Winter school on Physics with Trapped Charged Particles

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Ecole de Physique des Houches

Book of Abstracts

Contents

1

Detection of vorticity of trapped Bose-Einstein condensate using optical vortex beams

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Vortex states in Bose-Einstein condensate (BEC) play an essential role in macroscopic quantum phenomena like superfluidity and superconductivity. There have been studies to detect and measure the angular momentum of a BEC vortex state using different techniques, like, imaging the density distribution after free expansion , interference between vortex states , and exciting the quadrupole mode of a BEC using an auxiliary laser beam as stirrer . However, the matter-wave interference technique proposed by Bolda and Walls is the only technique till date to determine the handedness of angular momentum of a vortex state. Here we show how the Circular dichorism (CD) like effect that arises in interaction of a BEC with an Laguerre-Gaussian (LG) beam can be useful to propose a new technique to detect both the vorticity and its handedness of a matter-wave vortex of the BEC. Let the sodium BEC is initially prepared in electronic state 3S_1/2,F=1,m_F=-1. The condensate atoms are allowed to undergo two-photon transitions. But now, two sets of pulses are applied simultaneously. One pulse consists of an LG *0+l beam and a Gaussian beam G _1 (LG _0+lG _1 pulse). The other pulse consists of an LG _0-l beam and a Gaussian beam G _2 (LG _0-l/G _2 pulse). When a condensate atom undergoes two-photon transition due to interaction with the LG _0+l /G _1 pulse then the final electronic state is 3S_1/2,F=1 and let us call it as type-I two-photon transition. But if the atom undergoes two-photon transition due to interaction with the LG _0-l/G _2 pulse then the final electronic state will be 3S*{1/2},F=2 and let us call it as type-II two-photon transition. The final electronic states are decided by the polarization of the light fields. The intensities of the beams are selected such that electronic portions of Rabi frequencies corresponding to the type-I and type-II transitions are equal. The difference in Rabi frequencies will come from the center-of-mass portion of transition matrix element. The direction of the applied beams are such that after free expansion, the atoms undergoing type-I two-photon transition should be spatially separable from the atoms undergoing type-II two photon transition. Next, one can image how much fraction of the initial number of atoms has undergone type-I transition and how much fraction has type-II transition. If almost same number of atoms have taken part in both types of transitions then the initial BEC state is a non-vortex state. If a larger fraction of atoms takes part in type-I (type-II) transition then the initial BEC state has vorticity kappa >0 (kappa <0).

Cozzini M, Jackson B and Stringari S 2006 \textit{Phys. Rev. A} \textbf{73} 013603.
Bolda E L and Walls D F 1998 Phys. Rev. Lett. 5477.
Chevy F, Madison K W and Dalibard J 2000 Phys. Rev. Lett. 2223.

Summary:

We study the interaction of optical vortex beam with vortex states of trapped Bose-Einstein condensate. Both the center-of-mass and electronic motion of the condensate atoms are treated quantum mechanically. We demonstrate the dipole Rabi frequency in such interaction depends on the handedness of the orbital angular momentum of the beam. This circular dichorism-like effect can be used to detect matter-wave vortex state and its handedness.

2

A new measurement of the electron mass

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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 constants 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 of the most stringent tests of quantum electrodynamics [1,2,3].
Here an indirect method similar to [4,5] is applied to determine the atomic mass of the electron by measuring the spin-precession frequency of an electron bound to a carbon nucleus in a 3.76 T magnetic field. The single hydrogen-like carbon ion has been trapped for several months in a Penning trap apparatus with a cryogenic temperature of 4K working at an ultra-low pressure (p ≤ 10-16 mbar) vacuum chamber. The electron mass is then extracted from the g-factor of the bound state electron, where the ratio of the electron spin-precession frequency to the ion cyclotron frequency due to the magnetic field is required. The spin-precession frequency is determined based on the continuous Stern-Gerlach effect in a quantum non-demolition manner, while a phase-sensitive detection technique, PnA (Pulse and Amplify [6]), is crucial in determining the cyclotron frequency to an extremely high accuracy.

