Creation of NOON and Dicke states in trapped ions with composite pulses

Svetoslav S. Ivanov,[1,2] Natalia V. Korolkova,[1] and Nikolay V. Vitanov[2]
[1] *School of Physics and Astronomy, University of St. Andrews,*
North Haugh, St. Andrews, Fife, KY16 9SS, Scotland
[2] *Department of Physics, Sofia University, James Bourchier 5 Blvd, 1164 Sofia, Bulgaria*

(Dated: April 14, 2012)

We propose a novel method to create a class of highly entangled states in trapped ions, such as NOON states, Dicke states and superpositions of these. The ions are initialized in the phonon ground state and are addressed globally with a composite pulse that is resonant with the first sideband, red or blue. As a result the creation takes place on comparatively short time scales, typically less than 1 ms. The approach does not pose further restrictions on the Lamb-Dicke parameter and can be applied both inside or outside the Lamb-Dicke regime. Individual access to the ions in the trap is not required.

An ultracold deterministic single-ion source for implantation into solid-state substrates

Georg Jacob (University of Mainz), Stefan Ulm, Sebastian Wolf, Stefan Weidlich, Kilian Singer, Ferdinand Schmidt-Kaler

We have realized a deterministic single-ion source based on a linear segmented ion trap. This method is applicable to a wide range of elements and molecules [1,2]. The second generation of this ion source has the capacity to reach energies of up to 5 keV and trap frequencies in the MHz range, required to ground state cool the ions. For the purpose of solid state doping, the accelerated ions can be focused with an electrostatic lens. In addition, the setup includes a sample substrate, where we are able to image single NV centers, without compromising the UHV conditions.

[1] J. Meijer et al., Appl. Phys. A 91, 567 (2008)
[2] W. Schnitzler et al., Phys. Rev. Lett. 102, 070501 (2009)

Ions in a segmented trap with locally adjustable coupling costants

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

Lehrstuhl Quantenoptik, Department of Physics, Science and Technology, University of Siegen, Siegen, Germany

$*$ *johanning@physik.uni-siegen.de*

We discuss the manipulation of quantum information encoded into the spin states of Doppler-cooled ions with long wavelength radiation [1]. Such radiation with a sub-Hertz frequency stability can be easily obtained by commercial sources. The problem of addressing can be solved by applying a magnetic gradient along the spin chain, which lifts the degeneracy of the transition frequencies and thus allows for addressing in frequency space [2]. Furthermore, this creates an effective long-range spin-spin-coupling, mediated by the Coulomb interaction which allows to perform multiqubit gates [1, 3]. Decoherence due to fluctuating magnetic fields can be strongly suppressed using microwave-dressed states [4] and coherence times up to about 1 s are achieved.

Here we present recent experimental results obtained in a segmented trap with integrated microstructured solenoids [5], allowing for global and local tuning of the axial potential and thus tailored coupling patterns relevant for quantum simulations [6]. Local variations of the axial trapping potential are demonstrated by shuttling, splitting and merging ion strings, showing the general ability to tailor the inter ion separations. We use rf optical double resonance spectroscopy to measure small gradients and apply this technique to charecterize both the external magnetic field, as well as additional variable soleniod based magnetic fields. The inhomogeneity is used to selectively address single ions in a chain in frequency space.

References

[1] F. Mintert, and Chr. Wunderlich, *Ion-Trap Quantum Logic Using Long-Wavelength Radiation*, Phys. Rev. Lett. **87**, 257904 (2001); *Erratum:* Phys. Rev. Lett. **91**, 029902 (2003).

[2] M. Johanning, A. Braun, N. Timoney, V. Elman, W. Neuhauser, and Chr. Wunderlich, *Individual Addressing of Trapped Ions and Coupling of Motional and Spin States Using rf Radiation*, Phys. Rev. Lett. **102**, 073004 (2009).

[3] A. Khromova, Chr. Piltz, B. Scharfenberger, T. F. Gloger, M. Johanning, A. F. Varón, and Chr. Wunderlich, *A designer spin-molecule implemented with trapped ions in a magnetic gradient*, Phys. Rev. Lett. 108, 220502 (2012).

[4] N. Timoney, I. Baumgart, M. Johanning, A. F. Varón, M. B. Plenio, A. Retzker, and Chr. Wunderlich, *Quantum Gates and Memory using Microwave Dressed States*, Nature **476**, 185-188 (2011).

[5] D. Kaufmann, T. Collath, M. T. Baig, P. Kaufmann, E. Asenwar, M. Johanning, Chr. Wunderlich, *Thick-film technology for ultra high vacuum interfaces of micro-structured traps*, Appl. Phys. B 107, 935-943 (2012).

[6] M. Johanning, A. F. Varón, and Chr. Wunderlich, *Quantum simulations with cold trapped ions*, J. Phys. B **42**, 154009 (2009).

