Trapped-Ion Physics at GTRI: Towards Large-Scale Integration and Automation*

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Trapped-ion experiments have demonstrated the individual ingredients believed necessary for scalable quantum information processing, and, for small numbers of ions, many of these ingredients have been combined within the same experimental system. Scaling the capabilities of such test-bed systems to larger numbers of qubits will require a higher level of integration between traps, electronics, optics, and control systems than has been achieved to date. Moreover, calibrating and controlling such a complex system with the necessary speed and accuracy will demand a far greater degree of automation, because human intervention will become impractical.

To explore these challenges, the Quantum Information Systems Group at GTRI has microfabricated several ion traps incorporating 40+ control electrodes, including a variety of long linear traps, a trap with a curved mirror microfabricated onto its surface, a trap with integrated microwave lines, and an X-junction trap. In the linear traps we have loaded chains with more than 20 resolved ions, while the mirror trap enhanced the collection of ion fluorescence by a factor of 1.8. In the microwave trap, we have observed Rabi flopping between hyperfine ground states of 171Yb+ with a pi time below 1 us. In the junction trap, a single ion survived more than 65 consecutive round trips between its different legs without laser cooling. This last capability should allow us to reorder the ions in a multiple-species chain (e.g., a chain of Yb+ and Ca+ ions) into an arbitrary linear configuration. Finally, we have developed a machine language, known as “OPCODEs”, that translates high-level schedules directly into experimental operations for our ion traps. The success of OPCODEs relies on automated calibration and control of trap parameters, accurate modeling of the potentials required for compensation, and automated detection of ion positions. We will present our most recent experimental results in these areas.

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Coulomb Collision in Cryogenic Plasma

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An ion trap is a suitable device for the study of the effect of inter-particle correlation in plasma, since gas, liquid, and solid phase plasmas are able to be generated under well controlled condition using the laser cooling method without any change of the device. The correlation among the ions is indicated by the Coulomb coupling parameter Γ defined as the ratio of the Coulomb potential between ions to the average thermal energy of ions. We are interested in the transition of elementary processes between weakly coupled plasma (WCP; $\Gamma<1$) and strongly coupled plasma (SCP; $\Gamma>1$). Coulomb interaction affects many elementary processes in plasma; therefore, the screening mechanism of Coulomb potential is one of the important issues. Debye screening is commonly accepted as a screening mechanism valid in WCP, on the other side, the ion sphere model is adopted in SCP. The Debye length used as a screening length in WCP is proportional to $T^{1/2}$, while, the radius of the ion sphere, which is adopted as a screening length in SCP, does not depend on T. Therefore, the resulting Coulomb collision frequency is proportional to $T^{-3/2}$ and $T^{1/2}$, respectively [1]. It is interesting to study how these screening mechanisms change mutually at the intermediate region between SCP and WCP. In this paper, we report the temperature dependence of the spectral broadening in a laser-cooled one-component plasma confined in a linear rf trap.

Since the laser-cooled plasma is fragile, the measurement method was limited. We developed a non-intrusive laser induced fluorescence (LIF) method using a weak probe laser. Quantitative evaluation of the spectrum broadening becomes possible by using the probe-LIF system. The ion temperature and ion-ion Coulomb collision frequency are derived from the LIF spectrum. A series of the spectrum measurements are performed in the range of Γ = 0.1 to 10. The plot of the collisional broadening width versus T is well fitted by $T^{1/2}$. Therefore, the experimental results show that the ion sphere model is still valid in the intermediate region between WCP and SCP, and Debye screening is already not appropriate at Γ = 0.1.

[1] S. Ichimaru, Statistical Plasma Physics Vol.1, Addision-Wesley, New York, (1991).

Probing Many-Body States of Ion Coulomb Crystals by Ramsey Interferometry

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Recent progress in the creation and manipulation of many-body states of ion Coulomb crystals demands for detection techniques not only of the electronic but also the motional quantum states. Such states are used as a resource for quantum information processing, and were proposed for simulating quantum many-body Hamiltonians [1] as well as for the creation of crystalline cat-states [2,3].

We examine Ramsey interferometry to probe ion Coulomb crystals in state-dependent potentials by evaluating the overlap of the quantum states of the crystal, which determines the contrast of the Ramsey fringes.

We show that Ramsey interferometry can allow one to infer the details of the crystal dynamics [4] at the linear-zigzag structural transition.

