measurement of this ultra-weak (mHz) interaction strength was made possible by restricting their spin evolution to a decoherence-free subspace [1]. In a second experiment, resonant electric dipole-dipole interactions were measured during photon scattering on an allowed optical dipole transition in chains of up to eight ions. The resonance frequency of the transition was shown to slightly (10’ of kHz) shift whenever the separation between ions equaled an integer number of photon wavelength in what is known as a collective Lamb shift. This shift is due to emission and re-absorption of virtual photons between different ions in the chain, and is closely related to superradiance.

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PI-38
Full quantum state control of cold trapped molecular anions

D. Hauser, S.L. Lee, F. Carelli, S. Spieler, O. Lakhmanskaya, E.S. Endres, S.S. Kumar, F. Gianturco and R. Wester

Institut für Ionenphysik und Angewandte Physik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria.

E-mail: daniel.hauser@uibk.ac.at

Cold and ultracold molecules have become important for a number of applications ranging from fundamental precision measurements [1], quantum-controlled chemistry [2], quantum information processing [3], to understanding the cold interstellar medium [4]. Sympathetic collisions with cold atoms and/or atomic ions are widely used to prepare translationally cold molecules and molecular ions. Inelastic collisions with neutral atoms have proven to be a general approach to cool internal degrees of freedom [5]. Here we present a new scheme to measure the absolute quantum scattering rate coefficients (Fig. 1) for the rotationally inelastic collision of hydroxyl anions and their deuterium-containing counterparts upon interaction with helium in a multipole radio-frequency ion trap under full quantum state control. The measured rates and the ab initio quantum scattering calculations agree very well with each other. With the methods developed, improved quantum state-preparation of molecular ions for precision spectroscopy or quantum information research is achieved.

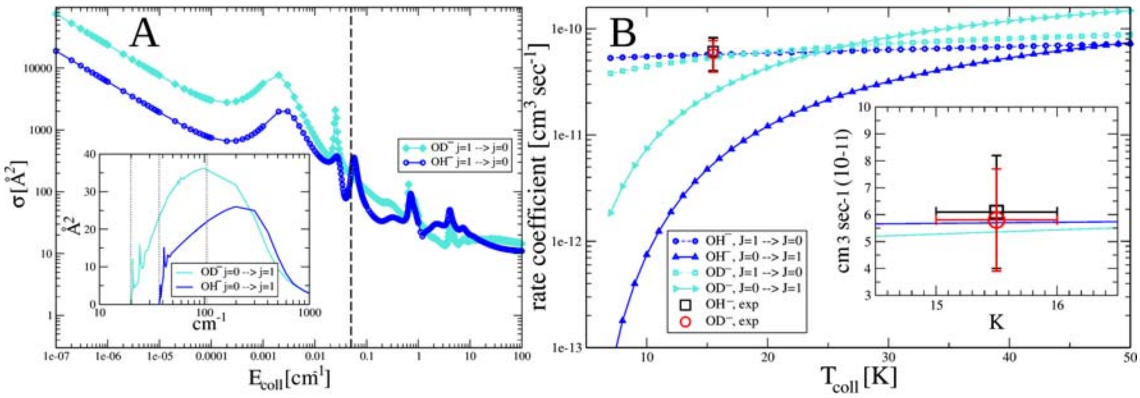

Figure 1: (**A**) Calculated absolute cross sections. (**B**) Measured and calculated rate coefficients.

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PI-39
Realizing a hybrid atom-ion trap for Li and Yb^+

H. Fürst, J. Joger, N. Ewald and R. Gerritsma

Johannes Gutenberg-Universität Mainz, Germany

E-mail: fuersth@uni-mainz.de

Mixtures of ultracold atoms and trapped ions are interesting for studying cold chemistry, ultra-cold collisions and quantum many-body physics [1]. Recent analysis has shown that the time-dependent trapping field of the Paul trap can cause heating in hybrid atom-ion systems. One proposed way to mitigate this problem is to employ ion-atom combinations with a large mass ratio [2]. The highest convenient mass ratio - for species that still allow for straightforward laser cooling - is ~29, and is achieved by using the combination Yb+ and Li. According to the classical analysis of [2] a reduction in heating of almost 2 orders of magnitude can be achieved as compared to the combination Yb+/Rb. Combining ultracold Li atoms with trapped ions poses particular technical challenges such as the necessity of very high magnetic fields close to the ions to reach the required Feshbach resonances. Also the application of different sub-Doppler cooling techniques for Li such as gray molasses [3,4] is of particular importance to produce a dense gas in the deep quantum regime. We present the design of a hybrid atom-ion experiment for Yb+ and Li that we are currently building up. We discuss the magnetic field coils, ion trap and dipole trap, as well as the Zeeman slower and atomic loading platform. We also introduce a two-ion-atom detector we plan to implement in the experiment. Here, a pair of ions is used to detect atoms or atom-ion interactions by making use of non-classical states [5].

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PI-40
Simulation of the motional and rotational dynamics of a trapped molecular ion

A. Hashemloo and C.M. Dion

Department of physics, Umeå university, SE-90187 Umeå, Sweden

E-mail: Avazeh.hashemloo@physics.umu.se

We develop a model for a single diatomic molecular ion, trapped in a radio-frequency electric field, taking into account all internal and external degrees of freedom. We study the translational and rotational motion of this singly trapped ion and also the effect of the time-dependent trapping field on these motions via the interaction of its dipole moment with the electric field. In order to study this effect we carry out full classical simulation. We also study the mere rotation of the ion under the influence of the trapping field in order to investigate the evolution of the rotational eigenstates by approaching the problem semi-classically. We focus in particular on linear Paul traps, which are devices that enable confining of ions along an axis due to their elongated configuration and consequently provide a suitable environment for laser control experiments and, by trapping many ions, study quantum information processing and quantum computing.

PI-41
State transformations and nonlinear effects in two-mode toroidal BEC

M. Kolář[1], **T. Opatrný and K.K. Das**[2,3]
[1] Department of Optics, Palacký University, 771 46 Olomouc, Czech Republic
[2] Department of Physical Sciences, Kutztown University of Pennsylvania, Pennsylvania 19530, USA
[3] Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, CA 93106

E-mail: kolar@optics.upol.cz

Recent advances in cold atoms trapping allow for creating a multiply connected (toroidal) Bose-Einstein condensate (BEC) by means of all-optical dipole traps. These traps can be created, e.g., by perpendicular crossing of two laser beams, one of these being a Laguerre-Gaussian (LG) [1] beam. Such a trap provides a quasi 1D (circular) smooth enough potential allowing for excitation of the atomic superfluid persistent (long-lived) current [2] similar to the motion of the superfluid He in a container [3]. This superfluid (circulating) state represents a macroscopically populated state of atomic motion where all atoms possess the same well defined value of the orbital angular momentum (OAM). The stability of circulation is usually tested by means of rotating the single-peaked potential barrier along the circle, creating an atomic gas SQUID analog with the weak-link junction [3].
We propose to use optical potential created by two counter-propagating LG beams with opposite winding numbers. These beams create a periodic potential closed around the circle instead of the single peaked potential of [2]. This optical lattice acts as a circular Bragg grating for atomic superfluid states. When the amplitude of the lattice is low compared to the kinetic energy per atom and the Bragg (resonance) condition is fulfilled the lattice couples states with the same magnitude but opposite sign of the OAM, hence restricting the evolution to the two dimensional Hilbert space. An analog of double well/spin half BEC [4] is created this way.
Using this model, we compare results of the mean-field approximation (Gross-Pitaevskii equation) with the full-quantum dynamics. These two approaches show remarkable differences for parameters corresponding to the transition from oscillatory to the self-trapped regime [4], following from strong correlations between the atoms in the respective modes.

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PI-42
Observation of Rydberg excitation of trapped $^{40}Ca^+$ Ions

T.Feldker[1], **M. Stappel[1,2]**, **P. Bachor[1,2]**, **J. Walz[1,2]** and **F. Schmidt-Kaler[1]**

[1] QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, D-55128 Mainz, Germany
[2] Helmholtz-Institut Mainz, D-55099, Germany

E-mail: Feldker@uni-mainz.de

Lasercooled ions in Paul traps are a promising candidate for quantum information applications. While excellent control over small samples of qubits and the execution of simple quantum algorithms has been demonstrated, the scaling to large numbers of qubit remains a major challenge. The use of highly excited electronic states has the potential to increase drastically the number of qubits available for quantum information processing. In such a system, the entanglement can either be created directly by dipole-dipole interaction between ions in Rydberg states [1] or by using localized vibrational modes in a Coulomb crystal, created by utilizing the high polarizability of ions in Rydberg states, which effectively changes the trapping potential for selected ions [2,3]. We present the first observation of Rydberg excitation of cold, trapped ions. $^{40}Ca^+$ ions where transferred to a Rydberg state with principal quantum number N=54 by means of a single photon excitation at a wavelength of 122 nm. The excitation process starts from the metastable $3D_{3/2}$ ($\tau \approx 1s$) level and is observed by measuring the additional decay of the metastable state due to the fast decay ($\tau \approx 100\mu s$) of the excited Rydberg state to the ground state. We measured the excitation wavelength to be 122.04192 nm and observed qualitatively the influence of the electric trapping field on the Rydberg excitation.

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PI-43
Sympathetic cooling of OH- -ions using Rb atoms in a MOT

P. Weckesser[1], **B. Höltkemeier**[1], **H. López**[1] **and Matthias Weidemüller**[1,2]

[1] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, INF 226, 69120 Heidelberg, Germany
[2] Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China, Hefei, Anhui 230026, PR China

E-mail: weckesser@physi.uni-heidelberg.de

Molecular ions are usually caught in a linear Paul trap and cooled sympathetically by He buffer gas. In order to reach lower temperatures for a wide range of molecular ions we investigate replacing He with laser-cooled atoms. Recent theories indicate that ultracold atom gases homogeneously filling the ion trap limit the cooling criterion by the mass ratio of the coolant and the to be cooled ion.
We derive that a localized cloud of ultracold atoms in higher order radio frequency traps overcomes the mentioned mass ratio limitation. A proper description of this local criterion and its features will be introduced. Furthermore the emergence of universal energy distributions due to the localization will be discussed.
Additionally we report on the status of a new setup employing a hybrid atom-ion trap that allows to sympathetically cool OH − ions by ultacold rubidium. Our setup consists of an octupole rf-trap of thin wires that has a large field-free region while allowing enough optical access to overlay a magneto optical trap inside.

PI-44
The Sr^+-Rb Hybrid Apparatus

Z. Meir, Y. Dallal, T. Sikorsky, and R. Ozeri

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

E-mail: ozeri@weizmann.ac.il

In recent years, the goal of reaching ultra-cold atom-ion collisions at μK temperatures had been pursued by several groups. The study of collisions at the μK range has thus far been impeded by the effect of excess-micro-motion [1] and inherent-micro-motion [2] which set a scale for the atom-ion collision energy.

We constructed a system capable of trapping Sr+ ions and Rb and Sr atoms and cooling both species to their quantum ground state. Atoms and ions are trapped and cooled in separate chambers. Then, the atoms are transported using an optical conveyer belt to overlap the Sr+ ions. Cold Sr atoms will also be used to load the ion trap with Sr+ ions.

In contrast to other experiments where sympathetic cooling is used to cool the ion, we intend to cool the ion to the ground state before immersing it into the atom cloud. In this way we will possibly be able to explore atom-ion collisions in the ultra-cold regime before the ion heats up. We will cool the ion to the ground-state and compensate for micro-motion using a narrow line-width laser on a quadrupole transition.

The study of ultra-cold atom-ion interactions will be performed using precision spectroscopy. To this end we developed spectroscopy tools that enabled hyperfine spectroscopy of Rb with sub Hz resolution [3], Zeeman spectroscopy of Sr+ with mHz resolution [4] and optical spectroscopy of the S→D optical quadrupole transition with below 100 Hz resolution. The above resolution compares favorably with the expected atom-ion interaction strength.