Summary:

Combining this state-of-the-art QED calculation, which has been calculated to a precision better than 10−11, and our measurement of the ratio of the electron spin-precession frequency to the ion cyclotron frequency, we can derive the electron mass with a relative uncertainty of 3 • 10−11 [7]. We have improved the electron mass by a factor of 13 with respect to the previous CODATA value [8].

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3

Estimation of RF heating and cooling rates of an electron-positron plasma confined in a Combined Trap

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Estimation of RF heating and cooling rates of an electron-positron plasma confined in a Combined Trap

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Abstract

The cross-sections have been estimated for heating of confined electrons and positrons due to two type of RF driven collisions, (a) elastic collisions between electrons/positrons and the background gas molecules (σ_n) (b) Coulomb collisions between electrons and positrons (σ_{ep}), in an electron–positron plasma confined in a RF quadrupole combined trap. Confinement is expected to improve if rate of cooling by cyclotron cooling mechanism as well as by inelastic collisions with CO_2 matches with the rate of heating. For this purpose, buffer gas assisted cooling rate at appropriate pressure as well as the required axial magnetic field have also been estimated in an extension of the case study that had been initiated earlier [1].

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4

Scaling behavior of the ground-state antihydrogen yield from CTMC simulations

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Poster is presented on CTMC simulation and antihydrogen level population calculation results.
Ref: Phys. Rev. A 90, 032704 (2014)

Summary:

Antihydrogen production has reached such a level that precision spectroscopic measurements of its properties are within reach. In particular, the ground-state level population is of central interest for experiments aiming at antihydrogen spectroscopy. The positron density and temperature dependence of the ground-state yield is a result of the interplay between recombination, collisional, and radiative processes. Considering the fact that antihydrogen atoms with the principal quantum number n=15 or lower quickly cascade down to the ground state within 1 ms, the number of such states is adopted as a measure of useful antihydrogen atoms. It has been found that the scaling behavior of the useful antihydrogen yield is different depending on the positron density and positron temperature.

5

Nuclear astrophysics and in-source laser spectroscopy using ISOLTRAP

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The four trap mass spectrometer ISOLTRAP is an experiment primarily dedicated to precision mass measurements of
radioactive nuclides. It is located at ISOLDE allowing investigations of ions produced via spallation, fission or fragmentation by impinging a 1.4 GeV
proton beam on hot targets. The current ISOLTRAP setup consists of a linear segmented radiofrequency cooler and buncher, a multi-reflection
time-of-flight mass separator (MR-ToF MS), a preparation Penning trap and a precision Penning trap. The unique combination of traps recently allowed us
to study the very neutron-rich isotopes of Cadmium. The masses of $^{129-131}$Cd isotopes around the $N = 82$ shell closure were determined. The studied
masses are of great importance as they serve as input parameters to the astrophysical r-process.
Furthermore, ISOLTRAP has the ability to assist the in-source laser spectroscopy program at ISOLDE by complementing the Resonance Ionization

Laser Ion Source (RILIS). RILIS is a chemically selective ion source using multi-step resonant excitation of atoms. In combination with the
MR-ToF MS we successfully obtained the hyperfine structure of Astatine isotopes, from which charge radii and electromagnetic moments can be extracted.
In this contribution the current setup of ISOLTRAP will be presented as well as the techniques for mass measurements of Cd isotopes and
furthermore the laser-spectroscopy measurements of the hyperfine structure in the isotopic chain of At.

6

Fast Coherent Transport in Cryogenic Ion Chip Trap

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Ion trap quantum control is among the most advanced in quantum science. This finds application in pioneering work on quantum information processing and quantum simulation. One of the major challenges at present is to scale these systems up, which requires the ability to "wire up" a larger system of traps by moving quantum information around.

In our newly-realised cryogenic ion trap setup, we are addressing both these challenges. The 4 Kelvin cryostat, greatly reducing background gas collisions and electrode temperature, provides an excellent vacuum preserved in the presence of components which are not compatible with room-temperature vacuum systems.