[1] D. Porras, F. Marquardt, J. von Delft, and J. I. Cirac, Phys. Rev. A 78, 010101 (2008)
[2] J. D. Baltrusch, C. Cormick, G. De Chiara, T. Calarco, and G. Morigi, Phys. Rev. A 84, 063821 (2011)
[3] W. Li and I. Lesanovsky, Phys. Rev. Lett. 108, 023003 (2012)
[4] T. Pruttivarasin, M. Ramm, I. Talukdar, A. Kreuter, and H. Häffner, New Journal of Physics 13, 075012 (2011)
[5] G. Morigi and S. Fishman, Phys. Rev. E 70, 066141 (2004)

Engineered 2D Ising interactions on a trapped-ion quantum simulator with hundreds of spins

Joe Britton (National Institute of Standards and Technology), Brian Sawyer, Hermann Uys, Mike Biercuk and John Bollinger

Ising interactions are one paradigm used to model quantum magnetism in condensed matter systems. Depending on the details of the interaction, ground states with very different order emerge (e.g. paramagnetic, ferromagnetic or antiferromagnetic). Of particular interest are systems where the underlying lattice structure can frustrate long-range ordering resulting in spin-liquid behavior.

At NIST in Boulder we work with laser cooled 9Be+ ions confined in a Penning trap. The valence electron of each ion behaves as an ideal spin-1/2 particle. Motivated by theory due to Porras and Cirac (PRL 2004), we recently demonstrated a uniform anti-ferromagnetic Ising interaction on a naturally occurring two-dimensional (2D) triangular crystal of $100 < N < 350$ ions in our trap (lattice constant $d0 \sim 20$ um). This number of spins is computationally interesting as it can't be modeled on a conventional computer. The Ising interaction is mediated by a spin-dependent optical dipole force. For spins separated by distance d, we show that the range can be tuned according to (d/d0)^-a, for $0<a<3$. At $a=0$ the coupling is infinite-range while $a=3$ it is a dipole-dipole coupling. Thus far, experiment confirms excellent agreement with mean field theory for $0.05<a<1.4$. For different operating parameters we can also generate an infinite range ferromagnetic Ising interaction.

The high spin-count, excellent quantum control and low technical complexity of the Penning trap brings within reach simulation of important and otherwise computationally intractable problems in quantum magnetism. This work is supported by NIST and the DARPA OLE program.

Heating Mechanisms in Ion Traps.

M. Brownnutt (University of Innsbruck), M. Kumph, P. Rabl, R. Blatt

There are many reasons to bring trapped ions close to things: bringing ions closer to the trap facilitates improved control, while hybrid systems require proximity of ions with other qubits. Trapped-ion quantum computing, however, requires the ions to be cold. The heating an ion experiences when close to (generally hot) external objects is thus a significant limitation to a number of possible developments of ion traps. Surprisingly, the question, “Why does a cold ion get heated when placed next to something hot?” is not simple to answer.

There is evidence that heating can be reduced by cooling the apparatus to cryogenic temperatures. There is further evidence that it can be reduced by cleaning the trap, or by careful design of electronics, or magnetic shielding. Importantly, these solutions are not different ways to solve the same problem, but rather demonstrate that there are multiple underlying problems to be solved. This poster reviews what is known experimentally about heating of trapped ions and considers the various mechanisms which could give rise to the observed behaviour.

Quantum Simulation of Interacting Fermion Lattice Models in Trapped Ions

J. Casanova (Universidad del Pais Vasco), A.Mezzacapo, L. Lamata, E. Solano

We propose a method of simulating efficiently many-body interacting fermion lattice models in trapped ions, including highly nonlinear interactions in arbitrary spatial dimensions and for arbitrarily distant couplings. We map products of fermionic operators onto nonlocal spin operators and decompose the resulting dynamics in efficient steps with Trotter methods, yielding an overall protocol that employs only polynomial resources. The proposed scheme can be relevant in a variety of fields such as condensed- matter or high-energy physics, where quantum simulations may solve problems intractable for classical computers.

Integrated quantum simulation and spectroscopy with trapped ions

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Laser-induced coupling between motional states and internal states of trapped ions enables both scalable quantum information processing and precision spectroscopy with trapped ions. It has recently been shown experimentally [1] how such operations can be realized using near-field microwave sources rather than laser beams, with important implications for scalability and potential high-fidelity operation. We discuss applications of these techniques to precision spectroscopy and quantum simulation.