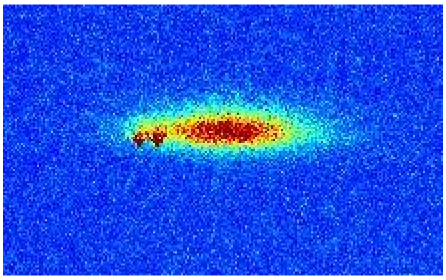

Figure 1. Two Sr+ ions overlapped with an ultra-cold cloud of ^{87}Rb atoms

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POSTER SESSION II

PII-1
Traps and technologies for novel quantum control with trapped ions

J. Alonso[1], F.M. Leupold[1], Z.U. Solèr[1], F. Lindenfelser[1], M. Marinelli[1], D. Bykov[2], P. Uebel[2], M. Schmidt[2], P. Russel[2] and J.P. Home[1]

[1] Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland
[2] Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1, 91058 Erlangen, Germany

E-mail: fleupold@phys.ethz.ch

One of the main challenges in ion-trap quantum information is to scale up quantum control to large numbers of qubits and gates. A key ingredient in several scalable schemes is information transport. One promising method for transporting quantum information stored in the internal states of trapped ions is to transport the ions themselves by dynamically changing the trapping potential [1,2]. The speed of this transport has thus far been limited by the update rates of the potentials applied to the trap electrodes.
In order to overcome these limitations, we have placed single-pole double-throw switches close to the ion trap itself, enabling the trap potentials to be changed on timescales fast compared to the oscillation frequency of the ion [3]. This could allow transport of ions over macroscopic distances within half an oscillation cycle, or the creation of squeezed states of motion using "bang-bang" control. To realize this proposal, we have micro-fabricated a surface-electrode ion trap and placed it in an ultra-high vacuum system cooled to 4K.
In a second line of research we are developing novel ion traps based on gold-filled photonic-crystal-fiber techniques. This allows for pixelation and miniaturization of surface-electrode ion traps. To explore these possibilities, we have fabricated a prototype with 100μm electrode diameter using a partially drawn fiber as the glass former.
The fabrication process is less demanding than that of conventional surface-electrode traps in the sense that it does not require a cleanroom, other than for drawing the fiber. This realizes a trap with a geometry that is advantageous from the perspective of optical access, offering possibilities for combining these traps with optical cavities and tightly focused laser beams.
In both systems, we have recently trapped ions and realized qubit control, laying the ground for further experiments.

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PII-2
Fast transport technologies

<u>L.E. de Clercq</u> and J.P. Home

ETH Zürich, Institute for Quantum Electronics, Trapped Ion Quantum Information

E-mail: ludwigd@phys.ethz.ch

I will present our developed technologies and techniques that will allow us to perform mixed-species ions experiments in a micro fabricated ion trap. The trap is a four-layer design which includes segmented compensation electrodes for controlling stray electric fields throughout the trap array. We have demonstrated simultaneous detection and quantum control of calcium and beryllium ions, and cooled both to the ground state. We are currently investigating various transport routines, using waveforms generated using Tikhonov regularization [1]. We have designed waveforms for multiple operations (e.g. splitting, combining and transport of ions), which allow simultaneous control of multiple controllable potential wells. In order to implement these routines in our trap we have developed a system with an array of 4-channel waveform cards, each of which contain an FPGA with an in-built ARM processor. The system produces 16 channels of analog voltage control with output update rate of 50 MHz for each DAC output. Using the Tikhonov routines and the developed waveform cards we have demonstrated transport of ions through multiple segments of our 15-segment ion trap. Transport times of 50 us over 1.8 mm in the trap have been achieved.

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PII-3
Study of Quantum Motion in a Penning Trap

G. Stutter, J.F. Goodwin, P. Hrmo, J. Liu1, M. Simpson1, D.M. Segal1 and R.C. Thompson

Quantum Optics and Laser Science, Blackett Laboratory, Physics Department, Imperial College London, Prince Consort Road, London SW7 2AZ United Kingdom

E-mail: graham.stutter10@imperial.ac.uk.

In comparison with radio-frequency Paul traps, the use of ions stored in a Penning trap for quantum information applications is relatively rare. However, recent experiments and proposals have shown that study of this platform is a worthwhile avenue of research [1,2]. The main advantage of a Penning trap is the ability to trap and control multi-dimensional crystals without driven rf micromotion [3]. We report optical sideband cooling a single Ca+ ion to the quantum ground state of motion in a Penning trap for the first time [4] as well as measurement of the heating rate of the trap, which we find to be 2.5 ±.3 phonons per second, which is consistent with the large ion-electrode distance.

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PII-4
The CPW Planar Penning Trap

J. Pinder, A. Cridland, J. Lacy and J. Verdú

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

E-mail: J.Pinder@sussex.ac.uk, J.L.Verdu-Galiana@sussex.ac.uk

At Sussex we are developing the CPW-Penning trap, based upon the projection of the well-known cylindrical Penning trap onto the surface of a chip [Figure.1]. The CPW-Penning trap design should enable the detection of a single electron and the accurate measurement of its eigenfrequencies [1,2]. In this poster we present the status of the experimental apparatus, including the mechanism for loading the trap with electrons with UV-light, a description of the low-noise amplifiers used to amplify the electron's signals induced on the trap electrodes and their associated tuned superconducting resonators. These are based upon similar ion detection systems used in [3]. Furthermore, we present details of the first micro fabricated CPW-Penning trap chip currently under construction. We describe our original cryogenic vacuum chamber, featuring a 3D microwave cavity for enhancing the Purcell effect [4]. The compact cryogenic vacuum chamber is self-manufactured in our lab with a CNC machine and its design avoids the use of cryogenic vacuum feedthroughs, while permitting an ultra low rest gas pressure in the trapping volume. Finally, we briefly introduce the magnetic field source currently under construction. It employs shimming wires capable of creating a localised homogeneous field at the position of the electron and it is conceived to be implemented in the trap chip in the near future.

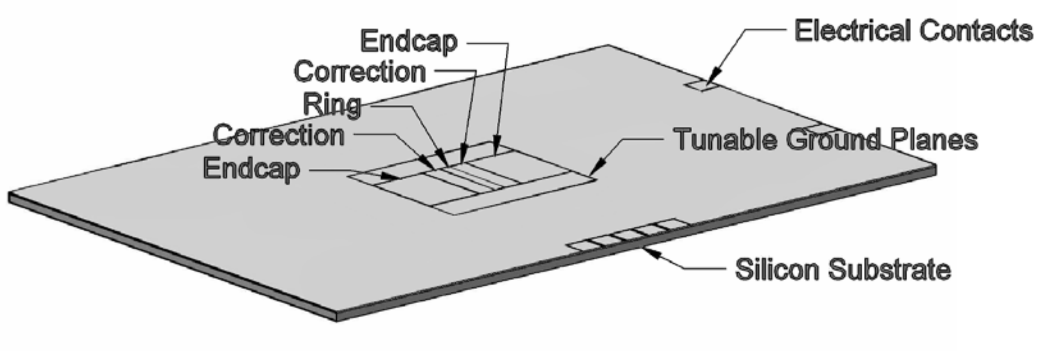

Figure 1. The CPW planar Penning trap

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PII-5
Wiring up charged particles

S. Möller, P. Schindler, D.Gorman, N. Daniilidis and H. Häffner

Dept. of Physics, University of California, Berkeley, CA 94720, USA

E-mail: pschindler@berkeley.edu

Coupling charged particles to electronic devices has a long history in the ion trapping community (for example ref [1]). It seems therefore natural to combine ultracold trapped ions and superconducting quantum electronics into a hybrid quantum information processor. Such a device would allow access to the advantages of both architectures: The exquisite and fast control of superconducting electronics combined with the astonishing coherence times of atomic systems. Furthermore, the well established laser-cooling toolbox can be transferred onto superconducting quantum electronic devices.

We report on our experimental results towards a quantum interface between a single ion and a superconducting resonator. We confine a single Ca ion in a surface trap at 200 um distance from a pick-up wire. This wire is connected to a superconducting tank circuit with resonance frequency of around 2MHz and a quality factor of above 30000. We expect to cool the mode of the resonator by more than two orders of magnitude when coupling it to a continuously Doppler-cooled ion.

The long-term goal is to reach the quantum regime where the resonator is cooled close to its motional ground state. At cryogenic temperatures this regime can only be reached if the resonance frequency is on order of several GHz. Since the ion's motional frequency is typically a couple of MHz, a frequency conversion scheme is required to overcome this mismatch. We propose a parametric up-conversion mechanism exploiting the non-linear the trapping potential [2]. This method converts the frequency before the signal enters any solid state device thus avoiding the excessive low-frequency noise present in these systems.

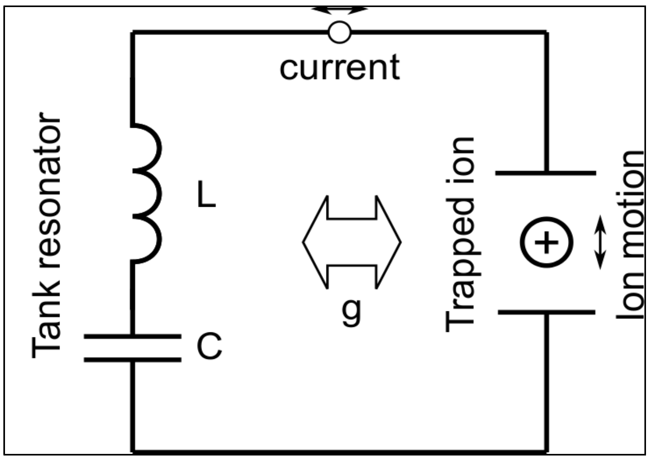

Figure 1

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PII-6
An integrated fibre-trap for ion-photon quantum interface

H. Takahashi, E. Kassa and M. Keller

University of Sussex, Department of Physics and Astronomy,
Pevensey 2, Falmer, Brighton, UK BN1 9QH

E-mail: ht74@sussex.ac.uk

The complementary benefits of trapped ions and photons as carriers of quantum information make it appealing to interface them at the single quantum level. Single ions provide long storage times, high fidelity coherent control and efficient state readout, whereas single photons travel over a long distance with small decoherence. The need for coherently interfacing single ions and photons naturally leads to cavity QED with single ions, where an optical cavity with small mode volume is used to achieve quantum mechanical coupling between two physical systems.

We have developed a novel endcap-type ion trap which tightly integrates a high finesse fibre cavity inside cylindrical electrodes [1]. This hybrid design significantly reduces disturbances to the trap caused by the fibres' dielectric surfaces and as a result allows us to bring the fibres as close as 150 μm to the ion. We have fabricated fibre cavities with negligible birefringence and finesse up to 50,000 over a wide range of cavity length. Recently we succeeded in trapping localised single ions in this trap. With strong ion-photon coupling, a deterministic transfer of quantum states between ions and photons will become possible. We present the current status and future prospects of the experiment.

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PII-7
Near-field microwave manipulation of $^{43}Ca^{+}$ qubits

<u>M.A. Sepiol</u>[1], T.P. Harty[1], C.J. Ballance[1], D.T.C. Allcock[2], H.A. Janacek[1], D.N. Stacey[1] and D.M. Lucas[1]

[1] Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
[2] National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

E-mail: martin.sepiol@physics.ox.ac.uk

Quantum logic with trapped atomic ions relies on coupling the ions via their shared motional modes. This coupling is provided by the gradient of a driving field over the extent of the atoms' motion. Traditionally this driving field has been produced by lasers due to the favorable short wavelengths. However, when ions are confined tens of microns above a waveguide, strong magnetic field gradients can be generated at microwave frequencies despite their long free-space wavelength.
Compared with lasers, this approach promises a higher level of control and integration along with a reduction of technical complexity thanks to the relative ease of generating and manipulating microwave fields. So far, this method has been applied once by the NIST-group, resulting in a two qubit gate of 76% fidelity [1].
We present our research on this technique and work towards applying it to implement a Mølmer-Sørensen gate with two $^{43}Ca^{+}$ ions at 146G. Using an in-house designed and microfabricated surface ion trap, we made progress towards minimizing possible sources of error including technical improvements for better radial motional mode stability.
We also present a simple two-photon cooling scheme allowing for $^{43}Ca^{+}$ to reach temperatures below the Doppler limit in spite of its complicated level structure at 146G.