Towards a Precise Measurement of Parity Violation in a Single Ra+ Ion

K. Jungmann (University of Groningen), H. Becker, J.E. van den Berg, G.S. Giri, S. Hoekstra, A. Mohanty, M. Nunez Portela, C.J.G. Onderwater, B.K. Sahoo, R.G.E. Timmermans, O.O. Versolato, L. Wansbeek, L. Willmann, H.W. Wilschut

A precise measurement of atomic parity violation in a single Ra+ ion promises a most precise determination of the Weinberg angle at low energies. A comparison of the values of that quantity determined at various values of momentum transfer can set stringent limits on physics beyond the standard model or provide information on its existence. The ongoing experiment at KVI is geared towards a precise measurement of the light shift in the 7S_{1/2} - 6D_{3/2} transition in a single trapped Ra+ ion localized in the center of a Paul trap within a fraction of an optical wavelength. The experimental program includes a determination of the atomic and nuclear properties of various Ra isotopes such as transition frequencies, excited state lifetimes and nuclear charge radii. They are crucial for testing the available atomic structure calculations the extraction of the Weinberg angle.

Recent progress includes also the work of several groups who have improved the atomic theory of Ra+ ions. Our report includes in particular recent experimental the tests of the Ra+ atomic structure calculations and a status report of the parity experiment.

Large Ion Coulomb Crystals in rf Traps

C. Champenois, J Pedregosa-Gutierrez, D Guyomarc'h, M. Houssin, G. Hagel, O. Morizot,
M. Knoop (CNRS/Aix-Marseille Université)

The trapping of large ion clouds or crystals is gaining interest for various applications. Quantum information processing and microwave metrology are only two of possible topics. Our group experimentally studies the dynamics and thermodynamics of trapped ions. In particular the use of very large ion clouds is a challenge but may allow to reach interesting regimes for the study of phase transition and crystallization behavior, or long-range interactions.

Our trapping device is composed of zones of different geometry aligned along a common z-axis. A quadrupole and an octupole linear trap are mounted in line, the quadrupole part being separated in two zones by a center electrode. The geometry of trapping potentials has been optimized numerically [1]. The traps have been dimensioned to allow for the confinement of an ion cloud filling half the trap and reaching crystallization. Variation of the geometry of the trapping potential has an influence on the ion density distribution in the trap. One of the experimental challenges is the shuttling of a large cloud from the quadrupole part to the multipole part without heating or loss of the ions. In order to maximize ion clouds and to optimize shuttling probabilities, protocols have been optimized numerically. Results of experiments and simulations will be reported.

[1] J. Pedregosa, C. Champenois, M. Houssin, M. Knoop, IJMS 290, 100-105 (2010).

Heralded photonic interaction between distant single ions

Christoph Kurz (1), Michael Schug (1), Jan Huwer (1,2), Joyee Ghosh (1,2), Philipp Müller (1), Nicolas Piro (2), Francois Dubin (2) and Jürgen Eschner (1,2)

(1) Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany
(2) ICFO – The Institute of Photonic Sciences, Castelldefels (Barcelona), Spain

A prerequisite for the realization of a quantum network is controlled emission and absorption of single photons by a single atom. Here we present controlled quantum interaction between two remotely trapped calcium ions by single photons.

We release a single photon with controlled temporal shape from the sender ion and transmit it over one meter distance to another ion. At the receiver ion we detect photon absorption with a quantum jump scheme. In cw mode, the absorption reduces significantly the lifetime of the long-lived metastable state at the receiver ion. In triggered photon generation mode we observe coincidences between the quantum jump event and the emission trigger of a photon. Furthermore we use a single ion to detect and characterize the entanglement of photon pairs from a spontaneous parametric down-conversion source [1]. The absorption of a photon at the ion is heralded by coincident detection of the partner photon. We correlate the absorption and coincident detection in three different polarization bases. The reconstruction of the density matrix of the maximally entangled photon state yields that the polarization entanglement of the photons is manifested in the absorption-herald correlation.

[1] J. Huwer et al., arXiv: 1111.1085
http://www.uni-saarland.de/lehrstuhl/eschner

Scalable Ion Quantum Technology

K. Lake[1], B. Lekitsch[1], R. C. Sterling[1], M. D. Hughes[1], J. D. Siverns[1], J. J. McLoughlin[1], S. Weidt[1], D. De Motte[1], S.C.Webster[1], G.S Giri[1], A H. Nizamani[1], P. Srinivasan[2], H. Rattanasonti[2], Jessica Maclean[3], C. Mellor[3], M. Kraft[2] and W. K. Hensinger[1]

[1] Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK
[2] School of Electronics and Computer Science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[3] School of Physics and Astronomy, University of Nottingham, University Park Nottingham NG7 2RD, UK

Scalability is a challenging yet key aspect required for large scale quantum computing and requires the development of ion trap arrays capable of performing high fidelity shuttling, detection and gate operations.