We want to take advantage of this by placing CMOS switch electronics inside the vacuum system close to the ion trap chip itself. This should in turn allow us to realize a new scheme for quantum state control which involves switching the trapping potentials on nano-second timescales [1]. These timescales are much faster than the ions oscillation frequency, which sets the response time of the ion.

In this setup we have now performed quantum state control of single calcium ions and cooled the motion to the quantum ground state. Current experimental challenges include vibrations due to the pulse-tube head, for which I am investigating several mechanical solutions.

In order to perform quantum state control on radial modes of motion, we would like to actively stabilize the radio-frequency drive of the ion trap. I will present our approaches to doing this, including possible schemes and the current status of our implementation.

I would like to thank ETHZ, SNSF and the QSIT NCCR for funding.

[1] J. Alonso, F.M. Leupold, B.C. Keitch, J.P. Home, *Quantum control of the motional states of trapped ions through fast switching of trapping potentials*, New Journal of Physics **15 (1367-2630/13/023001)**, 25 (2013).

Summary:

Results from a cryogenic ion trap experiment in which we have recently trapped calcium ions will be presented. We are working towards the use of this setup to investigate control of ions by switching the trap potentials much faster than the ions can respond. This opens up new directions in quantum control of trapped ions. I will present work towards this goal, focusing on my own recent work, e.g. vibration isolation and RF amplitude stabilization of the system.

7

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

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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.
On my poster I report on quasiparticle dynamics observed in a quantum many-body system of trapped atomic ions [1]. In detail I present the implementation of the Ising Hamiltonian and the performed experiments on the system: We investigated how entanglement is distributed by quasiparticles, as they trace out lightcone-like wavefronts, and observed the predicted non-local transport of information and breakdown of the light-cone picture.
Furthermore we artificially constructed approximate Eigenstates of the system, to perform spectroscopy on low lying energy levels and observe signatures of quasiparticle interactions.

[1] P. Jurcevic et al., Nature, 511, 202-205 (2014).

8

Towards sympathetic cooling and quantum logic based readout of single trapped (anti-)protons

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CPT test, g-factor measurement, quantum logic operations, optical manipulation system, imaging system

Summary:

We present quantum logic inspired manipulation and detection schemes for a CPT test experiment based on a g-factor comparison between single trapped protons and antiprotons. The basic idea is to

cool, detect and manipulate single trapped (anti-)protons through their interaction with a co-trapped and laser-cooled atomic ion following the proposal by Heinzen and Wineland [1]. We discuss ion trap geometries and spin state transfer schemes as well as laser systems and optical systems for manipulating and detecting the atomic ion.
We acknowledge funding by the ERC (ERC StG "QLEDS"). This project is supported by the BASE collaboration. [1] Heinzen and Wineland, PRA 42, 2977 (1990)

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Microwave near-field quantum logic techniques for a cryogenic surface-electrode trap

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Surface-electrode traps, microwave-quantum-logic techniques, field-insensitive $^9Be^+$ qubit, reconfigurable rf voltages, microwave pulse-shaping, cryogenic ion trap

Summary:

We describe the necessary control infrastructure for experiments with integrated microwave near-field surface-electrode ion traps at cryogenic temperatures with applications in quantum simulation and quantum logic. A trap geometry recently developed in our group [1] implements the coupling between the ions'motional and internal state using only a single meander-shaped microwave-conductor. The realization of high-fidelity quantum-logic-operations requires a static bias magnetic field, microwave control fields for single-qubit rotations and sideband transitions, dc voltages for trapping fields and reconfigurable rf trapping potentials. We present the current status of the experiment at room temperature and give an outlook for a future setup at cryogenic temperatures.

Transistor amplifiers with preceding control stages on three rf trap electrodes are used to generate a reconfigurable rf trapping potential. In order to realize a field-independent $^9Be^+$ qubit at 22.3 mT, we have designed a set of water-cooled magnetic field coils. The microwave currents are generated in FPGA controlled DDS-modules and pass a frequency multiplier and pulse shaping stage. We use fast DAC-modules [2] from NIST to generate arbitrary waveforms for the pulse shaper and also for the dc voltages in the trap.