Reference

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PII-8
Fast separation of entangled ions in segmented Paul traps

T. Ruster, H. Kaufmann, C.Warschburger, C.T. Schmiegelow, M. Dillmann, V. Kaushal, F. Schmidt-Kaler and U. Poschinger

Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

E-mail: rustert@uni-mainz.de

We present our experimental results on the separation of ion crystals, which is a fundamental building block for scalable quantum information experiments with trapped ions in segmented Paul traps [1]. Separation is performed on a timescale of less than 100 µs, which is considerably faster than the decoherence time of our $^{40}Ca^{+}$ spin-qubits. Moreover, the energy transfer on the few phonon level allows for subsequent gate operations. We show how to design and generate optimized voltage ramps for precise control of the ion trajectories near the *critical point*, where the harmonic confinement by the external potential vanishes. Precision on the mV level is required to achieve motional excitation of less than 5 vibrational quanta per ion.
As a first step towards scalable experiments, we demonstrate tomography measurements on two ions prepared in Bell states (Figure 1). For a complete tomography, the analysis pulses are applied successively to the single ions. We achieve this by separating both ions and transporting them to the laser interaction zone one after each other (Figure 2).

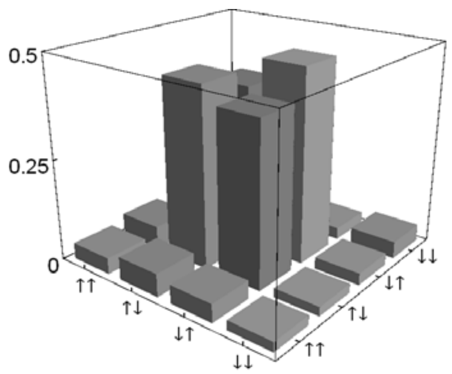

Figure 1: Density matrix reconstruction of the Bell State $|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

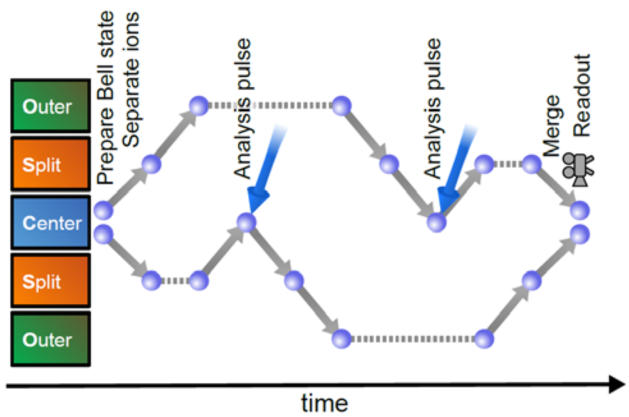

Figure 2: Experimental sequence for performing state tomography

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PII-9
Heating-rate measurements in micro-fabricated surface traps containing Sr^+ ions

B. Szymanski[1], L. Gabardos[1], J.-P. Likforman[1], S. Guibal[1], C. Manquest[1], L. Guidoni[1] and M. Woytasik[2]

[1] Univ Paris Diderot, Sorbonne Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162, Bat. Condorcet, 75205 Paris Cedex 13, France
[2] Institut d'Electronique Fondamentale, UMR CNRS 8622, Université Paris Sud, Centre Scientifique d'Orsay, France

E-mail: luca.guidoni@univ-paris-diderot.fr

We designed, realized and operated a micro-fabricated ion surface trap [1] with Copper electroplated electrodes on a silica substrate. We load the trap with single $^{88}Sr^+$ ions that are Doppler cooled by addressing the 5s $^2S_{1/2}\rightarrow$5p $^2P_{1/2}$ transition (ν = 711 THz, λ = 422 nm) using two different strategies in order to avoid the accumulation of the population into the metastable 4d $^2D_{3/2}$ state during the cooling process (see figure).
In a first (quite usual) case we drive the 4d $^2D_{3/2}\rightarrow$5p $^2P_{1/2}$ 275 THz transition with a "repumping" fiber laser. In a second case we drive both the 4d $^2D_{3/2}\rightarrow$5p $^2P_{3/2}$ (299 THz) and 4d $^2D_{5/2}\rightarrow$5p $^2P_{3/2}$ (290 THz) transitions in order to avoid coherent population trapping phenomena that originate in the previous Λ scheme [2].
We characterize the heating-rate of the trap by applying the Doppler re-cooling method that has been first developed and applied in the case of ions that do not have metastable states [3,4]. We analyze and compare the Doppler re-cooling experimental results obtained with the same trap and under identical conditions but using these two different "repumping" strategies.

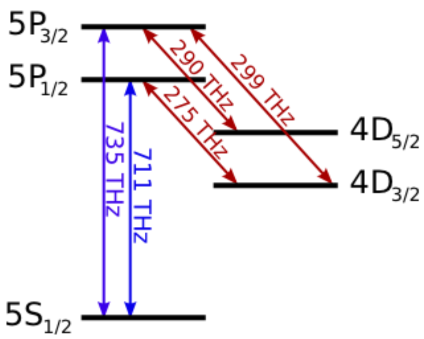

Figure 1. Low energy levels scheme for Sr^+.

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PII-10
Transport of cold ion clouds in a multi-zone linear trap

M.R. Kamsap, C. Champenois, J. Pedregosa, M. Houssin, O. Morizot G. Hagel and M. Knoop

Physique des Interactions Ioniques et Moléculaires (PIIM-UMR 7345), Aix-Marseille Université, CNRS, Centre de Saint Jérôme, 13397 Marseille cedex 20, France.

E-mail: marius.kamsap@univ-amu.fr

Radio-frequency (RF) or Paul traps are used to store ions in a well defined region of space by applying alternating voltages. The trappedions can be cooled by means of various techniques to temperatures of the order of the millikelvin. In this work, we study collective phenomena on large ion samples in potentials with different geometries. Our trapping device is composed of a quadrupole and an octupole linear trap mounted inline. Compared to the quadrupole configuration, higher order traps present the interesting feature to generate a flatter potential well, which induces smaller RF-driven motion and lower RF-heating. Moreover, multipole traps have been at the heart of a promising microwave ion clock based on adouble trap, a quadrupole plus a 16-pole [1]. The frequency of the clock is affectedby the variation on the number of trapped ions. As different parts of the traps are used 100% shuttling efficiency is needed. Thanks to numerical and experimental work, we begin to understand and to

control the transport of large clouds in macroscopic quadrupole traps, which present different challenges compared to the transport of f

ew ions in micro-fabricated traps. Under laser cooling, the ions reach temperatures of the order of several millikelvins and organize in elliptical structures with uniform density which depends on the radial potential [2]. The ion number can be determined by fitting an ellipse. Extract knowledge of the number of trapped ions is necessary to quantify the efficiency of the transfer. The transport is performed by variation of the potential barrier between the trap zones. In our experiment, we use a hyperbolic tangent gate function [3]. We are able to shuttle more than 90% of the ion cloud (up to 10 000 ions) between two quadrupole traps (separated by 23 mm) in 100μs [4]. Our future work will focus on transport protocolsfrom the quadrupole to the octupole trap. The first ion samples have been shuttled and detected in the octupole trap. Our aim is to trap more than 10 billion ions and transport them into the octupole trap without loss and heating.

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PII-11
Trajectory-based micromotion compensation

T.F. Gloger, M.T. Baig, T. Collath, D. Kaufmann, P. Kaufmann, M. Johanning, Ch. Wunderlich

Faculty of Science and Technology, Dept. of Physics,
Siegen University, 57068 Siegen, Germany

E-mail: wunderlich@physik.uni-siegen.de

For experiments with ions confined in a Paul trap, minimization of micromotion is often essential. This is the case, for example, for experiments in quantum information science, for optical ion trapping, in combined traps for neutral atoms and ions, or for precision measurements. In order to diagnose and compensate micromotion we have implemented a method that allows for finding the position of the rf null reliably and efficiently, in principle, without any variation of dc voltages.

We apply a trap modulation technique [1] and tomographic imaging to extract 3-d ion positions for various rf drive powers and analyze the power dependence of the equilibrium position of the trapped ion. We find, that, for harmonic potentials, an ion moves on a hyperbolic trajectory towards the rf null with increasing rf power. Given sufficient knowledge about the trapping potential, it is possible to efficiently find the position of the rf null without any variation of dc voltages by extrapolating the ion's path to infinite rf power. If the trapping potential is not known accurately, or the potential substantially deviates from being harmonic, then a parallel analysis of measurements for different compensation fields quickly gives not only a prediction of the rf null position but also of the required compensation voltages. This method varies from commonly used methods in the sense that the search algorithm is based on physics as opposed to efficient numerical minimization in a high-dimensional parameter space.

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PII-12
Current Status of Ion Trap Microfabrication and Experiments of SKT-SNU Collaborative Research

M. Lee[1], S. Hong[1], H. Cheon[1], T. Kim[2], J. Sik Ahn[2], M.H Kim[2] and Dong-Il "Dan" Cho[1,*]

[1] ASRI/ISRC and Department of Electrical and Computer Engineering,
Seoul National University, Seoul, 151-744, Republic of Korea
[2] Quantum Technology Lab, SK Telecom, Seongnam-si, Gyeonggi-do, 463-784, Republic of Korea

**Corresponding Author: dicho@snu.ac.kr*

Seoul National University (SNU) and SK Telecom (SKT) launched an ion trap research project in 2011. This paper describes our results on trapping ions, single qubit operations, as well as MEMS fabrication methods.

In our ion trap chip fabrication, a 14-µm thick PECVD-deposited SiO_2 layer with low residual stress is used as an insulating layer. An Al layer is deposited on top of the SiO_2 layer and is patterned to form RF and DC electrodes. Overhang electrode structures to reduce the disturbance from the charge build-ups on the sidewalls of dielectric layers are fabricated using two different fabrication methods. In the first method, an oxide wet etching using a buffered hydrogen fluoride (BHF) solution is applied to dissolve the outer side of the oxide layer. This method is simpler than the other method but results in non-uniform overhang lengths and jagged edges (Fig. 1). In the other method, an electroplated Cu layer is used as a sacrificial layer. This technology is new in ion trap fabrication research. In this method the overhang length is uniformly defined (Fig. 2). Microfabricated chips are packaged on the commercial ceramic chip carrier (CPGA10039, Spectrum Semiconductor Materials Inc.) and installed in an ultra-high vacuum (UHV) chamber. Figure 3 shows a trapped $^{171}Yb^+$ ion at 1×10^{-11} Torr. The image of electrode structure was taken separately and was overlaid with the image of trapped ion for clarity.

A single qubit operation using a $^{171}Yb^+$ ion [1] has also been successfully demonstrated in our experiment. Rabi oscillations of the qubit state are induced by a microwave, and we can clearly distinguish $|0\rangle$ and $|1\rangle$ states from the photon statistics with error probability less than 3% as shown in Figure 4, where the qubit state is prepared as $(|0\rangle + |1\rangle)/\sqrt{2}$.

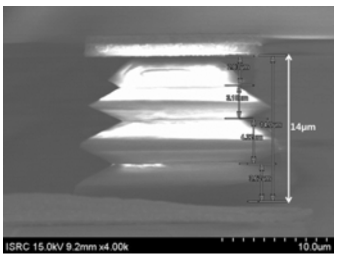

Figure 1

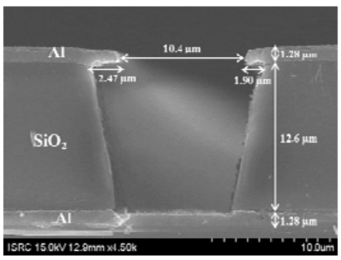

Figure 2

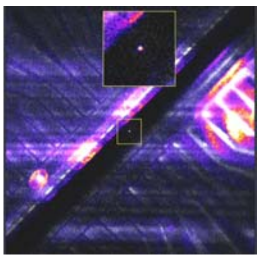

Figure 3

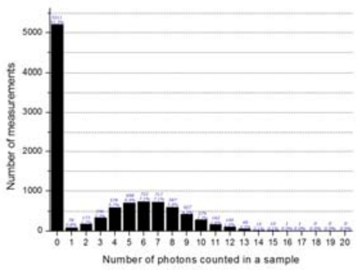

Figure 4

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PII-13
Towards Microwave Entanglement Generation for Quantum Simulation and Computing

S. Weidt, K. Lake, J. Randall, S.C. Webster,
E.D. Standing, D. Murgia and W.K. Hensinger

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

E-mail:w.k.hensinger@sussex.ac.uk

A promising route for large scale quantum computing relies on the use of stable and easily controllable microwaves [1, 2] combined with static magnetic field gradients, which provides ion selectivity as well as the simultaneous entanglement of a large number of ions [1]. Such gate operations are vulnerable to decoherence due to fluctuating magnetic fields [3]. However, the use of microwave-dressed states as qubits protects against this source of noise; with radio-frequency fields being used for qubit manipulation [4].