In particular, we discuss the perspective of inducing spin-spin interactions in a quantum emulator through near-field techniques. The realization of this goal will require quantitative modelling and optimization of near-field microwave geometries. As a first step, we report on efficient numerical simulations of the trap structure used in [1]. We obtain excellent agreement with experimental "tomographic" data using the ion as a field probe.

Furthermore, we present the design of a low-vibration closed-cycle cryogenic ion trap setup. The setup features an integrated 1 Tesla vector magnet which will be used to access field-independent qubits as well as for a proposed experiment on precision quantum logic spectroscopy of the (anti-)proton [2,3]. The setup features excellent optical acces, a bakeable internal vacuum system as well as rapid turnaround for trap testing.

[1] C. Ospelkaus *et al.*, Nature **476**, 181 (2011).
[2] D. J. Heinzen and D. J. Wineland, Phys. Rev. A **42**, 2977 (1990).
[3] D. J. Wineland *et al.*, J. Res. NIST **103**, 259 (1998).

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Rydberg excitation of 40Ca+ ions in a Paul trap

Thomas Feldker (Gutenberg Universität Mainz), Julian Naber, Daniel Kolbe, Matthias Stappel, Ferdinand Schmidt-Kaler

We will present recent progress in our experiment working on Rydberg excitation of trapped calcium ions.

The combination of the high degree of control of quantum states of trapped ions with the dipole interaction of Rydberg states offers interesting possibilities such as fast gates that are independent of vibrational modes.

We are aiming to excite the 3D5/2 to 67P3/2 Rydberg transition in 40Ca+.

For this transition, light with a wavelength of 122.04 nm is provided by a VUV laser source based on four wave mixing in mercury.

Our goal is to study the interaction between the trapping fields(1) and the Rydberg state, effects of Rydberg excitation on the structure of the ion crystal(2) and the dipole interaction between Rydberg ions.

(1) F. Schmidt-Kaler et al., " Rydberg excitation of trapped cold ions: a detailed case study", NJP 13 (2011)
(2) W. Li and I. Lesanovsky, "Electronically Excited Cold Ion Crystals", PRL 108 (2012)

High-precision mass measurements of stored and cooled highly charged ions for fundamental studies at PENTATRAP

Mikhail Goncharov (MPIK), Klaus Blaum, Ch. Boehm, Jos√© R. Crespo L√≥pez-Urrutia, Andreas Doerr, Sergey Eliseev, Christian Hoekel-Schmoeger, Yuri N. Novikov, Julia Repp, Christian Roux, Sven Sturm, Stefan Ulmer

Precise values of atomic masses are of a great importance in many fields of physics. The cryogenic Penning trap mass spectrometer PENTATRAP is currently under commissioning at the Max-Planck-Institute for Nuclear Physics (Heidelberg, Germany). This factory aims for high-precision mass measurements of single stable nuclides with q/m up to bare uranium.

Measurements on PENTATRAP will, e.g., open a way to an experimental determination of an upper limit for the neutrino mass in the electron capture sector with accuracy ~ 1 eV. PENTATRAP aims for a relative mass uncertainty below 10^-11, which is required for QED in strong electric fields and some other tests for the determination of fundamental physical constants.

PENTATRAP R&D has been done to minimize major problems, common for Penning trap mass spectrometers. The setup consists of five Penning traps connected in series and put into cryogenic environment together with detection electronics. One of the traps can be used to monitor a magnetic field. This will minimize a systematic error caused by the drift of the magnetic field in time. Measurements of two ions at the same time (the ion of interest and the reference) will exclude the magnetic field from the resulting mass formula coming from the definition of the cyclotron frequency. This will also increase the final precision. Low-noise cryogenic amplifiers together with high quality factor tuned circuits will provide an extremely high frequency resolution. In the future, Heidelberg EBIT will be connected to the setup allowing one to trap and measure H- like, or even bare uranium ions.

Besides the basis mentioned above, the poster presents a sketch of the measurement procedure, a detection principle used, and gives overall status of the experiment.