The distance between the trapped ions and the trap surface is in the order of 30 µm. As a result, anomalous heating of the ions'motion may be considerable. In the cryogenic setup currently under construction, we expect these effects to be suppressed [3,4].

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10

Towards improved experimental control of calcium ion experiments

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In our laboratory, we focus on quantum state engineering with beryllium and calcium ions, including recent demonstrations of squeezed states and spin-motion entangled state interferometry by combining reservoir engineering with unitary operations (Kienzler et al.). In order to improve the quality with which we control our ions, we are currently working to upgrade the system.

One of the primary problems in working on motional state control (including the control required for two qubit gates) is laser frequency noise at the trap frequency. This is problematic because it leads to off resonant carrier excitation when driving sideband transitions. In our system we address the calcium quadrupole transition using a 729 nm laser with a narrow spectrum. The current laser system consists of a Pound-Drever-Hall locking scheme onto a ULE high finesse cavity. The servo-system's limited bandwidth leads to an amplification of frequency components detuned by about 1 MHz, which is close to trap frequencies which we would like to use. I am working to solve this problem by building a laser system based on a filter cavity with subsequent laser power amplification by diode injection and backward seeding of a tapered amplifier.

A strong source of decoherence for our calcium ions are magnetic field fluctuation, which arises due to noise coming from the power lines going to the laboratory and also directly from the current driving our Helmholtz coils. The latter is exacerbated by working at relatively high (11.9 mT) magnetic field at which a field independent quibt is available in beryllium. I will describe different approaches to cancel the mains magnetic fluctuations as well as the fluctuations due to noise in the Helmholtz current.

Summary:

Progress in improving our laser spectra and suppressing magnetic field fluctuations in our laboratory are discussed.

11

Investigation of a ring ion trap for the production of multiply–charged cluster anions

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A multipole ring-electrode trap was built for systematic studies of cluster anions. The Coulomb barrier and electron binding energies of multiply-charged metal clusters are experimentally hardly investigated. Because poly anionic metal-clusters do not exist in nature, they have to be produced in laboratories by cluster electron collision. This can be achieved by combinations of cluster sources

and ion traps 1. A method to investigate the Coulomb barrier is the production of negative charge states with precise electron energies. To do so, one needs a field free region for the cluster-electron interaction where, the cluster ions are trapped simultaneously.
For this purpose a multipole ring-electrode trap [2] was built. The experiment consists of a magnetron sputter source [3], a quadrupole bender, the ring-electrode trap and a section for time-of-flight mass spectrometer (ToF MS). The sputter source is used to produce singly-charged negative metal clusters, which are guided into the trap. Cooled cluster ions can gain multiple charge states by cluster-electron interactions. For those interactions the cluster and electrons need a field free enviroment, which a ring-electrode trap provides. The reaction products can be investigated by ToF-MS. In a next step, the experiment should provide defined charge states for laser interaction experiments. The contribution will discuss the principle and design of the ring electrode trap, preliminaryion-confinement tests and corresponding mass spectra.

1 F. Martinez et al. AIP Conf. Proc. 1521, (2013) 230.
[2] D. Gerlich Inhomogeneous RF fields (1992) III. E
[3] H. Haberland et al. Z. Phys. D, 20 (1991) 413.

Summary:

A multipole ring-electrode trap was built for systematic studies of Coulomb barreiers of cluster anions. A method to investigate the Coulomb barrier is the production of negative charge states with precise electron energies. The experiment consists of a magnetron sputter source, a quadrupole bender, the ring-electrode trap and a section for time-of-flight mass spectrometer.The contribution will discuss the principle and design of the ring electrode trap, preliminaryion-confinement tests and corresponding mass spectra.

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Quantum logic spectroscopy of molecular ions

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Compared to atoms, molecules offer a rich level structure, permanent dipole moment, large internal electric field and additional symmetries. Therefore, molecular quantum systems are well suited for many applications such as quantum computing, high precision spectroscopy, test of fundamental physics, as well as quantum chemistry and astrochemistry.