The 2nd order Zeeman effect removes the degeneracy of the radio-frequency transitions within the F=1 manifold of the ion's ground state. We use this property to demonstrate a powerful method for manipulating the dressed-state qubit. We will also show that our method allows for the implementation of arbitrary rotations of our dressed-state qubit on the Bloch sphere using only a single rf field [5].

We have constructed an efficient setup based on multiple in-vacuum permanent magnets which produce a magnetic field gradient of 24 T/m. This enables individual addressing of closely spaced ions in frequency space and coupling between the bare internal and motional states of the ions. We also present results showing that this coupling is present in the microwave dressed-states and that while our dressed-qubit is insensitive to magnetic field fluctuations, it remains sensitive to a magnetic field gradient. We present results showing the experimental realisation of driving motional sideband transitions using such dressed states.

The creation of entanglement between the internal and motional states of a single ion is an important step towards two ion entanglement. We will report the experimental demonstration of such spin-motion entanglement using microwaves and a static magnetic field gradient in both the bare and dressed states.

Finally, we have successfully cooled single ions in a magnetic field gradient close to the motional ground state using a sideband cooling technique making use of microwaves rather than laser radiation. We have also measured the heating rate of the single ion following such cooling to be 0.27(3) quanta/ms in our given setup.

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PII-14
Cryogenic Ion Trapping and Technology Development for Quantum Simulation, Computing and Hybrid Systems

D. De Motte , G. S. Giri , B. Lekitsch, A.Grounds, T.Navickas and W.K. Hensinger

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

E-mail: w.k.hensinger@sussex.ac.uk

We report on progress on a new experiment to operate a variety of surface electrode ion trap chips in a cryogenic environment. Using this setup we aim to study microwave entanglement, anomalous heating, quantum simulations using 2D arrays of trapped ions and technology development towards quantum hybrid systems. We also present progress on a superconducting ion trap microchip with integrated high quality factor microwave resonator. The central DC electrode and the two lateral RF electrodes for ion trapping provide a natural CPW/stripline structure for on-chip MW radiation delivery. The ion trap has vertical ion shuttling capability to achieve high and low ion electrode spacing required for laser and MW interactions respectively.

Finally we present progress on an analogue voltage generation system for simultaneous generation of 90 channels with 16 MSPS update rate for fast ion transport. The system is designed using very low noise components and filters to produce highly stable outputs of -/+100V.

PII-15
A microstructured Paul trap - cavity system for light-ion interaction

M. Hettrich, **A. Pfister, M. Salz and F. Schmidt-Kaler**

Johannes Gutenberg - Universität Mainz,
Institut für Physik, Staudinger Weg 7,
55128 Mainz

E-mail: hettrich@uni-mainz.de

While being standard in experiments with neutral atoms [1,2], strong light-matter coupling hasn't been achieved so far with cold ions. The main challenge is the inevitable vicinity of the ion to the dielectric material of high-quality mirrors, which may statically charge up and thereby deteriorate the trapping potential. Nonetheless, as cold ions form a well-proven system for quantum information processing, strongly coupling them to single photons would be the heart of a quantum repeater, enabling long-distance distribution of quantum information.

Here, we present a system, which enables us to pursue this goal (Fig. 1). We integrate a micro fabricated fibercavity into a segmented linear Paul trap. The trap structure allows for precise control over the external degree of freedom, like fast transport [3] and splitting [4] operations. The cavity we use consists of two fiber facets facing each other, which provides us with a small mode volume while keeping the amount of dielectric material close to the ion at a minimum [5]. We established a novel technique for shaping the surface of the fiber facets by milling them with a focused ion beam (FIB) (Fig. 2). We produced fibercavites with a length of 240 μm which feature a Finesse of ~25000, opening the door for cavity quantum electrodynamics in the strong coupling regime with cold ions.

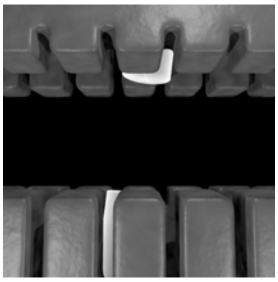

Fig. 1. Sketch of a segmented trap with integrated fibercavity

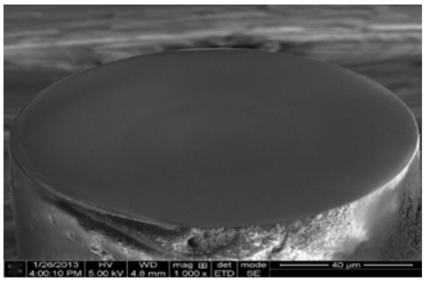

Fig. 2. Electron microscope picture of FIB-treated fiberend

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PII-16
Anomalous Heating of Trapped Ions

K. McKay, D. Hite, D. Allcock, D. Leibfried, D. Wineland, and D. Pappas

National Institute of Standards and Technology, Boulder, CO 80305

E-mail: kyle.mckay@nist.gov

A major barrier to the development of trapped-ion quantum computers is electric-field noise from the trap-electrode surfaces, which results in heating of the ions motional modes, limiting the fidelity of multi-qubit quantum operations. In recent years, motional heating rates have been reduced by more than two orders of magnitude through use of *in situ* ion bombardment [1,2] and cryogenic cooling [3–5] of the trap electrodes. However, the added complexity of cryogenic cooling and *in situ* ion bombardment has prevented widespread adoption of these techniques. Furthermore, the physical changes responsible for the reduced heating rates have not been identified and the source of the anomalous heating remains poorly understood.

At NIST, we have integrated a surface-science system with a stylus ion trap [6] to enable studies of how altering surface properties such as composition, contamination, and structure impact motional heating rates of trapped ions. Using this surface-science system we prepare and characterize sample surfaces and then transfer them *in situ* to the stylus trap, where the electric-field noise from the surface is measured using the ion as a sensor. This allows us to characterize the surface properties responsible for ion heating in a direct and high-throughput manner.

We will present results on the use of an *ex situ* ion-bombardment treatment to Au trap electrodes just prior to final trap assembly. This treatment is shown to reduce motional heating rates by more than an order of magnitude [7], thus enabling new experiments without the need for *in-situ* treatments. Additionally, we will discuss the use of the surface-science system to study the microscopic surface changes induced by surface cleaning techniques and their impact on the heating rates of trapped ions.

This work was supported by IARPA under ARO Contract No. DNI-017389, ONR, and the NIST Quantum Information program.

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PII-17
Towards High-Fidelity Multi-Qubit Gates in Multi-Layer Ion Traps

A. Bautista-Salvador[1,2], M. Carsjens[1,2], T. Dubielzig[2], S. Grondkowski[2], M. Kohnen[1,2] and C. Ospelkaus[1,2]

[1] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2] Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany

E-mail: bautista@iqo.uni-hannover.de

In quantum technologies –quantum information and quantum simulation– based on trapped atomic ions, internal and motional states are routinely manipulated using laser light. However, scaling laser-based qubit manipulation techniques to a large number of atomic ions and reaching fault-tolerant operation levels remain challenging. Among the alternative schemes in the quest of scalability stands qubit manipulation by microwave quantum control where the ion's internal states are coupled to motional states assisted by strong magnetic field gradients [1, 2].
The fidelities in the single- and multi-qubit gates demonstrated with the laser-less approach of [2] are limited, in addition to anomalous heating, by a required fine matching on the signal phase and amplitude applied on three independent microwave lines to achieve the desired field configuration.
Here we discuss on integrating a single meander-like microwave conductor [3] into a multi-layer ion trap. We detail the multi-layer fabrication process involved which extends a previous single-layer fabrication [2] by including chemical-mechanical polishing (CMP) of spin-on-glass (SOG) dielectrics and copper electroplating for forming interconnects and vias.
A single meander-like microwave conductor, right below a trapped ion, connected to a base plane conductor by copper vias will reduce eddy currents on neighboring electrodes. The corresponding reduction in residual magnetic fields will minimize off-resonant carrier excitations and thus improve gate fidelities. The conceptual separation between feed lines and gate drive conductors into different layers will benefit the overall scalability of the approach.

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PII-18
Vertical shuttling of ions in a planar electrode ion trap

I.A. Boldin, A. Kraft, M. Ziolkowski and C. Wunderlich

Chair for Quantum Optics, Department of Physics, University of Siegen, D-57068 Siegen, Germany

E-mail: boldin@physik.uni-siegen.de

Planar electrode ion traps are considered to have great potential for quantum information science as they are supposed to be easy to scale up and allow for complex electrode structures that might be needed for future quantum processors [1]. Another feature of planar traps is the possibility of strong interaction between ions and electrodes as the ions can be trapped tens of micrometers away from the electrode surface. This feature can be utilized in the realization of microwave qubit processing with the electrodes of the trap producing near-field microwave field in the trapping position.

There are conflicting requirements to the design of a planar electrode trap: on the one hand it is desirable to have strong interaction with electromagnetic fields created by the electrodes and therefore to have a small separation between ions and electrodes; on the other hand decreasing ion height over the surface leads to stronger undesired interactions such as the so-called anomalous heating. Therefore one can think of a trap where the distance between ions and electrode surface can be changed. Then one could store ions far away from the surface when they are used as quantum memory and bring them into closer proximity when quantum gates should be applied.

One of the methods to realize movement of ions perpendicular to the electrode surface is applying additional RF with adjustable amplitude to some electrodes of the trap [2]. We present a realization of this mechanism in our planar electrode ion trap.

We trap $^{172}Yb^{+}$ ions in a 5-electrode planar electrode trap [3]. The electroplated gold electrodes are 150 and 180 μm wide and unbiased trapping height is 160 μm. Additional RF voltage in phase with the main RF is applied to the central electrode through a special electric circuit that allows for tuning of RF amplitude while staying on the constant drive frequency and with sufficient phase synchronization. Shuttling of ions perpendicular to the trap surface is observed with an EMCCD camera.

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PII-19
Coherent operations in a monolithic array of 3D ion traps

G. Wilpers[1], **J. Thom**[1,2], **B. Yuen**[1,3], **K. Choonee**[1], **P. See**[1], **E. Riis**[2], **P. Gill**[1], **and A. G. Sinclair**[1]

[1] National Physical Laboratory, Teddington, TW11 0LW, UK
[2] University of Strathclyde, Glasgow, G4 0NG, UK
[3] Imperial College, London, SW7 2BB, UK

E-mail: guido.wilpers@npl.co.uk

Coherent control and entanglement of trapped ions have been successfully applied in quantum metrology. Examples include spectroscopy towards the Heisenberg limit [1], "designer atoms" with tailored sensitivities [2], and quantum logic spectroscopy [3]. We have developed a monolithically fabricated linear ion trap with a 3D potential and unit aspect ratio electrode configuration for scalable entanglement [4,5]. For coherent operations and entanglement on optical qubits we have developed an agile laser system [6] enabling fast and accurate phase, frequency and amplitude control of a stable laser system. We report on coherent manipulation of ions in our present microtrap (Fig. 1a). For this trap we have demonstrated motional frequencies in excess of 4 MHz and a low heating rate of $\omega_z S_e(\omega_z) = 1.7 \times 10^{-5}\ V^2 m^{-2}$ ($\omega_z/2\pi$ = 750 kHz) [4]. We present shaping of optical pulses achieving suppression of off-resonant excitation by a factor of 20 and more (Fig. 1b), frequency resolved optical pumping with 99.8 % efficiency and a laser beam pointing stabilisation setup enabling positioning on the ion to within 600 nm. We are working on intensity stabilisation and resolved sideband cooling and aiming towards the entanglement of 2 or more ions with Mølmer-Sørensen gates [7].