IRMPD spectroscopy on differently sized flavins trapped in an ICR cell

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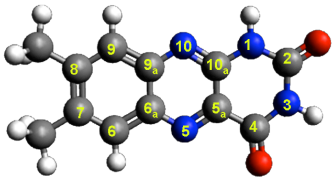

Fig. 1: Structure of lumichrome

Flavins play a very important role in many biochemical metabolic processes. They are involved in the repair of DNA, act as electron donors and acceptors in redox cycles, as catalysts in the *GOx* enzyme responsible for the oxidation of glucose, and as blue-light receptor triggering signal transduction [1]. During its redox cycle the flavin undergoes several protonation states. In this contribution we present the IR multiphoton dissociation (IRMPD) spectra from the protonated flavin molecules of different sizes in the gas phase, starting with the smallest flavin precursor lumichrome LC (neutral structure see Fig.1) going to lumiflavin LF and riboflavin RF. The ions are produced via electrospray ionization, selected and trapped in a FT-ICR spectrometer before interacting with the IR free electron laser FELIX. The photodissociation spectra of the products and the depletion of the parent as function of the wavelength were measured simultaneously in the ICR cell.

The structure of the parent species was identified by performing B3LYP calculations at the cc-pVDZ level and comparing theoretical IR spectra of different low-energetic isomers with the experimentally measured spectrum. The results reveal a dependency of the protonation position on the nature of the N10 substituent X: LC (no X) protonates preferentially at N5 and RF (X=ribose) at N1. In contrast to the literature [2], LF (X=methyl) behaves differently and protonates at the carbonyl C2 oxygen. All identified isomers correspond to the respective, energetically lowest-lying protonated form of each compound. Also the fragmentation pattern is discussed.

In the next future, we plan to measure IR and UV spectra of the flavin ions in a cryogenic 22 pole trap. The set-up of the experiment is still in progress.

[1] V. Massey, Biochem. Soc. Trans. 28, 283 (2000); T.E. Swartz et al., Science 316, 1090 (2007).

[2] S. Salzmann, C.M. Marian, Chem. Phys. Lett. 463, 400 (2008).

Single layer Coulomb crystals of Sr^+ in a surface trap

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We designed and operated a surface ion trap with an ion-substrate distance of 500 μm, realized with standard printed-circuit-board techniques. The trap has been loaded with up to a few thousand Sr^+ ions in the Coulomb-crystal regime. An analytical model of the pseudo-potential allowed us to determine the parameters that drive the trap into anisotropic regimes in which we obtain large ($N > 150$) purely two dimensional (2D) ion Coulomb crystals. These crystals may open a simple and reliable way to experiments on quantum simulations of large 2D systems.

A practical way to realize a large-scale computer architecture relies on surface electrode radio-frequency (rf) traps [1, 2] in which a pseudo-potential well is created above the surface of a substrate by a set of deposited metallic electrodes. The vast majority of the surface traps developed so far [3, 4] are devoted to the trapping and shuttling of short ion strings (one dimensional ion Coulomb crystals). However, the planar geometry can also be exploited to create single layer ion Coulomb crystals. As suggested by Porras and Cirac [5], such crystals are well adapted to simulate quantum phase transitions in spin systems.

In this work we present a linear surface rf ion trap based on a standard printed circuit board and we demonstrate the versatility of such a device that allows for the trapping of large crystallized ion ensembles. Depending on the trap parameters, different crystal shapes can be obtained. In particular, we demonstrated the formation of single-layer Coulomb crystals containing more than 150 ions.

We used a copper FR4 printed circuit board on which strip-lines, forming the ion trap electrodes, were chemically etched and gold-plated (thickness < 1 μm) using standard commercial procedures.

Sr^+ ions are created in the trapping region (typical rate ~ 20 s^{-1}) out of an atomic vapor using a photoionization technique based on two-photon absorption of femtosecond pulses [6]. The ions are Doppler cooled using the 711 THz $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ optical transition ($\lambda = 422$ nm). To avoid optical pumping into the metastable $4^2D_{3/2}$ state we use an additional laser addressing the 275 THz $4^2D_{3/2} \rightarrow 5^2P_{1/2}$ transition ($\lambda = 1092$ nm). The laser setup is very similar to the one described in reference 7.

Following reference 8, we performed an analytical calculation of the pseudo-potential associated to this particular trap geometry. The calculation gives us useful information such as the ion motional frequencies as a function of the trap parameters V_{rf}, V_{CC}, V_{LC} and V_{EC} that determine the trap axial and transverse anisotropies. The ion distance from the trap surface (504μm, imposed by the geometry) and the trap depth are also obtained. Using an approach similar to that described in reference 9, we also calculate the generalized q and a stability parameters: q_x, q_y, q_z a_x, a_y and a_z. As an example, Fig. 1 shows three theoretical radial (xy) cross sections of the pseudo-potential obtained with three sets of trapping parameters that produce anisotropic or isotropic potentials.