We will present several new trap ion chips developed towards scaling ion trap architectures. These include two-dimensional arrays with tunable interactions between individual sites as well as circular ion trap arrays. We also present a new study on how to more than double the breakdown voltages in ion chips and other microfabricated devices[1]. This discovery is applicable in the entire field of microfabricated and nanofabricated devices and should have large impact in many applications. We will also show how to design optimal two dimensional ion trap arrays for quantum simulation[2].

The use of microwaves improves the scalability of gate operations by allowing ion selectivity as well as the simultaneous entanglement of a large number of ions[3]. The additional use of microwave dressed states reduces the main sources of decoherence[4] which increases the potential for high fidelity gates. We will discuss our work towards the performance of high fidelity scalable gates using these microwave dressed states.

Ion trapping in a cryogenic environment has a multitude of applications. We will present our progress constructing a cryogenic ion trap experiment.

[1] R. C. Sterling, M. D. Hughes, C. J. Mellor and W. K. Hensinger, submitted
[2] J. D. Siverns, S. Weidt, K. Lake, B. Lekitsch, M. D. Hughes, and Winfried K. Hensinger, arXiv:1203.4277, to appear in New Journal of Physics.
[3] F. Mintert and C. Wunderlich, Phys. Rev. Lett. 87, 257904 (2001); 91, 029902 (2003).
[4] N. Timoney, I. Baumgart, M. Johanning, A. F. Varón, M. B. Plenio, A. Retzker and Ch. Wunderlich, Nature 476, 185-188 (2011).

Modes of Oscillation in Radiofrequency Paul Traps

Haggai Landa (Tel-Aviv University), Michael Drewsen, Benni Reznik, Alex Retzker

We examine the time-dependent dynamics of ion crystals in radiofrequency traps. The problem of stable trapping of general three-dimensional crystals is considered and the validity of the pseudopotential approximation is discussed. We derive analytically the micromotion amplitude of the ions, and relate our findings to recent experimental results. We use a recently proposed method to find the decoupled modes which diagonalize the linearized time-dependent dynamical problem. The calculations can be readily generalized to multispecies ion crystals in general multipole traps, and time-dependent quantum wavefunctions of ion oscillations in such traps can be obtained.

Development of a cryogenic surface-electrode ion trap for quantum control

Florian Leupold (ETH Zürich), Joseba Alonso, Ludwig de Clercq, Ben Keitch, Daniel Kienzler, Jonathan Home

We are developing a cryogenic setup with a micro-fabricated ion trap for investigating quantum control and state engineering with multiple ion species. The use of a cryogenic environment aims to realize suppressed ion heating and longer ion lifetime [1, 2], facilitating quantum control of the motion of the ions [3]. We have designed and built a surface-electrode ion trap, which will be placed in an ultra-high vacuum inside an OFHC copper chamber and cooled to 4K by a liquid helium recondenser cryostat. The cryogenic environment and multiple ion species aspects of these experiments present a number of challenges, which must be overcome. Among other developments, I will present details of laser heated atomic ovens, a cryogenic helical rf resonator, cryo-compatible low-stress vacuum windows, and a novel reflective single-piece objective with minimal chromatic aberrations.

[1] Labaziewicz, J. et al. *Phys. Rev. Lett.* **100**, (2008).
[2] Antohi, P. B. et al. *Rev. Sci. Instrum.* **80**, 013103 (2009).
[3] Brown, K. R. et al. *Nature* **471**, 196–199 (2011).

Isotope shifts of Sr^{+} measured in a sympathetically cooled Coulomb crystal.

Brice Dubost,* Benjamin Szymanski, Samuel Guibal, Jean-Pierre Likforman, and Luca Guidoni
Univ Paris Diderot, Sorbonne Paris Cite, Laboratoire Materiaux et Phenomenes Quantiques,
UMR 7162, Bat. Condorcet, 75205 Paris Cedex 13, France

We measured by laser spectroscopy the isotope shifts between natural even-isotopes of strontium ions for both the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ (violet) and the $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ (infrared) dipole-allowed optical transitions. The fluorescence spectra have been taken by simultaneous measurements on a two-species Coulomb crystal in a linear Paul trap containing $\sim 10^4$ laser-cooled Sr^+ ions. The isotope shifts are extracted from the experimental spectra by fitting the data with the analytical solution of the optical Bloch equations describing a three-level atom in interaction with two laser beams. This technique allowed us to increase the precision with respect to previously reported data obtained by optogalvanic spectroscopy or fast atomic-beam techniques. The results for the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ transition are $\nu_{88} - \nu_{84} = +378(3)$ MHz and $\nu_{88} - \nu_{86} = +170(2)$ MHz, in agreement with previously reported measurements. In the case of the unexplored $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ transition we find $\nu_{88} - \nu_{84} = +822(6)$ MHz and $\nu_{88} - \nu_{86} = +400(2)$ MHz. These results provide more data to a stringent test for theoretical calculations of the isotope shifts of alkali-metal-like atoms. Moreover, they simplify the identification and the addressing of Sr^+ isotopes for ion frequency standards or quantum-information-processing applications, especially in the case of multi-isotope ion strings.