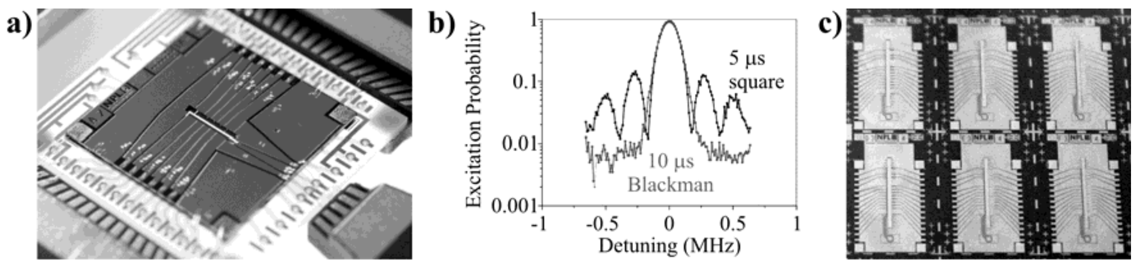

Figure 1. a) NPL's monolithic 3D ion trap package, **b)** tailored temporal pulse shaping to reduce off-resonant excitation: square versus Blackman pulse, **c)** 6 7-segment microtraps on a wafer.

We also present first results from a revised fabrication run with yield of 90 % on the first 4 stages now carried out on a wafer level. Completion of the last 2 stages will produce a revised design. It includes 7 operation segments and a separated loading region (Fig. 1c). Tests on more intricate electrode structures show promising yield.

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PII-20
Quantum Simulation of Dissipative Processes without Reservoir Engineering

J. S. Pedernales

Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain

E-mail: julensimon@gmail.com

I will present a quantum algorithm to simulate general finite dimensional Markovian processes without the requirement of engineering the system-environment interactions. The proposed method [1] consists in the quantum computation of the dissipative corrections to the unitary evolution of the system of interest, via the reconstruction of the response functions associated with the Lindblad operators. Trapped ions, being one of the most promising quantum technologies to date, is a prime candidate to harbor the first generation of experiments on these concepts. The simulation of dissipative processes is of great scientific interest as every system is indeed coupled to the environment, and may help to understand issues as the quantum-classical frontier. Moreover, the computation of dissipative processes may have a strong impact in technologies that rely on the simulation of open quantum systems, as for example the study of photosynthetic processes for the development of light-harvesting nanodevices.

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PII-21
Using microwaves to control motional states of a trapped ion in a running optical lattice

S. Ding[1], H. Loh[1], R. Hablützel[1], M. Gao[1], G. Maslennikov[1] and D. Matsukevich[1,2]

[1] Centre for Quantum Technologies, National University of Singapore, 3 Science Dr 2, 117543, Singapore
[2] Department of Physics, National University of Singapore, 2 Science Dr 3, 117551, Singapore

E-mail: r.hablutzel@nus.edu.sg

Quantum control of atomic and molecular motion is fundamental for quantum information processing, quantum simulations, metrology and other areas of physics. In this work we experimentally demonstrate coupling between the spin and the motional state of a trapped ion effected by a uniform microwave field, when an ion is placed in a spin-dependent optical lattice.
In our scheme the running optical lattice is formed by two orthogonally polarized laser beams, such that the polarization of the laser light in the lattice is changing from left to right circular. This polarization gradient field gives rise to a state dependent ac-Stark shift. As a result, transitions between the hyperfine states of the ion driven by microwave radiation result in a change of the ion motional state, leading to spin-motion coupling. Both the optical lattice depth and the running lattice frequency provide tunability of the spin-motion coupling strength, and the use of the running optical lattice removes the requirement for interferometric stability of the optical lattice with respect to the ion position.
As a proof-of-principle, a (Doppler cooled) $^{171}Yb^{+}$ ion was placed in the spin-dependent potential generated by the optical lattice and cooled down to the ground state of motion by resolved sideband cooling [1]. We also discuss the possible application of this technique to the quantum logic spectroscopy of molecular ions.

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PII-22
Two-dimensional spectroscopy for the study of ion Coulomb crystals

A. Lemmer[1], C. Cormick[1], C.T. Schmiegelow[2], F. Schmidt-Kaler[2] and M.B. Plenio[1]

[1] Institut für Theoretische Physik, Albert-Einstein Alle 11, Universität Ulm, 89069 Ulm, Germany
[2] QUANTUM, Institut für Physik, Universität Mainz, 55128 Mainz, Germany

E-Mail: andreas.lemmer@uni-ulm.de.

Ion Coulomb crystals are currently establishing themselves as a highly controllable test-bed for mesoscopic systems of statistical mechanics. The detailed experimental interrogation of the dynamics of these crystals however remains an experimental challenge. In this work, we show how to extend the concepts of multi-dimensional nonlinear spectroscopy to the study of the dynamics of ion Coulomb crystals. The scheme we present can be realized with state-of-the-art technology and gives direct access to the dynamics, revealing nonlinear couplings even in systems with many ions and in the presence of thermal excitations. We illustrate the advantages of our proposal showing how two-dimensional spectroscopy can be used to detect signatures of a structural phase transition of the ion crystal, as well as resonant energy exchange between modes. Furthermore, we demonstrate in these examples how different decoherence mechanisms can be identified.

PII-23
Coupling several ions to an optical cavity.

M. Keller, S. Begley and M. Vogt

University of Sussex

E-mail: s.begley@sussex.ac.uk

Our experimental setup consists of a linear Paul trap with cavity mirrors embedded in the endcap electrodes to shield them from charging effects. The RF trap centre and cavity mode are overlapped to optimise ion-cavity coupling, and the cavity mode has been mapped in the axial direction, confirming localisation of a single ion. A caesium reference laser is used to lock the cavity length, and a Scanning Cavity Transfer Lock is used to confer the medium and long-term stability of this reference onto the cooling laser, which is also the excitation laser. Pulsed cooling/probe spectroscopy across the full width of the cooling transition has been used to verify effective cooling and a lifetime-limited linewidth of 23MHz. Cavity fluorescence occurs via a Raman transition, and has been experimentally observed for single ions. By tuning the local magnetic field and cavity length, selection of a single output polarisation is possible, enabling the generation of single polarised photons on demand. In the near future we plan to demonstrate the optimal coupling of several ions in a string simultaneously to cavity antinodes, and Hong-Ou-Mandel interference between successive generated single photons. Ultimately we anticipate being able to generate entangled ion pairs using the heralded probabilistic entanglement scheme described above.

PII-24
Efficient light-matter coupling in free space

M. Bader[1,2], M. Fischer[1,2], S. Heugel[1,2], M. Sondermann[1,2] and G. Leuchs[1,2]

[1] Max-Planck-Institute for the Science of Light, Erlangen, Germany
[2] Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Department of Physics, Institute for Optics, Information and Photonics, Erlangen, Germany

E-mail: marianne.bader@mpl.mpg.de

The efficiency of the interaction between light and a single quantum system can be maximized by mode-matching the incident light field and the radiation pattern of the system. We follow a free-space approach where the radiation properties of the quantum system are not affected. To this end, we trap a single $^{174}Yb^{+}$ ion in the focus of a deep parabolic mirror [1]. The latter is capable of transforming a suitably shaped plane wave into a focused dipole wave [2]. Having a depth of approximately six times its focal length, the parabolic mirror covers 94% of the linear dipole pattern [3].
As a benchmark for the achieved coupling efficiency we use saturation measurements [4] (fig. 1). Using half solid-angle illumination, we measure a power of 165pW to reach an upper-level population of ρ=¼ at approximately half-linewidth detuning. This corresponds to a coupling efficiency of 27% to the linear dipole transition. This is the highest reported value for the coupling efficiency between light and a single emitter in free space so far.

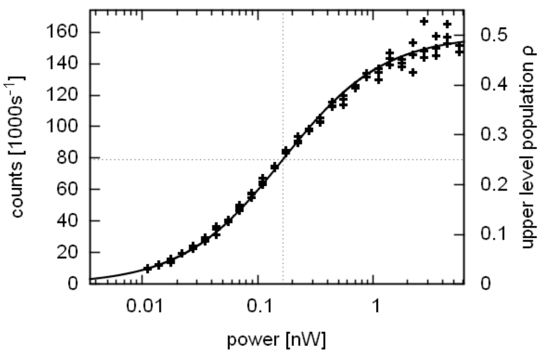

Figure 1. Saturation of a single ion using a focused dipole wave incident from half solid angle. Symbols: measurement, solid line: fit. The power to achieve ρ=¼ amounts to 165pW, corresponding to a coupling efficiency of 27% to the linear dipole transition.

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PII-25
High fidelity entangling gates in $^{43}Ca^{+}$

C.J. Ballance, **V.M. Schäfer, S. Woodrow,**
T.P. Harty, N.M. Linke, D.M. Lucas

Clarendon Laboratory, University of Oxford, Parks Road, Oxford, U.K.

E-mail: ballance@physics.ox.ac.uk

Quantum computation and simulation rely on high-fidelity multi-qubit entangling gates. Crucial to achieving the desired fidelities is understanding and controlling the many potential sources of errors. We present a study of the speed/fidelity trade-off for a two-qubit phase gate implemented in $^{43}Ca^{+}$ hyperfine trapped-ion qubits [1]. We characterize various error sources contributing to the measured fidelity, allowing us to account for errors due to single-qubit state preparation, rotation and measurement (each at the ~0.1% level), and to identify the leading sources of error in the two-qubit entangling operation. We achieve gate fidelities ranging between 97.1(2)% (for a gate time $t_g = 3.8$ μs) and 99.9(1)% (for $t_g = 100$ μs), representing respectively the fastest and lowest-error two-qubit gates reported between trapped-ion qubits by nearly an order of magnitude in each case (figure 1). We have used the same gate mechanism to entangle two different isotopes of calcium, $^{43}Ca^{+}$ and $^{40}Ca^{+}$, with F≈99%.
We also present work towards implementing high fidelity single-qubit and entangling operations in the 'clock' states of $^{43}Ca^{+}$. We have implemented a Mølmer-Sørensen two-qubit gate with F≈99%, and single-qubit operations with Raman lasers with an error-per-gate of $<10^{-4}$.

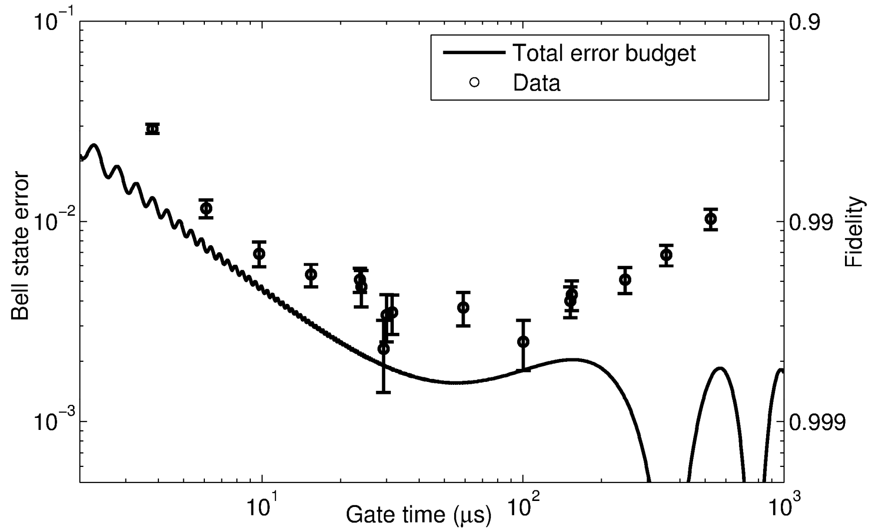

Figure 1. Measured Bell state infidelity (data points) and error model (lines), plotted against the two-qubit gate duration. The lowest gate error is found at t_g=100 μs, where the measured Bell state fidelity is F=99.75(7)%, subtracting the modelling single-qubit error, we infer a gate fidelity of 99.9(1)%.

Reference

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PII-26

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

P. Jurcevic[1,2], B.P. Lanyon[1,2], P. Hauke[1,3], C. Maier[1,2], C. Hempel[1,2], P. Zoller[1,3], R. Blatt[1,2] and C.F. Roos[1,2]

[1] Institut für Quantenoptik und Quanteninformation,
Österreichische Akademie der Wissenschaften, Technikerstr. 21a, 6020 Innsbruck, Austria
[2] Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
[3] Institut für Theoretische Physik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria

E-mail: christine.maier@uibk.ac.at
christian.roos@oeaw.ac.at

The key to explaining and controlling a range of quantum phenomena is to study how information propagates around many-body systems. Quantum dynamics can be described by particle-like carriers of information that emerge in the collective behaviour of the underlying system, so called quasiparticles. These elementary excitations are predicted to distribute quantum information in a fashion determined by the underlying system's interactions.