Typical fluorescence images of the trapped ions obtained for different trap parameters are shown in Figure 2. In Fig. 2(a) the ions organize themselves in a large three dimensional (3D) Coulomb crystal. We observed 3D crystals containing up to a few thousand ions, comparable to the typical numbers obtained in three dimensional macroscopic linear Paul traps [10]. Another particularly interesting configuration is the single layer Coulomb crystal, demonstrated in Fig. 2(b). Using an imaging system aligned along the x direction, we have checked the single layer character of this Coulomb crystal (bottom image). The non-fluorescing ions visible on the top view of the crystal (left side) are probably sympathetically-cooled strontium isotopes not addressed by the cooling lasers (only $^{88}Sr^+$ is laser-cooled in this experiment). Trap potential calculations allowed us to find a very unusual working point in which the Coulomb

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crystal forms a single layer perpendicular to the trap surface, as shown in Fig. 2(c). Up to sixteen ions have been trapped in this configuration. As mentioned above, these 2D structures may be exploited for the quantum simulation of two dimensional systems [5]. In particular, the "vertical" arrangement could allow for an easier ion addressing by lasers since the control beams could freely propagate without impinging on the trap surface.

[1] J. Chiaverini, R. B. Blakestad, J. Britton, J. D. Jost, C. Langer, D. Leibfried, R. Ozeri, and D. J. Wineland, Quantum Inf. Comput. **5**, 419 (2005).

[2] S. Seidelin, J. Chiaverini, R. Reichle, J. J. Bollinger, D. Leibfried, J. Britton, J. H. Wesenberg, R. B. Blakestad, R. J. Epstein, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, N. Shiga, and D. J. Wineland, Phys. Rev. Lett. **96**, 253003 (2006).

[3] J. Britton, D. Leibfried, J. A. Beall, R. B. Blakestad, J. H. Wesenberg, and D. J. Wineland, Appl. Phys. Lett. **95**, 173102 (2009).

[4] D. L. Moehring, C. Highstrete, D. Stick, K. M. Fortier, R. Haltli, C. Tigges, and M. G. Blain, arXiv:1105.1834v1 [quant-ph] (2011).

[5] D. Porras and J. I. Cirac, Phys. Rev. Lett. **96**, 250501 (2006).

[6] S. Removille, R. Dubessy, Q. Glorieux, S. Guibal, T. Coudreau, L. Guidoni, and J.-P. Likforman, Appl. Phys. B **97**, 47 (2009).

[7] S. Removille, R. Dubessy, B. Dubost, Q. Glorieux, T. Coudreau, S. Guibal, J.-P. Likforman, and L. Guidoni, Journal of Physics B: Atomic, Molecular and Optical Physics **42**, 154014 (2009).

[8] M. G. House, Phys. Rev. A **78**, 033402 (2008).

[9] A. Ozakin and F. Shaikh, Stability analysis of surface ion traps, arXiv:1109.2160v1, 2011.

[10] M. Drewsen, C. Brodersen, L. Hornekær, J. S. Hangst, and J. P. Schifffer, Phys. Rev. Lett. **81**, 2878 (1998).