Isotope shift measurements by optical spectroscopy provide information about nuclear structure and constitute an important complement to nuclear-physics experiments that investigate nuclear-charge distribution (e.g. muonic x-ray isotope shifts or electron-scattering) [1]. The case of strontium ($Z = 38$) is particularly studied because it belongs to the elements close to the $Z = 40$ subshell closure that causes rapid variation of the nuclear properties as a function of the neutron number [2]. In order to extract information about nucleus, spectroscopic data (i.e. isotope shifts and hyperfine-splitting) have to be compared to some theoretical model, able to evaluate the "electronic factors" that take into account the effect of nuclear charge distributions on the electronic wave-functions. For the alkali-earth elements, these factors are calculated in an easier way for the singly-ionized state, with a single electron in the outer shell. During the last years, impressive progress has been done in performing these calculations that estimate hyperfine structures and the sequences of energy-levels, also in the particular case of strontium [3, 4]. Typical precisions for these calculations can reach the THz for the energy-levels and some tens of MHz for the isotope shifts [5], therefore experimental data are precious to put constraints on it.

In the present work, we report the measurements of the isotope shifts for both natural even-isotopes $^{84}\mathrm{Sr}^+$ and $^{86}\mathrm{Sr}^+$ with respect to $^{88}\mathrm{Sr}^+$.

We address the case of the dipole-allowed transitions $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ ($\nu = 711$ THz) and $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ ($\nu = 275$ THz, $\lambda = 1092$ nm) that we study in laser-cooled trapped-ion samples consisting of two-species Coulomb crystals.

This technique allows us to probe the two isotopes in the same sample during the same frequency-scan, reducing the requirements for laser stabilization needed in the case of sequential experiments [6]. The isotope shifts are extracted from the spectra by fitting the experimental data with the solution of the optical Bloch equations (OBE) describing a Λ three-level atom in interaction with two laser beams. The final precision, estimated by the dispersion of the data and mainly affected by the laser stabilization technique, is between 2 and 6 MHz, depending on the isotope. As mentioned above, such information can feed theoretical models of isotope shifts that are, at the moment, available with larger uncertainties [5, 6]. In the case of the 711 THz transition, we also report a measurement of the frequency-shift of each isotope wit respect to the reference transition $5s^2S_{1/2}(F = 2) \rightarrow 6p^2P_{1/2}(F' = 3)$ of neutral $^{85}\mathrm{Rb}$ [7, 8],

---

*Also at ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

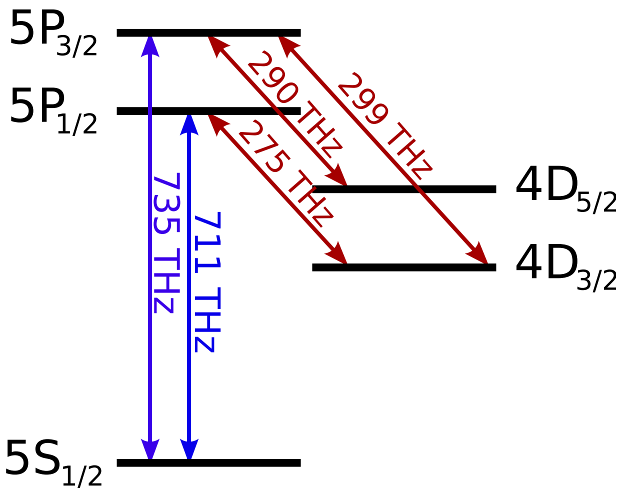

FIG. 1: Low energy levels scheme for Sr^+. In the present work we address the 711 THz violet transition (cooling) and the 275 THz infrared transition ("repumping").

allowing for an absolute referencing of these transitions [9]. This mapping of frequencies and isotope shifts in the case of Sr^+ is particularly useful for quantum information experiments based on this specie [10], especially in the case of multi-isotope sympathetically-cooled ion strings [11].