However, in general direct laser cooling and fluorescence state detection is not applicable, due to the lack of closed optical transitions. Thus, advanced quantum logic spectroscopy techniques, especially for states with short lifetimes lend themselves a powerful readout tool for molecular ions. For the implementation of quantum logic schemes for polar molecules, quantum state preparation poses another challenge, since the rotational states are strongly coupled by blackbody radiation, which makes rotational cooling necessary. Recently, different ro-vibrational cooling techniques ranging from optical pumping to sympathetic cooling have been reported. Although several techniques for rotational cooling were demonstrated, coherent manipulation of single molecular ions for quantum computing or spectroscopy has still remained unfeasible, due to the destructive nature of common state detection techniques e.g. state-selective dissociation (REMPD) or chemical reactions. Here, we present a non-destructive rotational state detection scheme and demonstrate its capability for spectroscopy by implementing an advanced quantum logic spectroscopy scheme combining methods of spectroscopy and quantum computing.

For this purpose, we prepare a translationally cold molecular ion ($^{24}MgH^+$) in a specific ro-vibrational state by employing a variation of the quantum logic technique in which a laser-cooled atomic ion ($^{25}Mg^+$) 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 is achieved via a quantum-non-demolition measurement (QNDM), where the internal state information of the molecule is mapped onto the shared states of motion. The motional state can be read out by applying sideband pulses on the atomic ion and subsequent detection of its internal state.

By analyzing the signal obtained from the QNDM we can extract spectroscopic information about the $X^1\Sigma^+ \rightarrow A^1\Sigma^+$ transition.

Summary:

We present a non-destructive rotational state detection scheme and demonstrate its capability for spectroscopy of a single molecular ion by implementing an advanced quantum logic spectroscopy scheme combining methods of spectroscopy and quantum computing.

13

Towards scalability of quantum computation using Ion traps technologies.

Author: Matteo Marinelli[1]

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One of the major challenges in quantum computation with trapped ions is to scale the system up to large number of ions. In our experiment, we work on the quantum CCD architecture 1, making use of a segmented trap which can load both beryllium and calcium at the same time. The trap has multiple qubit control zones in which we aim to achieve parallel sequences of operations. We have now demonstrated independently many aspects of this architecture, such as quantum logic gates in multiple trap regions, ion shuttling with minimal motional excitation, and sympathetic cooling.

In other to handle the complexity of experimentally demonstrating protocols such as quantum-error-correction, we have developed an FPGA-based controller that can run tens of phase-coherent RF pulses in parallel with fully parameterized pulses and real-time measurements. The experimental sequence is entirely written in C++ allowing for real-time branching and general decision-making to be made conditional on qubit measurements while maintaining phase-synchronous control. With this technology we have demonstrated full control of calcium and beryllium qubits. Using a field-independent qubit in beryllium we have measured coherence times of more than 600 ms.

In order to tackle the problem of fast transport we have developed a 16-channel ar- bitrary wave form generator which calculate the required electro voltages using Tikhonov regularisation and has a cutoff frequency of 50 MHz for each channel. With this approach we are able to perform quit gates by shuttling the ion through a static laser beam. This has advantages for operational latency as well as reducing the requirements on optical control complexity. We have demonstrated these gates for both calcium and beryllium ions. The significant Doppler shifts that we encounter in gates performed on calcium allow us to characterize the velocity profile of our ions during transport.