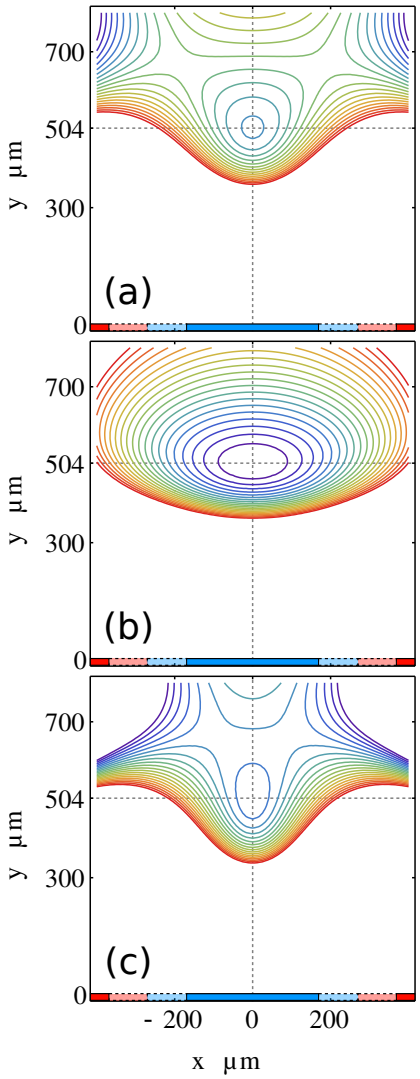

FIG. 1: Pseudo-potential cross sections calculated for three sets of trap parameters. In all cases the ion-surface distance is 504 μm, fixed by the trap geometry and q_x=0.173, q_y=-0.171 and q_z=-0.002. (a) isotropic potential obtained for V_{rf}=125 V (radio-frequency voltage), V_{CC}=-2.25 V (central control electrode), V_{LC}=-11 V (lateral control electrode) and V_{EC}=5 V (end cap electrode). The trap depth is 38 meV and the motional frequencies are ω_x=408 kHz, ω_y=404 kHz, ω_z=156 kHz. The stability parameters are a_x=-0.001, a_y=-0.001 and a_z=0.002. (b) anisotropic potential obtained for V_{rf}=125 V, V_{CC}=3.73 V, V_{LC}=5 V and V_{EC}=5 V. The trap depth is 141 meV and the motional frequencies are ω_x=266kHz, ω_y=529kHz, ω_z=39kHz. The stability parameters are a_x=-0.0091, a_y=0.0090 and a_z=0.0001. (c) anisotropic potential obtained for V_{rf}=125 V, V_{CC}=-6 V, V_{LC}=5 V and V_{EC}=-21.05 V. The trap depth is 13 meV and the motional frequencies are ω_x=474kHz, ω_y=297kHz, ω_z=197kHz. The stability parameters are a_x=0.0039, a_y=-0.0072 and a_z=0.0033. Isopotential curves are separated by 10 meV. The trap schematic cross-section is shown at the bottom of each figure. The dashed lines correspond to the electrode prolongations used to calculate the pseudo-potential

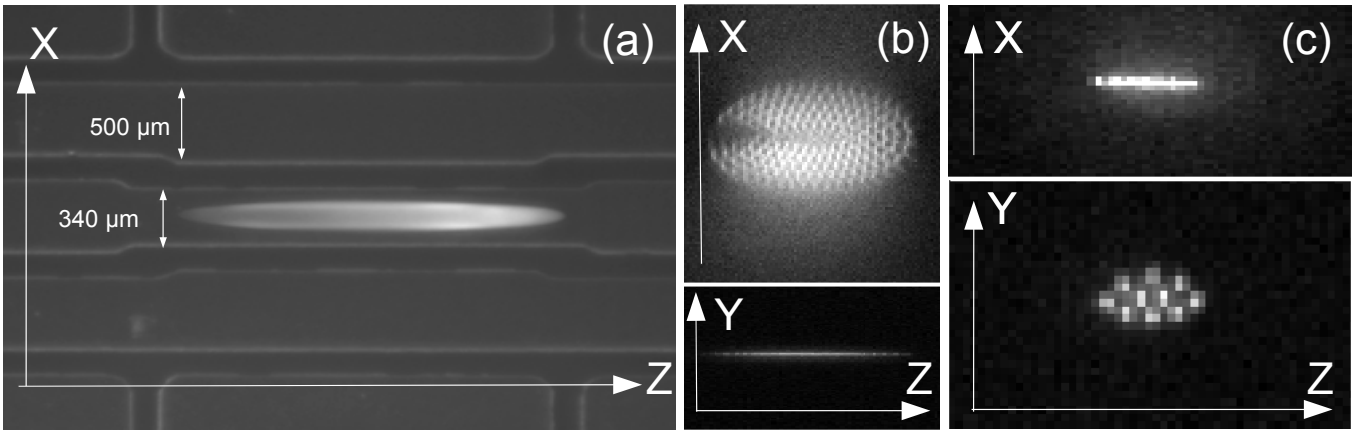

FIG. 2: Fluorescence images of the trapped ions. (a) top-view of a large 3D Coulomb crystal containing ~ 4500 ions. (b) 2D Coulomb crystal containing ~ 150 ions arranged in a plane parallel to the trap surface (the inter-ion distance is 11 μm). The single-layer character is evidenced by the lateral view. (c) Single-layer crystal arranged in the yz plane perpendicular to the printed circuit board (the inter-ion distance is 9 μm).