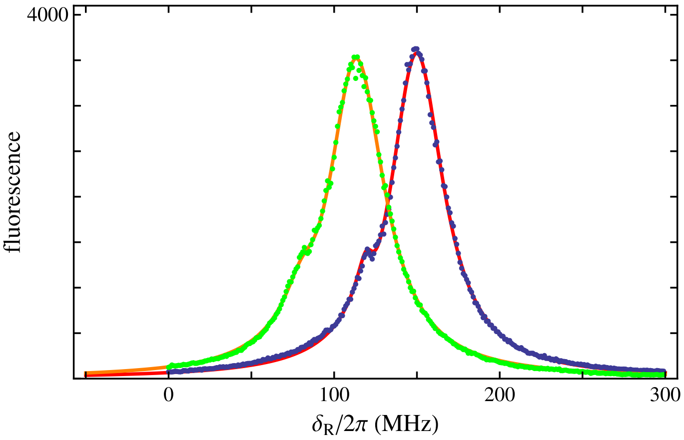

FIG. 2: Twin spectra obtained with a Coulomb crystal composed of equivalent proportions of $^{88}Sr^+$ and $^{86}Sr^+$ ions. The repumping laser detunings δ_r of the two isotopes are scanned simultaneously but there is a constant frequency-shift between the two beams imposed by fixed frequency acousto-optic modulators. The twin spectra in the lower graph are obtained with such a frequency-shift of ~ 40 MHz. The continuous lines are the best fit of the spectra by an a analytical model based on a three level atom (optical Bloch equations).

[1] W. H. King, Isotope Shifts in Atomic Spectra (Plenum, New York, 1984).

[2] F. Buchinger, E. Ramsay, E. Arnold, W. Neu, R. Neugart, K. Wendt, R. E. Silverans, P. Lievens, L. Vermeeren, D. Berdichevsky, et al., Phys. Rev. C **41**, 2883 (1990).

[3] U. I. Safronova, Phys. Rev. A **82**, 022504 (2010).

[4] B. K. Mani and D. Angom, Phys. Rev. A **81**, 042514 (2010).

[5] J. C. Berengut, V. A. Dzuba, and V. V. Flambaum, Phys. Rev. A **68**, 022502 (2003), URL `http://link.aps.org/doi/10.1103/PhysRevA.68.022502`.

[6] W. E. Lybarger, J. C. Berengut, and J. Chiaverini, Phys. Rev. A **83** (2011).

[7] A. Madej, L. Marmet, and J. Bernard, Appl. Phys. B **67**, 229 (1998), ISSN 0946-2171, 10.1007/s003400050498, URL `http://dx.doi.org/10.1007/s003400050498`.

[8] A. G. Sinclair, M. A. Wilson, and P. Gill, Opt. Commun. **190**, 193 (2001), ISSN 0030-4018, URL `http://www.sciencedirect.com/science/article/pii/S0030401801010574`.

[9] A. Shiner, A. Madej, P. Dubé, and J. Bernard, Appl. Phys. B **89**, 595 (2007), ISSN 0946-2171, 10.1007/s00340-007-2836-y, URL `http://dx.doi.org/10.1007/s00340-007-2836-y`.

[10] S. X. Wang, J. Labaziewicz, Y. Ge, R. Shewmon, and I. L. Chuang, Phys. Rev. A **81**, 062332 (2010).

[11] J. P. Home, M. J. McDonnell, D. J. Szwer, B. C. Keitch, D. M. Lucas, D. N. Stacey, and A. M. Steane, Phys. Rev. A **79**, 050305 (2009), URL `http://link.aps.org/doi/10.1103/PhysRevA.79.050305`.

Technologies for quantum control of multi-species ion chains

H.-Y. Lo,[1] D. Kienzler,[1] J. Alonso,[1] B. Keitch,[1] M. Sepiol,[1] F. Lindenfelser,[1] and J. Home[1]
[1]*Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland*

We are developing a new experimental setup in which it is designed to simultaneously trap both beryllium and calcium ions using a segmented linear Paul trap. The main advantage of using two species of ion is that we can individually manipulate each ion species with a wide range of light fields without disturbing the internal states of the other, which we plan to use for simulations of open quantum systems and for scalable quantum information processing. One of the primary challenges at this stage is to build the diverse set of laser light sources required to control both species of ion. We will present recent results in developing 235 nm and 313 nm light sources for photoionisation and control of beryllium ions, and the stabilization of calcium diode lasers to stable cavities. We will also describe our vacuum system and the ion trap, which is fabricated using gold coated laser-machined alumina wafers.

A single ion in the focus of a parabolic mirror – Building block towards efficient free-space light-matter interaction

Robert Maiwald[1,2], Andrea Golla[1,2], Martin Fischer[1,2], Marianne Bader[1,2], Simon Heugel[1,2], Benoît Chalopin[3], Markus Sondermann[1,2], and Gerd Leuchs[1,2]

[1] Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, 91058 Erlangen, Germany

[2] Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, 91058 Erlangen, Germany

[3] Laboratoire Collisions Agrégats Réactivité UMR5589, Université Paul Sabatier Bat. 3R1b4, 31062 Toulouse Cedex 09, France

Applications like quantum memories, gate operations and entanglement distribution benefit from an optimized process of light-matter interaction. Our approach to this active research field is based on an efficient interaction of light with single atomic ions in free space: For this a parabolic mirror can be used to convert a radially polarized Laguerre-Gaussian light field into a linear dipole mode concentrated in the mirror's focus [1, 2]. With the help of a specialized ion trap, the ion can be localized in the paraboloid's focus while keeping almost the entire solid angle optically accessible [3].