Here we report on quasiparticle dynamics observed in a quantum many-body system of trapped atomic ions [1]. In detail we present the implementation of the Ising Hamiltonian as well as the measurement of its coupling matrix and the dispersion relation for the 1-excitation subspace. We show how entanglement is distributed by quasiparticles, as they trace out lightcone-like wavefronts. Furthermore, using the ability to tune the effective interaction range, we observe the predicted non-local transport of information and breakdown of the light-cone picture. Our results will enable experimental studies of a range of quantum phenomena, including transport, thermalisation, localisation, and entanglement growth, and represent a first step towards a new quantum-optic regime of engineered quasiparticles with tuneable non-linear interactions.

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PII-27
Simulating quantum many-body dynamics with trapped atomic ions

P. Richerme, **C. Senko, J. Smith, A. Lee and C. Monroe**

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

E-mail: richerme@umd.edu

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

PII-28
Fault-tolerant Molmer-Sorensen gate

S. Ivanov[1] **and N. Vitanov**[1]

[1] Sofia University, Department of Theoretical Physics

E-mail: sivanov@phys.uni-sofia.bg

We present an ion-trap scheme for the implementation of Molmer-Sorensen's (MS) gate that is robust against variations in the laser intensity and detuning. A sequence of MS gates is applied in combination with single-ion rotations between the gates.

PII-29
Fault-tolerant Microwave Addressing of Trapped Ions

D.P.L. Aude Craik[1], N.M. Linke[1], D.T.C. Allcock[2], A.M. Steane[1] and D.M. Lucas[1]

[1] Clarendon Laboratory, Department of Physics, Oxford University, Oxford, OX1 3PU, UK
[2] National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

E-mail: d.pradolopesaude@physics.ox.ac.uk

We present preliminary results obtained with a two-zone, scalable prototype surface-trap for storing and individually addressing memory qubits [1]. The trap has 4 integrated microwave electrodes in each zone (Figure 1): microwave currents are run through these electrodes to generate oscillating magnetic fields at the ion with tailorable polarization, amplitude and frequency.

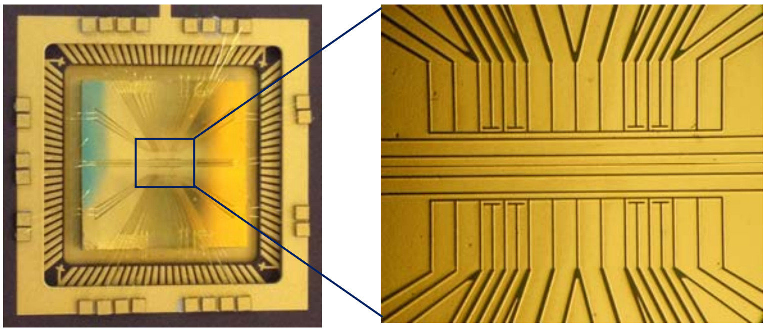

Figure 1. Microwave Addressing Trap. The eight microwave electrodes with 'T'-shaped slots can be seen in the magnified view of trap center on the right. The separation between the two trap zones is approximately 1mm.

In this initial experiment, we use two electrodes, one in each zone, to drive Rabi flops in the zone we wish to address while nulling the microwave field in the neighbour zone. We measure a Rabi frequency ratio between the addressed qubit and the neighbour qubit of up to 645 (Figure 2), which implies a spin-flip error of 6×10^{-6}.

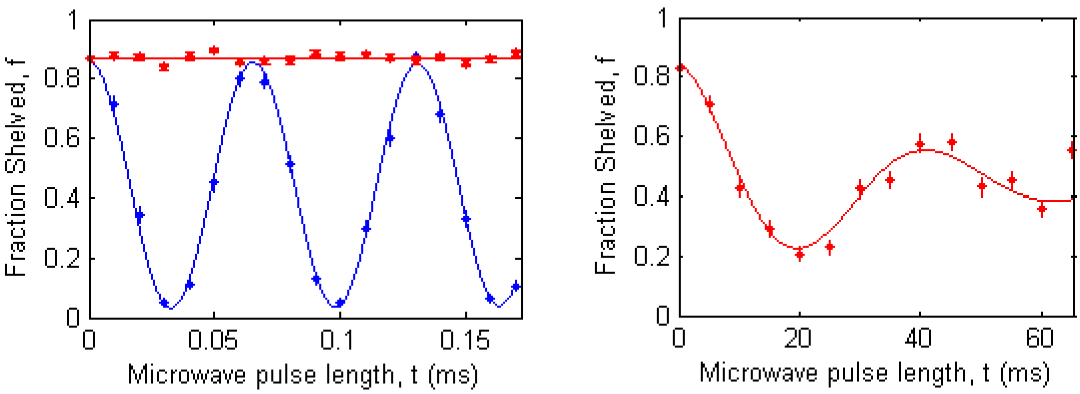

Figure 2. Left: Microwave pulse length scan in the addressed zone (blue) and neighbour zone (red). **Right**: Longer microwave pulse length scan in neighbor zone (up to 65ms).

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PII-30
Towards strong coupling with single ion CQED

M.S. Gutierrez, M. Shi, T. Wu, H. Zhang and I. Chuang

Massachusetts Institute of Technology

E-mail: m_g@mit.edu

We present two designs and preliminary test results for an ion trap with a high fidelity photonic interconnect. The goal of this project is to realize strong coupling between an optical cavity mode and single ion, allowing for high-fidelity state transfer between an ion electronic state and a single photon. The two systems we propose, and are developing, for this purpose consist of a Sandia Cavity trap with a near-confocal 2-mirror cavity and a Sandia HOA trap with a 4-mirror bow-tie cavity. Here we discuss the expected properties of each system, along with current tests of ion-trap and cavities separately. Additionally, we present preliminary data on the behavior of ultra-high reflectivity mirrors when placed in vacuum and brought through standard UHV baking procedure. Results of mirrors with two types of coatings, both coated for a reflectivity range of 400-430nm but with differing top-layers, are compared.

PII-31
Engineered Microwave Control for $^9Be^+$

M. Kohnen[1,2], M. Wahnschaffe[1,2], A. Bautista[1,2], T. Dubielzig[2], H. Hahn[2], S. Grondkowski[2] and C. Ospelkaus[2,1]

[1] Physikalisch-Technische Bundesanstalt, Quest Institut, Bundesallee 100, 38116 Braunschweig
[2] Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

E-mail: kohnen@iqo.uni-hannover.de

Common motional states of ions can be used for spin-dependent interactions between multiple ions. For this purpose, the motional states are coupled to the internal state of a single ion using sideband transitions. In contrast to carrier transitions, sideband transitions couple to the gradient of the driving field. Strong gradients across the size of the motional wavepacket of the ion are commonly produced with laser fields. We present an experimental setup in which we can address sideband transitions using microwave near-fields. Key advantages of using microwave near-fields instead of laser fields are the lack of spontaneous-emission decoherence, low motional-state dependence, potentially superior classical control and integration for scalability [1].

Heart of our experimental apparatus is a micro-fabricated chip containing electrodes for trapping ions and a single, meander-shaped microwave electrode. The near-field produced by this electrode has a local minimum of the magnetic field 30 µm above the chip and steep gradients around that minimum as required for addressing sideband transitions. The magnetic field and the current distribution in the microwave electrode itself as well as the currents induced in other electrodes are efficiently and accurately obtained using full-wave numerical simulations (cf. [2]). We optimised the electrodes' geometry with respect to the ratio of field gradient to residual field at the minimum. This value is proportional to the ratio of sideband-to-carrier excitations addressed by the microwave field. We present simulation results, fabrication techniques for building the chip and the experimental hardware required to test the fidelity of the quantum operation that can be performed with the chip.

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PII-32
Single Ion Heat Engine

J. Roßnagel[1], N. Tolazzi[1], O. Abah[2], E. Lutz[2], G. Jacob[1], F. Schmidt-Kaler[1] and K. Singer[1]

[1] Quantum, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany
[2] Institute for Theoretical Physics, University of Erlangen-Nürnberg, D-91058 Erlangen, Germany

E-mail: kilian.singer@uni-mainz.de

First experiments towards the realization of a single ion heat engine are presented. The proposed system would implement the first system which allows for the realization of a heat engine working with non-classical baths instead of thermal baths. To this goal a custom designed linear Paul trap (see Figure 1) was designed, where a single ion is trapped such that an Otto cycle could be performed. The radial state of the ion is used as the working gas analogous to the gas in a conventional heat engine. The conventional piston is realized by the axial degrees of freedom where the axial motional excitation stores the generated work, just like a conventional fly-wheel. The heat baths are realized by tailored laser radiation. Alternatively electrical noise can be used to control the state of the ion. Comparing the theoretical predictions with the experimental results our system possesses advantageous properties, as the working parameters can be tuned over a broad range and the motional degrees of freedom of the ion can be accurately determined.

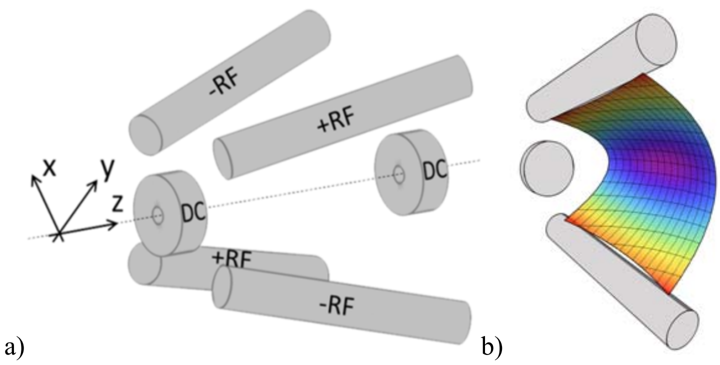

Figure 1. a) Schematic design of a heat engine based on a modified Paul trap geometry: A symmetric radio frequency (RF) drive applied to the tapered rod electrodes is supplying the radial confinement. DC electrodes biased to positive potentials traps the ion in the axial z-direction. b) Calculated funnel shaped pseudopotential in the radial direction.

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PII-33
Collective emission of two ions in a cavity for an enhanced quantum interface

B. Casabone[1], K. Friebe[1], B. Brandstätter[1], K. Schüppert[1], R. Blatt[1,2] and T. Northup[1]

[1] Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
[2] Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

E-mail: konstantin.friebe@uibk.ac.at

We prepare a maximally entangled state of two ions and couple both ions to the mode of an optical cavity. The phase of the entangled state determines the collective interaction of the ions with the cavity mode, that is, whether the emission of a single photon into the cavity is suppressed or enhanced. By adjusting this phase, we tune the ion-cavity system from sub- to superradiance. We then encode a single qubit in the two-ion superradiant state and show that this encoding enhances the transfer of quantum information onto a photon. These results constitute a proof of principle that cooperative effects can improve the performance of a quantum interface.

PII-34
Photon generation and absorption with a single ion coupled to an optical fiber cavity

H.-M. Meyer[1,2], **M. Steiner**[2, §], **R. Stockill**[2], **C. Le Gall**[2], **C. Matthiesen**[2], **J. Reichel**[3], **M. Atatüre**[2] **and M. Köhl**[1,2]

[1] Physikalisches Institut, Universität Bonn, Wegelerstraße 8, D-53115 Bonn, Germany.
[2] Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, CB3 0HE, UK.
[3] Laboratoire Kastler-Brossel, ENS/UPMC-Paris 6/CNRS, F-75005 Paris, France.
[§] Present Address: Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore.

E-mail: hmeyer@physik.uni-bonn.de

Trapped atomic ions are among the most promising candidates for stationary qubits within a quantum network. In such a network, information can be distributed between ions by the exchange of photons. This requires a highly efficient light-matter interface, which can be implemented by coupling the ion to a high finesse optical cavity in order to make use of the concepts of cavity QED. Since the ion-cavity coupling scales inversely with the square root of the mode volume, we have developed a light-matter interface consisting of a single $^{174}Yb^{+}$ ion coupled to a miniaturized optical fiber-cavity of only 170µm length [1,2]. Single photons at 935nm are emitted into the cavity mode. Despite the photon being intrinsically coupled into a single mode fiber, the correlation between the polarization of the photon and the spin state of the ion is preserved [3]. When a faint laser beam is coupled into the cavity the absorption of photons is also enhanced. This allows coupling to other key quantum systems, where the efficiency can drop due to a significant bandwidth mismatch.