Cold atomic and molecular collisions in ion – atom hybrid traps

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We present the results of experimental investigations into cold reactive collisions between laser- or sympathetically cooled ions and Rb atoms in an ion-atom hybrid trap. We compare the collision systems of Ca^+ + Rb [1] and Ba^+ + Rb, in which both species are laser cooled, and find that for both systems the rate of reaction is considerably enhanced in electronically excited channels. We find that radiative processes play an important role in both systems, verified by the observation of the radative association products $CaRb^+$ and $BaRb^+$. Despite the chemical similarities in these two systems, we observe that the Ba^+ + Rb system has an aggregate reaction rate which is an order of magnitude slower than that for Ca^+ + Rb. We also compare these results on atomic ion systems with collisions of sympathetically cooled N_2^+ molecular ions in their vibrational ground state with ultracold Rb atoms, with average collision energies ($<E_{coll}/k_B>$) down to 20 mK. To our knowledge, this is the first time that reactive collisions with molecular ions have been studied at mK energies. We find that the reaction rate is close to the Langevin rate (i.e the collision rate), and is two orders of magnitude faster than the atomic Ca^+ + Rb system. The results are interpereted with reference to the energetic structure of the reaction partners, and computed potential energy curves calculated using high level electronic structure calculations. The comparison of these results point to a general framework of radiative and nonradiative processes dominating cold reactive collisions in ion-atom hybrid systems.

[1] F. H. J. Hall *et al; Phys. Rev. Lett.* **107**, 243202 (2011)

Quantum logic with calcium ions at Oxford

Thomas Harty (Oxford), David Allcock, Christopher Ballance, Norbert Linke, Derek Stacey, Hugo Janacek, Diana Prado Lopes Aude, David Lucas

In this poster I present recent work done by the ion trapping group at the University of Oxford on Quantum Information Processing (QIP) using trapped calcium ions. I focus on four recent projects. Firstly, we have designed and constructed a surface-electrode ion trap incorporating three half-wave microwave resonators. These resonators are optimised to give high microwave field gradients at the ion in order to produce state dependent forces. Our aim is to carry out microwave-driven two qubit gates [1] in this trap. Secondly, using this trap, we have successfully implemented a magnetic-field-insensitive “clock-state” qubit in the ground state manifold of 43Ca+ at 146G with a coherence time of tens of seconds. Using robust optical pumping and microwave techniques we demonstrate preparation, single qubit gates and readout at fidelities well above those previously demonstrated for a hyperfine qubit.

Thirdly, we have investigated the possibility of reducing the rate of anomalous heating of a surface-electrode ion trap by using laser cleaning [2]. This heating, whose origin is still not well understood, can be a large source of error in multi-qubit experiments. We demonstrated for the first time that it can be reduced by cleaning processes.

Finally, I report on our work to entangle mixed-species crystals of 40Ca+ and 43Ca+ ions. The isotope shift (>1GHz) allows us to individually address the two ions. Transitions are driven by two Raman lasers, which manipulate both isotopes with low scattering error and high Rabi frequency [3]. We have achieved Raman sideband cooling close to the ground state ($n < 0.1$) and simultaneous readout on both isotopes.

[1] C Ospelkaus et al. Nature 476, 181 (2011)
[2] D.T.C. Allcock et al New J. Phys. 13 123023
[3] R. Ozeri et al Phys. Rev. A 75(4), pp. 1-14 (2007)

New implementation of an indium-ion optical clock

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Exceptional fractional frequency uncertainty of parts in 10^{-18} has been reported using $^{27}Al^{+}$ in a single-ion optical clock [1]. Here we investigate another promising ion candidate; indium ($^{115}In^{+}$) which, like $^{27}Al^{+}$, has small blackbody radiation shift compared to other neutral and ionic clock candidates. Although current techniques using indium have been unable to reach this level of performance, recently proposed new implementations [2] indicate this exceptionally low uncertainty is attainable. This new approach sympathetically cools an indium ion using laser-cooled Ca^{+} ions, and detects the clock transition ($^{1}S_0$-$^{3}P_0$, 237nm) by electron shelving using CW light at the $^{1}S_0$-$^{3}P_1$ transition (230nm, 360kHz), or using the $^{1}S_0$-$^{1}P_1$ transition (159nm, ~200MHz) by pulses prepared by high harmonic generation. In the former detection scheme, high stability of the clock laser of a Sr optical lattice clock is transferred to that of the In^{+} optical clock, and reduces frequency drift during the relatively long feedback cycle. This *hybrid clock* approach might integrate the high stability of the Sr optical lattice clock and the high accuracy of the In^{+} clock. The details of recent progress are reported in the poster.