We have combined our design of a stylus trap [3] with a parabolic mirror (Fig. 1, *left*) that covers 81% of the solid angle surrounding an ion at the focus. Correcting for the reflectivity of the mirror we infer that more than half the fluorescence from the ion is collected, surpassing the theoretical limit of conventional imaging set-ups based on single lenses/objectives. Furthermore, the unique geometry of our imaging set-up allows observing the movement of an ion in all three spatial directions at once, a useful feature for focus alignment and micromotion compensation. The isotropic fluorescence emission of a single, saturated $^{174}Yb^{+}$ ion is converted by the parabolic mirror into the intensity distribution shown below (Fig. 1, *right*). We present recent results from our experiments.

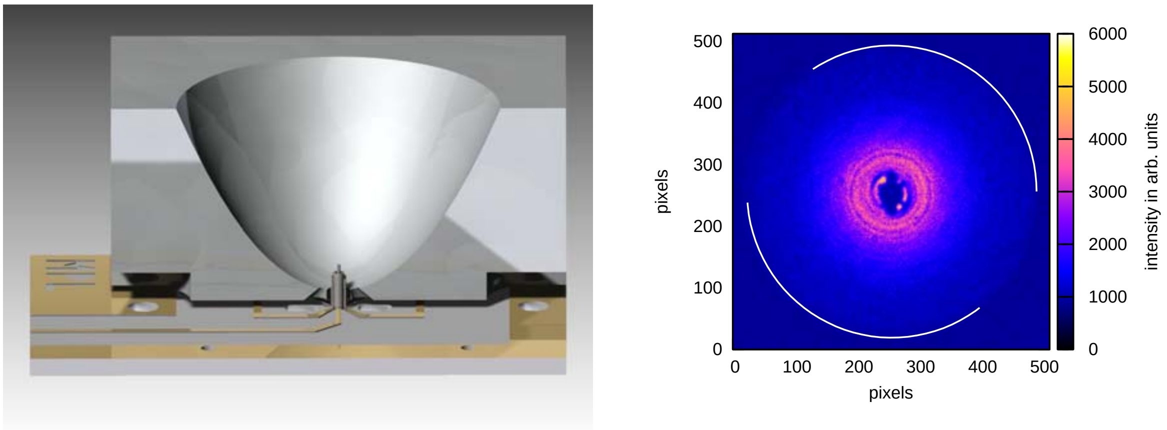

Figure 1: *(left)* Schematic of the set-up, showing a part of the parabolic mirror and the modified stylus trap. *(right)* Intensity distribution of the fluorescence of a single, saturated $^{174}Yb^{+}$ ion located in the focus of a parabolic mirror. The image is taken at the parabolic mirror's front plane and corrected for background counts.

[1] M. Sondermann, R. Maiwald, H. Konermann, N. Lindlein, U. Peschel and G. Leuchs, Design of a mode converter for efficient light-atom coupling in free space, Applied Physics B, **89** (4), 489-492 (2007)

[2] N. Lindlein, R. Maiwald, H. Konermann, M. Sondermann, U. Peschel and G. Leuchs, A new 4π-geometry optimized for focusing onto an atom with a dipole-like radiation pattern, Laser Physics, **17**, 927-934 (2007)

[3] R. Maiwald, D. Leibfried, J. Britton, J. C. Bergquist, G. Leuchs, D. J. Wineland, Stylus ion trap for enhanced access and sensing, Nature Physics **5**, 551 (2009)

Controlled manipulation of a particle motion in a double-well potential

G. Ciaramicoli and I. Marzoli
School of Science and Technologies, Physics Division,
Università degli Studi di Camerino, 62032 Camerino, Italy[*]

(Dated: July 26, 2012)

Recent experiments [1, 2] demonstrated the exchange of quantum information between two ions trapped at a distance of tens of micrometers. Here, instead, we investigate the tunneling dynamics of a single trapped particle in a double-well potential, with the aim of controlling its motional state in a coherent fashion. This requires the ability to drive the transitions between the left and right well with high fidelity and fast rate.

To this end, we propose and compare different methods to manipulate the particle motional states by means of radiofrequency radiation. Depending on the height of the energy barrier and the inter-well separation, it can be easier to drive the direct transition or to resort to a three-level scheme. In the latter case, the localized motional states are coupled, by radiofrequency fields, to a third energy state close to the top of the energy barrier. This setting allows for the application of adiabatic techniques to induce the particle tunneling [3], as well as to prepare its motional state in any arbitrary superposition of left and right [4].