To demonstrate this, we measure the absorption of photons from a semiconductor quantum dot (QD), which is tuned to the ion's resonance frequency. We investigate how the absorption probability is altered depending on the QDs spectral emission properties, which depend on the QD driving regime [4]. This builds the foundation for a hybrid quantum network consisting of two fundamentally different quantum systems potentially serving as quantum processor (QD) and quantum memory (ion), respectively.

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PII-35
Microfabricated ion traps for quantum information and simulation

B. Lekitsch[1], M. D. Hughes[1], R. C. Sterling[1], H. Rattanasonti[2], S. Weidt[1], K. Lake[1], P. Srinivasan[2], S.C. Webster[1], J.O. Maclean[3], G.S. Giri[1], T. Navickas[1], D.C.S. DeMotte[1], D.F. Murgia[1], J. Randall[1], M. Kraft[2], C. Mellor[3], 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] School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

E-mail: w.k.hensinger@sussex.ac.uk

Microfabricated ion traps based on the linear Paul trap only allow ions to be confined in a 1-dimensional string due to the requirement that they are positioned at the RF nil. However, some applications require alternative ion geometries, such as 2-dimensional (2D) ion lattices for analogue quantum simulation [1]. Furthermore, in operating a microfabricated ion surface trap, restrictions on the RF voltage that can be applied due to low flashover voltages exist which prohibits a large trap depth and ion-electrode distance. This limits the achievable ion lifetime and secular frequencies and results in large heating rates of the ion motion.

We will report on the operation of a two-dimensional ion trap lattice integrated on a microchip [2]. For this purpose we first developed a fabrication process that allows extremely large voltages to be applied to microfabricated devices (one or two orders of magnitude higher than in previously fabricated ion traps).

We will also report the successful demonstration of trapping single Yb ions on a centrally segmented microfabricated ring trap featuring 90 electrodes and a microfabrication technique which allows buried RF and static voltage interconnects.

In addition, we will present our progress towards linear and X-junction traps with current-carrying wires intended to produce large static magnetic field gradients. Traps with large adjustable gradients can be used to perform microwave based quantum gates and to perform digital quantum simulations. Optimization and design of X-junction geometries for minimal RF barrier height is described first, followed by trap designs with loading and detection slots.

We will describe a microchip vacuum system capable of operating advanced microfabricated ion traps featuring up to 100 electrical connections, high power microwave and current feedthroughs and short turnaround times as well as an in-situ argon ion gun surface cleaning setup for the suppression of anomalous heating.

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PII-36
Ideal Single Photons from a Cavity-Free Trapped Ion

D. Higginbottom[1,2], **L. Slodicka**[1], **M. Hennrich**[1] **and R. Blatt**[2,3]

[1] Centre for Quantum Computation and Communication Technology, The Australian National University, Canberra, ACT 0200 Australia
[2] Institute for Experimental Physics, University of Innsbruck, Innsbruck, A-6020 Austria
[3] Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, A-6020 Austria

E-mail: Daniel.higginbottom@anu.edu.au

Single photon Fock states are a desirable resource for quantum cryptography protocols and a necessary component of some optical quantum computation schemes. Here we realize a deterministic, tunable, high purity source of single photons using a single Barium ion confined in a linear Paul trap without a cavity. Multi-photon events from this photon source are almost completely suppressed; this allows us to measure with precision the higher order quantum character of the emitted light field using the non-Gaussian optical state witness proposed by Filip and Mista [1].

The ion is trapped at the common focus of two high aperture lens objectives that collect a combined 12% of the ion's dipole emission on the 493 nm Doppler cooling transition. The second order intensity correlation function $g^2(\tau)$ of the field emitted by our photon source violates the coherent state condition $g^2(0) = 0.003 \leq 1$, Fig. 1a, both when driven continuously and when pulsed with a 650 nm repump beam to produce photons on demand, Fig. 1b (inset). Multi-photon events are suppressed to the level of the detector dark count rate. In addition to measuring this high degree of anti-bunching we can demonstrate that the photon statistics of our field display higher order quantum behavior, and cannot be produced by any mixture of Gaussian states, by violating the non-Gaussian witness proposed by Filip and Mista. Under this measure the pulsed field produced by our single photon source is non-Gaussian to more than 50 s.d. in its optimal configuration and produces ideal attenuated single photons under a wide variety of driving conditions, Fig. 2a.

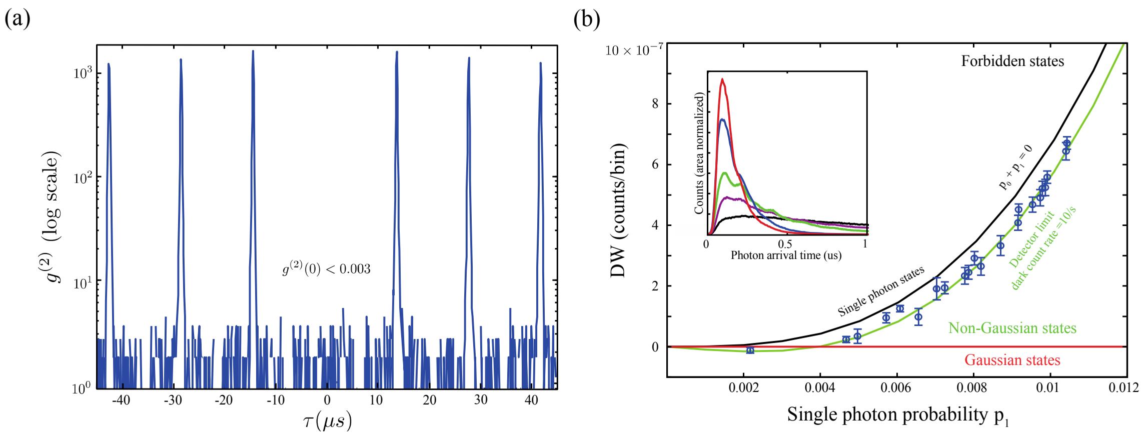

Figure 1. The second order correlation function (a) and non-Gaussian witness (b) of on-demand photons generated by our source under various driving conditions (inset).

Reference

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PII-37
Unconditional classical-to-quantum transition of oscillator interacting with single atom

L. Slodička, P. Marek and R. Filip

Department of Optics, Palacký University
17. listopadu 12, 77146 Olomouc, Czech Republic

E-mail: slodicka@optics.upol.cz

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

PII-38
Topological Quantum Computation with Trapped Ions

D. Nigg[1], M. Müller[2], E.A. Martinez[1], P. Schindler[1], M. Hennrich[1], T. Monz[1], M.A. Martin-Delgado[2] and R. Blatt[1]

[1] Institut für Experimentalphysik, Universität Innsbruck,
Technikerstrasse 25, A–6020 Innsbruck, Austria
[2] Departamento de Fısica Teorica I, Universidad Complutense,
Avenida Complutense s/n, 28040 Madrid, Spain

E-mail: daniel.nigg@uibk.ac.at

The construction of a quantum computer remains a fundamental scientific and technological challenge, in particular due to unavoidable presence of noise. Quantum states and operations can be protected from errors using protocols for fault-tolerant quantum computing (FTQC). Here we present a step towards FTQC by implementing a quantum error correcting code, encoding one qubit in entangled states distributed over 7 trapped ions. We demonstrate the capability of the code to detect one bit flip, phase flip or a combination of both, regardless on which of the qubits they occur. Furthermore, we apply combinations of the entire set of logical single-qubit Clifford gates on the encoded qubit to explore its computational capabilities. The implemented 7-qubit code is the first realization of a complete Calderbank-Shor-Steane (CSS) code and constitutes a central building block for FTQC schemes based on concatenated elementary quantum codes. It also represents the smallest fully functional instance of the color code, opening a route towards topological

Reference

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PII-39
An eight-qubit register with 10^{-5} cross-talk

Ch. Piltz, Th. Sriarunothai, A. F. Varón, and Ch. Wunderlich

Faculty of Science and Technology, Dept. of Physics,
Siegen University, 57068 Siegen, Germany

E-mail: christof.wunderlich@uni-siegen.de

Trapped atomic ions are well suited for many types of experiments in quantum science. Here, we report on recent experimental progress using $^{171}Yb^{+}$ ions confined in a Paul trap that interact via magnetic gradient induced coupling (MAGIC) and are coherently manipulated using microwave and radio-frequency radiation.
The addressing of a particular qubit within a quantum register is a key prerequisite for scalable quantum computing. In general, executing a quantum gate with a single qubit, or a subset of qubits, affects the quantum states of all other qubits. This reduced fidelity of the whole quantum register could prevent the application of quantum error correction protocols and thus preclude scalability. We demonstrate addressing of individual qubits within a quantum byte (eight qubits) and measure the error induced in all non-addressed qubits (cross-talk) associated with the application of single-qubit gates [1]. The quantum byte is implemented using microwave-driven hyperfine qubits in a Paul trap augmented with a static magnetic gradient field. The measured cross-talk is on the order of 10^{-5} and therefore below the threshold commonly agreed sufficient to efficiently realize fault-tolerant quantum computing.

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PII-40
A novel high sensitivity magnetometer with large RF-bandwidth

I. Baumgart[1], J.-M. Cai[2], A. Retzker[3], M.B. Plenio[2] and Ch. Wunderlich[1]

[1] Department Physik, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, 57068 Siegen, Germany
[2] Institut für Theoretische Physik, Universität Ulm, 89069 Ulm, Germany
[3] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Givat Ram, Israel

E-mail: wunderlich@physik.uni-siegen.de

We present a novel method for magnetometry robust against amplitude fluctuations and capable to operate over a large bandwidth of radio frequencies. Current high sensitivity magnetometry relies on dynamical decoupling [1,2] in which fast pulses or continuous fields drive a two level system. These pulses decouple the system from the environment, while at the same time retaining the ability to sense a signal being on resonance with the Rabi frequency or the pulse rate of the decoupling field. Thus, the sensitivity is limited by the stability of the amplitude of the decoupling field. This typically restrains magnetometers to low sensing frequencies, as sensing high frequencies would require large Rabi frequencies which are challenging to stabilize to the required degree. Our new method of quantum sensing relies on the stability of the frequency of the decoupling field and does not depend on its amplitude fluctuations and thus can sense across a broad range of frequencies.
We demonstrate this method using a single $^{171}Yb^{+}$ ion. We utilise the decoupling scheme introduced in [3] that it is robust against amplitude noise by making use of the multilevel structure of atomic systems and demonstrate that it can be merged with a magnetic sensing protocol to achieve a sensitivity of 0.47 Hz/√Hz (16 pT $Hz^{-1/2}$), which is close to the standard quantum limit. In this scheme, the signal to be sensed is controlled by the frequency difference between two microwave sources which is set to be of the order of the Zeeman splitting between the utilised Zeeman sublevels. This method could be used for increasing the signal-to-noise ratio for magnetometry in various physical systems.

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PII-41
Realization of a deterministic single ion source with nanometer resolution

G. Jacob, K. Groot-Berning, S. Wolf, S. Ulm, F. Schmidt-Kaler, K. Singer

[1] Quantum, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany

E-mail: georg.jacob@uni-mainz.de

Our recent progress with a deterministic single ion source which is implemented as a segmented Paul trap with laser cooled ions in the mK regime is presented. The trap geometry is customized for deterministic high resolution ion implantation and obtained by highly efficient field calculation methods [1]. It can operate with a huge range of sympathetically cooled ion species, isotopes or ionic molecules. We have deterministically extracted a predetermined number of ions on demand [2] and focused them with a lateral resolution of less than 10nm [3]. These results are a first step towards the realization of an atomic nano assembler, a device capable of placing an exactly defined number of atoms or molecules into solid state substrates with sub nano meter precision in depth and lateral position. The project is motivated by the quest for novel tailored solid state quantum materials generated by deterministic high resolution ion implantation.