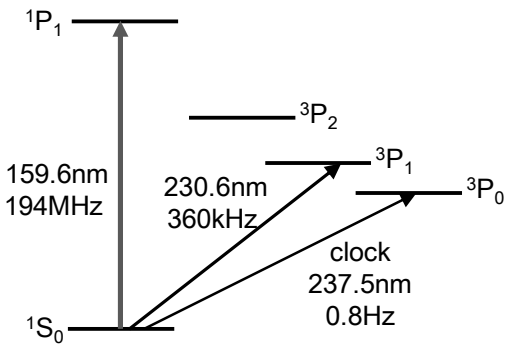

Figure 1. Relevant energy levels and transitions in In^{+}

[1] C.-W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, Phys. Rev. Lett. **104**, 070802(2010)
[2] K. Hayasaka, Appl. Phys. B. Doi: 10.1007/s00340-012-4909-9 (2012)

Trapping and shuttling in a microfabricated 2-dimensional ion trap lattice array

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Microfabricated ion traps have shown significant advances in the past few years towards scalable quantum computing, with the demonstration of ever more advanced features and capability [1]. Architectures for the implementation of quantum simulations are challenging to prepare [2]. Here we report trapping and shuttling within a 2-dimensional microfabricated ion trap array consisting of a two-dimensional ion trap lattice [3]. Each lattice site has 4 neighbouring lattice sites where interactions can occur. Shuttling of single ions between lattice sites allows for additional flexibility increasing the overall functionality of the ion trap array. Our ion chip represents a versatile architecture for 2-dimensional quantum simulations with trapped ions.

[1] M. D. Hughes, B. Lekitsch, J. A. Broersma and W. K. Hensinger, Microfabricated ion traps, Contemp. Phys. 52, 505 (2011).

[2] J. D. Siverns, S. Weidt, K. Lake, B. Lekitsch, M. D. Hughes and W. K. Hensinger, Optimization of two-dimensional ion trap arrays for quantum simulation, New J. Phys. 14 085009

[3] R. C. Sterling, H. Rattanasonti, S. Weidt, K. Lake, P. Srinivasan, M. Kraft and W. K. Hensinger, Trapping and shuttling in a microfabricated 2-dimensional ion trap lattice array, In preparation

Controlling the motional state of an ion during fast transport

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To scale up quantum information processing with trapped ions, fast transport while controlling the ion's motional state is a major challenge. Here, we report on the transport of a single, ground-state-cooled ion over a distance of 280 um in only 5 motional cycles of the trap (3.6 us) with a total energy increase as low as 0.1+/- 0.01 motional quanta. We could also show, that a spin-motion entangled state is preserved throughout such a transport operation.
(A. Walther et. al, arxiv:1206.0364, 2012)

A generalized Ramsey excitation scheme with suppressed light shift

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The most impressive progress in the field of optical frequency standards has recently been made with optical transitions between states with vanishing electronic angular momentum ($J = 0$) in single ions or neutral atoms. We investigate an optical clock referenced to a very different type of transition, an electric-octupole transition ($\Delta J = 3$) connecting the $^2S_{1/2}$ ground state with the $^2F_{7/2}$ first excited state in $^{171}\mathrm{Yb}^+$. The extraordinary features of this transition result from the long natural lifetime on the order of five years and from the $4f^{13}6s^2$ configuration of the upper state. The coefficients for field-induced shifts of the $^2F_{7/2}$ state are smaller than for the metastable D states in the alkaline earth ions. The small natural linewidth of this transition offers a huge potential for stability. However, the high optical power required for driving the transition leads to a large light shift. Another interesting aspect of the transition is the strong sensitivity of its frequency to variations of the fine structure constant α.

Recently, we have realized an optical clock based on the octupole transition in a single laser-cooled trapped $^{171}\mathrm{Yb}^+$ ion with a fractional frequency uncertainty of 7.1×10^{-17} [1]. A significant contribution to this uncertainty is caused by the light shift induced by the laser driving the octupole transition. We have therefore realized for the first time a generalized Ramsey excitation scheme proposed in [2] – using two pulses that are tailored in duration, frequency and phase. We demonstrate the elimination of the light shift sensitivity of the frequency of the central Ramsey resonance, which largely reduces the corresponding uncertainty and suppresses the shift effect by four orders of magnitude.

References

[1] N. Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012).

[2] V. I. Yudin *et al.*, Phys. Rev. A **82**, 011804 (2010).