In principle, it is possible to achieve a tunneling rate of the order of several kilohertz with a fidelity of 99%. Our proposal can be implemented, for instance, in segmented Paul traps [1, 2] as well as planar Penning traps [5–11], able to store a single particle in a double-well potential.

Finally, our scheme opens up a further possibility to encode quantum information in the motional states of a trapped particle, by associating the logical states $|0\rangle$ and $|1\rangle$ of a qubit to the particle position in the left or right well.

[1] K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, and D. J. Wineland, Nature **471**, 196 (2011).
[2] M. Harlander, R. Lechner, M. Brownnut, R. Blatt, and W. Hänsel, Nature **471**, 200 (2011).
[3] N. V. Vitanov, T. Halfmann, B. W. Shore, and K. Bergmann, Annu. Rev. Phys. Chem. **52**, 763 (2001).
[4] N. V. Vitanov, K.-A. Suominen and B. W. Shore, J. Phys. B: At. Mol. Opt. Phys. **32** 4535 (1999).
[5] S. Stahl, F. Galve, J. Alonso, S. Djekic, W. Quint, T. Valenzuela, J. Verdú, M. Vogel, and G. Werth, Eur. Phys. J. D **32**, 139 (2005).
[6] F. Galve, P. Fernandez, and G. Werth, Eur. Phys. J. D **40**, 201 (2006).
[7] F. Galve and G. Werth, Hyperfine Interact. **174**, 41 (2007).
[8] P. Bushev, S. Stahl, R. Natali, G. Marx, E. Stachowska, G. Werth, M. Hellwig, and F. Schmidt-Kaler, Eur. Phys. J. D **50**, 97 (2008).
[9] J. Goldman and G. Gabrielse, Phys. Rev. A **81**, 052335 (2010).
[10] J. Goldman and G. Gabrielse, Hyperfine Interactions **199**, 279 (2011).
[11] G. Ciaramicoli, I. Marzoli, and P. Tombesi, Phys. Rev. A **82**, 044302 (2010).

---

[*] `irene.marzoli@unicam.it`

Silicon microfabricated surface traps for trapped ion quantum information processing

Peter Maunz, Emily Mount, Soyoung Baek, Daniel Stick, Matthew Blain, Stephen Crain, Daniel Gaultney, Rachel Noek, Seongphill Moon, Andre van Rynbach, and Jungsang Kim

Duke University, Durham, NC 27708
*Sandia National Laboratories, Albuquerque, NM 87185

Scaling trapped ion quantum computing to the larger number of qubits needed to demonstrate flexible multi-qubit protocols will rely on the integration of advanced microfabricated trap structures with a quantum computing architecture that enables one to extend quantum information processing beyond the number of ions that can be stored on a single trap chip. Remote entanglement and quantum information processing [1] combined with an optical cross-connect switch [2] is a promising approach for achieving moderate scale quantum information processing.

State of the art, monolithically integrated micro-trap structures can store multiple chains of ions on a single chip and provide junctions to deterministically re-order different ion species within multiple ion chains.
Here, we present and characterize microfabricated surface traps developed at Sandia National Laboratories [3]. Our characterization includes trapping single ytterbium-171 ions in a surface trap, measuring heating rates, and demonstrating state initialization and detection with more than 98% fidelity. We use an off-resonant picosecond pulsed laser with stabilized repetition rate to drive Raman transitions between the hyperfine qubit states. Ramsey interferometry demonstrates a coherence time of more than 1.4s.

References
[1] P. Maunz et al., Phys. Rev. Lett. 102, 250502 (2009).
[2] J. Kim and C. Kim, Quant Inf. Comput. 9, 0181 (2009).
[3] D. T. C. Allcock et al., New J. Phys. 13 123023 (2011).

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Towards ground state laser cooling $^{40}\text{Ca}^{+}$ in a Penning trap

Sandeep Mavadia*, Dan Crick, Sean Donnellan, Joe Goodwin, Shamim Patel,
Graham Stutter, Stefan Zeeman, Richard Thompson and Danny Segal
Blackett Laboratory, Imperial College London, London SW11 3NJ, UK
*sandeep.mavadia@imperial.ac.uk

Penning traps use static magnetic and electric fields to trap ions in three dimensions. For a single particle the axial frequency is set by the voltage applied to the endcaps. The radial frequencies are set by a combination of the magnetic field and the electric field. We use a 1.8 T superconducting magnet for radial confinement giving us a cyclotron frequency of 710 x 2π kHz.