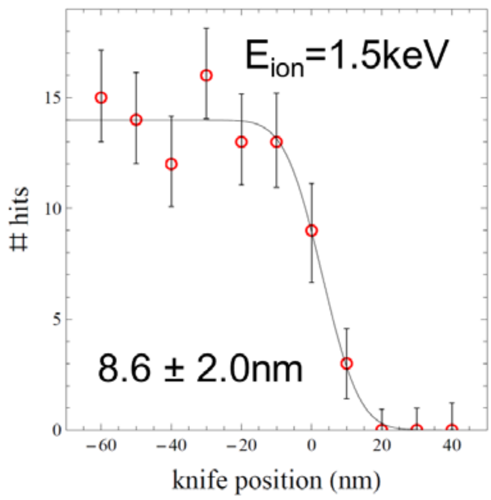

Figure 1

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PII-42
High-fidelity heralded transfer of a photonic polarization state onto an atomic quantum memory

P. Eich, C. Kurz, M. Schug, J. Huwer, P. Müller and J. Eschner

Universität des Saarlandes, Campus E2 6, 66123 Saarbrücken, Germany

E-mail: juergen.eschner@physik.uni-saarland.de

An important building block of an ion-based quantum network is single-photon to single-atom quantum state transfer by controlled absorption. Here we demonstrate heralded mapping of the polarization state of a single laser photon onto the spin state of a single trapped $^{40}Ca^{+}$ ion [1,2]. Successful mapping is signaled by the detection of a single Raman-scattered photon, and reaches 97.85(8) % mean fidelity. We record >80/s successful state transfer events out of 18,000/s repetitions. Fig. 1 illustrates the protocol.

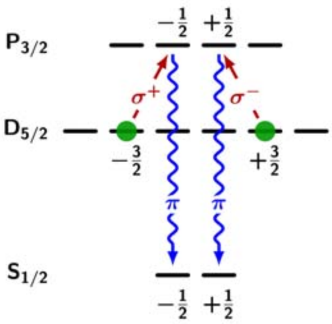

Fig. 1. Experimental procedure [1,2]: first the ion is optically pumped into the |−1/2> sublevel of its $S_{1/2}$ ground state, then an RF π/2-pulse creates a symmetric superposition state of the two sublevels of $S_{1/2}$; this superposition is transferred to the |±3/2> sublevels of the metastable $D_{5/2}$ state through two π-pulses from a laser at 729 nm. A laser pulse at 854 nm in a superposition of σ^+ and σ^- polarization excites the ion from $D_{5/2}$ to $P_{3/2}$. The absorption of a laser photon transfers the ion back to $S_{1/2}$ (with 93.5 % probability), releasing a single Raman photon at 393 nm [3]. Detection of a π-polarized 393 nm photon projects the ion into a superposition state of the $S_{1/2}$ qubit, which is a faithful representation of the polarization qubit of the absorbed 854 nm photon.

Upon detection of a 393 nm heralding photon, successful transfer is verified through atomic state analysis, consisting of an RF rotation pulse (for analysis in a superposition basis), a shelving pulse, and state-selective fluorescence probing with the cooling lasers (at 397 nm and 866 nm). As shown in Fig. 2, the Larmor precession phase of the initial superposition at the moment of the absorption process is imprinted into the final state of the atomic qubit [2]. From the contrast of the oscillation, we derive the fidelity of the transfer for a specific absorbed polarization. From a full quantum process tomography of our mapping procedure we find the average fidelity to be 97.85(8) %.

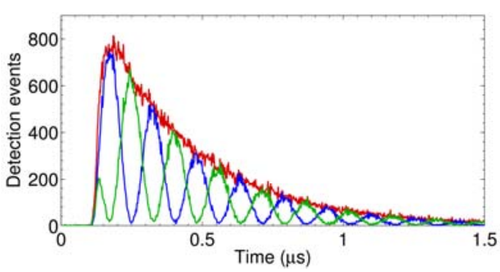

Fig. 2. Arrival-time histograms for 393 nm heralding photons after onset of the 854 nm pulse (2 ns bin-size, 20 min measuring time). Blue and green: conditioned on the outcome of the atomic state analysis (blue: ion in |+1/2>, green: ion in |−1/2>). The oscillation corresponds to the Larmor precession of the initial atomic superposition in $D_{5/2}$; the phase of this oscillation shifts with the orientation angle of the absorbed linear polarization Red: unconditioned, showing no oscillation.

While the single absorption events in this experiment are driven by laser pulses, the results show that the protocol may be readily implemented with true single photons.

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PII-43
Telecom-heralded single-ion single-photon quantum interface

A. Lenhard, M. Bock, S. Kucera, J. Brito, P. Eich, P. Müller, J. Eschner and C. Becher

Experimentalphysik, Universität des Saarlandes, Campus E 2 6, 66123 Saarbrücken, Germany

E-mail: philipp.mueller@physik.uni-saarland.de

We demonstrate the absorption of a single photon by a single ion, heralded by a telecom photon. We use an optical parametric oscillator (OPO) as a source of time-correlated photon pairs. The signal photons in the near infrared cover a region of atomic resonances while the simultaneously created idler photons are at telecom wavelengths. The combination of the OPO cavity together with external filters results in spectral bandwidths in the MHz range, compatible with the aforementioned resonances.
In the present experiment we address the $D_{5/2}$–$P_{3/2}$ transition in a single trapped $^{40}Ca^{+}$ ion at 854 nm. This corresponds to an idler wavelength of 1411 nm (within the telecom-E-band), which is narrow-band filtered by fiber Bragg gratings.
Correlation measurements between signal and idler exhibit a comb-like structure of the photons with an envelope corresponding to the OPO-cavity decay of 22.7 ns (fig. 1). To stabilize the frequency of the signal photons, we send a part of them to the filter system described in [1] and use the transmission signal to give a feedback to the OPO cavity (side-of-fringe stabilization).
The calcium ion is prepared in the metastable $D_{5/2}$ state. It decays with an average lifetime of 1.17 s to the $S_{1/2}$ ground state. This quantum jump is detected through the onset of fluorescence. The lifetime is immensely reduced by the absorption of a signal photon—exciting the ion to the short-lived $P_{3/2}$ state from where it immediately decays to the $S_{1/2}$ state (with 95%). The correlation of the detection times of the quantum jumps with the telecom photons (fig. 2) reveals the possibility to use the telecom photon as a herald of the absorption process [2]. Due to the low losses such telecom photons may form long-range quantum channels via several km of optical fiber.
The lifetime reduction is a direct indicator of the absorption efficiency. By detuning the filter system we carry out a single-photon spectroscopy (fig. 3). This curve agrees very well with the expected dependence.

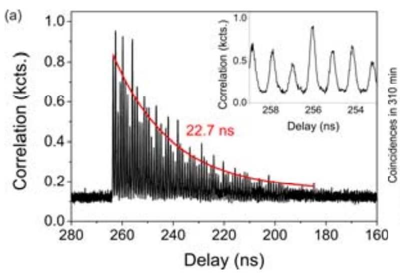

Figure 1

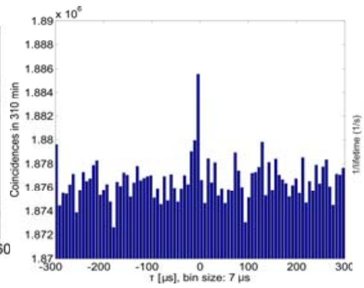

Figure 2

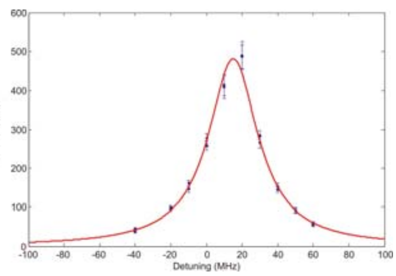

Figure 3

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PII-44
Isospaced ion crystals

M. Johanning

Faculty of Science and Technology, Dept. of Physics,
Siegen University, 57068 Siegen, Germany

E-mail: johanning@physik.uni-siegen.de

We describe the static and dynamic properties of strings of ions stored in segmented electrodynamical Paul traps with a uniform ion separation. In this work, this specific ion arrangement is not achieved by microtraps with uniformly spaced minima but, similar to [1], by an anharmonic effective potential generated by suitable voltages applied to segmented dc electrodes or by appropriate electrode shaping. We find analytic expressions that describe the desired potential which yields uniform spacing and from that calculate normal modes which form a finite width band and the effective spin coupling when the ion string is exposed to a magnetic gradient. We show how the potential, normal modes and couplings can be altered while still maintaining a homogeneous spacing. We show numerical examples for how this potential can be achieved in segmented Paul traps and discuss applications of such ion strings.

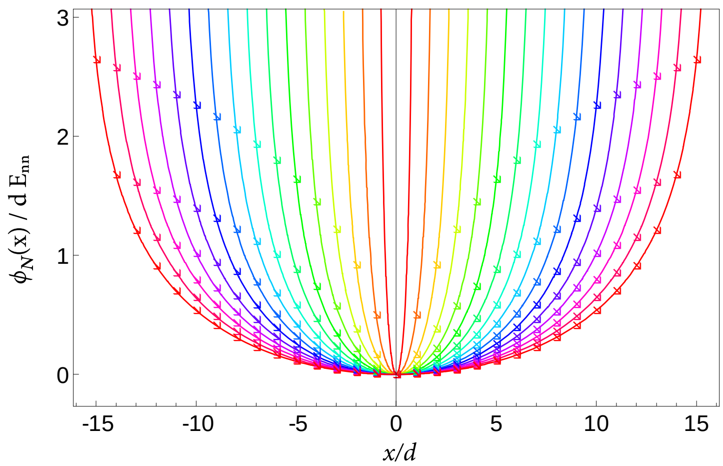

Figure 1. Electrostatic potential to generate equally spaced strings with uneven ion number from 1 (orange) to 31 (red) ions and a next neighbor separation of d in units of the field E_{nn} generated by the next neighbour ion. The notion of constant spacing starts to be meaningful for symmetric potentials and string lengths above three; the formal potential solutions for smaller N exist and are included for completeness. The ion positions with their energy in the external potential are indicated by dots.

Reference
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	Sunday	Monday 15.9.2014	Tuesday 16.9.2014	Wednesday 17.9.2014	Thursday 18.9.2014	Friday 19.9.2014
		Ferdinand Schmidt-Kaler	**Jochen Walz**	**Klaus Wendt**	**Martina Knoop**	**Ernst Otten**
9.00		Wolfgang Hofmeister / Achim Denig	Jens Dilling (TRIUMF Canada)	Gerd Rempe (MPQ Garching)	Mark Reed (Yale)	Rene Gerritsma (Mainz)
9.30		Rainer Blatt (Innsbruck)	Sven Sturm (MPI Heidelberg)	Jeroen Koelemeji (Amsterdam)	Lutz Schweikhard (Greifswald)	Zbigniew Idziaszek (Warschau)
10.00		Jonathan Home (ETHZ)	Robert Wolf (Greifswald)	Stefan Willitsch (Basel)	Danny Segal (Imperial London)	Michael Köhl (Bonn)
10.30		Coffee	Coffee	Coffee	Coffee	Coffee
		Klaus Blaum	**Joachim Ullrich**	**Rainer Blatt**	**Rene Gerritsma**	**Ulrich Poschinger**
11.00		Martin Plenio (Ulm)	Jim Freericks (Georgetown)	Dietrich Leibfried (NIST Boulder)	Tracy Northup (Innsbruck)	Kenji Toyoda (Osaka)
11.30		Ekkehard Peik (PTB)	José Crespo (Heidelberg)	David Lucas (Oxford)	Eric Hudson (UCLA)	Cornelius Hempel (Innsbruck)
12.00		David Leibrandt (NIST Boulder)	Simon van Gorp (RIKEN)	Winfried Hensinger (Sussex)	Michael Drewsen (Aarhus)	David Hucul (JQI Maryland)
12.30		Lunch	Lunch		Lunch	Lunch
		Winfried Hensinger	**Ekkehard Peik**		**Günter Werth**	**Departure / Bus shuttle**
14.30		Tanja Mehlstäubler (PTB)	Niels Madsen (Swansea)		Kelvin Cossel (Boulder)	
15.00	Registration	Stefan Ulm (Mainz)	Jochen Walz (Mainz)	Excursion	Vladimir Shabaev (St. Petersburg)	
15.30		Alex Retzker (Jerusalem)	Yuri Litvinov (GSI)		Sergey Eliseev (MPI Heidelberg)	
16.00		Coffee	Coffee		Coffee	
		Martin Plenio	**Posters 1**		**Posters 2**	Labtours in Mainz
16.30		Roee Ozeri (Weizmann)				
17.00	Welcome	Julen Pedernales (Bilbao)				
17.30		Mikel Palmero (Bilbao)				
19.00	Reception	Dinner	Dinner	Conference Dinner	Dinner	
20.30			Joachim Ullrich (PTB)		Martina Knoop (Marseille) - COST	