Initially, we Doppler cool the ions on the broad S1/2 ↔ P1/2 transition. The Zeeman splitting due to the large magnetic field means that this transition requires two different lasers separated by 69 GHz to stimulate sigma transitions. There are two metastable states, D3/2 and D5/2, which the ion can decay to during Doppler cooling and need to be repumped. There are a total of 10 magnetic sublevels in these two manifolds which are also Zeeman split by many GHz. We are able to repump these levels using just two lasers by making use of a wide bandwidth electro-optic phase modulator.

With only a small magnetic field, the D5/2 manifold would not normally become populated. In our large magnetic field however, LS coupling no longer exactly describes the system and J is not a good quantum number. Thus the forbidden P1/2 ↔ D5/2 transition becomes partially allowed [1].

Ground state cooling using one of the electric quadrupole transitions S1/2 ↔ D5/2 should be possible. We have recently set up a narrow linewidth laser system at 729 nm based on a diode locked to a high finesse (60,000) cavity in a temperature stabilised vacuum chamber at a pressure of 10^{-7} mbar. Laser control has also recently been improved using an FPGA based control system with 20 ns laser pulse length resolution. The same FPGA also counts fluorescence and relays the information to a control computer. We intend to do spectroscopy on the electric quadrupole transitions to detect motional sidebands followed by resolved sideband cooling.

References

[1] D. R. Crick, S. Donnellan, D. M. Segal, and R. C. Thompson, "Magnetically induced electron shelving in a trapped Ca^{+} ion", Phys. Rev. A **81**, 052503 (2010).

Parametric nonlinear oscillator in a Paul trap

Bogdan M. Mihalcea (Natl. Inst. for Laser, Plasma and Radiation Phys)

Many oscillating systems can be modeled by equations similar to the Duffing equation. We assimilate the Hill equation which describes ion motion in a nonlinear Paul trap with the damped, Duffing equation with external forcing. In a more realistic approach, we assume that the trapped ion undergoes interaction with a standing wave laser field. Depending of the five control parameters in the equation of motion, different patterns of motion can be observed, such as stationary long‚Äìterm response (in absence of the kicking term), periodic and quasi-periodic motions as well as chaotic dynamics. Depending on the initial conditions, different types of motion may co-exist. If a sensitive dependence on the initial conditions occurs, then it can be traced back to either the emergence of fractal boundaries between the basins of attraction of rival attractors or to chaotic long-term behavior. In each case, careful numerical investigations possibly combined with analytical procedures are required in order to get a more accurate picture of the complex system dynamics. For sufficiently small perturbation values, according to the Kolmogorov-Arnold-Moser (KAM) theory, we expect to find invariant closed curves (KAM tori). The system under study will be also characterized by means of the bifurcation theory. To visualise periodic, quasiperiodic and chaotic attractors of the system, phase portraits together with Poincar√© cross-sections are used. The Lyapunov spectra used to characterize these transitions will be also investigated.

The analysis can be extended to the case of two ions in a Paul trap, treated as two coupled double or single well Duffing oscillators.

An Ion Trap for Very Large Clouds

C. Champenois, G. Hagel, M. Houssin, **O. Morizot** (Univ Aix Marseille), J Pedregosa-Gutierrez, M. Knoop

The trapping of large ion clouds or crystals is gaining interest for various applications. Quantum information processing and microwave metrology are only two of possible topics. Our group is setting up an experiment destined to the investigation of the dynamics and thermodynamics of trapped ions. In particular the use of very large ion clouds is a challenge but may allow to reach interesting regimes for the study of phase transition and crystallization behaviour, or long-range interactions. Our trapping device is composed of zones of different geometry aligned along a common z-axis. A quadrupole and an octupole linear trap are mounted in line, the quadrupole part being separated in two zones by a center electrode. The geometry of trapping potentials has been optimized numerically [1]. The traps have been dimensioned to allow for the confinement of an ion cloud filling half the trap and reaching crystallization. Therefore the applied trapping voltages are of the order of several MHz with amplitudes of a couple of hundred volts (in order to trap Ca+-ions).

Ions are created by photoionization from an atomic calcium beam crossing the first quadrupole zone. Clouds of more than 105 ions have been trapped and crystallized in the quadrupole part. These ion numbers correspond to cloud sizes which are still largely below 50 percent of the trap radius.

Shuttling of the ions between the different zones of the device is one of the challenges. In view of the large number of parameters (voltage amplitudes, durations, switching functions and times), protocols have to be optimized numerically. While different solutions for shuttling have been proposed for QIP, the present experiment has to take into account additional parameters, as for example the fact that the ion cloud is 3D, and or the ratio of transport distance to the number of DC electrodes which is several orders of magnitude larger than in microtraps. First experimental test are very promising and will be reported.

[1] J. Pedregosa, C. Champenois, M. Houssin, M. Knoop, IJMS 290, 100-105 (2010).