1 D. Kielpinski, C. Monroe & D. J. Wineland,Architecture for a large-scale ion-trap quantum computer, Nature 417, 709-711 (13 June 2002)

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Matrix Isolation Sublimation (MISu): Cryogenic Atoms and Molecules

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We present the Matrix Isolation Sublimation (MISu) technique for generating cryogenic beams of atoms and molecules for high precision spectroscopy. We have produced beams of Cr, Li, H and Li_2. We have measured temperatures from 16 K all the way down to 1 K, depending on the sublimation regime. The cold beams will be used for high-precision laser spectroscopy and for loading magnetic traps. Main applications are: comparison of hydrogen and antihydrogen spectra, production of cold samples of dipolar molecules for Quantum Information studies and other fundamental physics studies besides ultra-cold chemistry and astrochemistry.
The MISu process is as follows: (1) A matrix of rare or inert gas (Ne, H_2) is first produced by directing a flux of rare gas towards a cold sapphire substrate at ˜4 K. (2) The atomic/molecular species of interest are implanted into the matrix by laser ablation of a solid precursor containing the species. (3) The matrix gas along with the atomic/molecular species of interest is released by a sublimating heat pulse applied to the sapphire substrate. (4) The atoms/molecules fly out into vacuum, entrained or not into the inert gas cloud, depending on the sublimation regime.

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Optimized Setup for Quantum Logic of Molecular Ions

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Molecular ions have a rich level structure and therefore are useful for applications ranging from precision measurements to quantum information processing. Besides the motional degrees of freedom, they exhibit also vibrational and rotational degrees of freedom, rendering direct laser cooling a challenge. We demonstrate sympathetic motional ground state cooling of a $^{24}MgH^+$ molecular ion through a co-trapped $^{25}Mg^+$ ion in this chamber. In this setup, magnesium ions are loaded into the trap via isotope-selective photo-ionization of an atomic beam from a resistively heated effusive source. MgH^+ molecules are created by leaking hydrogen gas into the vacuum system while simultaneously exciting the magnesium ion with a laser to trigger photo-induced chemical reaction between the magnesium ion and the hydrogen molecule. The increased hydrogen background gas pressure of on the order of 10^{-8} mbar degrades the vacuum quality and induces collisions between the ions and the residual gas, mixing rotational states.

This situation can be improved in a newly designed vacuum system by using molecular beams for the loading process. A design of a new vacuum system will be presented which will improve loading and allow trapping of other molecular ion species with applications for tests of fundamental physics. Besides the experimental environment, the control of the various states of the molecular ions is necessary to perform spectroscopy. Our MgH^+ molecular ion is in the vibrational ground state at room temperature and can be laser-cooled sympathetically. A remaining task is the control of rotational states. This can be achieved by coupling these states via a frequency comb to coherently transfer the population from higher to lower rotational states. A non-destructive projective measurement of the target rotational state allows efficient population pumping. Once the rotational ground state is achieved ($J = 0$), the molecular ion can only move to the $J = 1$ state. When this transfer is detecting a pulse from a THz source can be applied to bring it back to the ground state. By combining the newly designed vacuum chamber with the radiation sources mentioned here, quantum logic spectroscopy of molecular ions will become practicable.

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Towards Quantum Logic Spectroscopy of Highly Charged Ions

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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 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 cryogenic linear 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, injection and subsequent trapping of HCIs within a Coulomb crystal of trapped Be^{+} ions.

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 compact EBIT based on permanent magnets and an ultra-low-vibration cryogenic Paul trap.

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Non-Neutral Plasmas in SMall Aspect Ratio Toroidal Electron plasma eXperiment - C

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Stability, equilibrium and transport of electron plasmas in cylindrical traps have been comprehensively investigated owing to their exceptional confinement properties1. In recent times non-neutral plasmas in various toroidal configurations have also raised considerable interest ascribed to the capability of producing equal mass plasmas in such configurations[2], [3]. Investigations of equilibrium, confinement and toroidal effects on non-neutral plasmas are being carried out in several traps [4], [5]. While equilibrium and stability have been theoretically established, fundamental limitation to confinement in toroidal geometries has been predicted to be posed by magnetic pumping transport driven by electron-electron collisions[6]. Present work reports the successful confinement of toroidal electron plasmas for more than a second in SMARTEX-C[7], [8], a SMall Aspect Ratio Toroidal Electron plasma eXperiment in a C-shaped trap. Steady state confinement that outlives single particle toroidal drifts and most non-toroidal losses have now allowed transport studies. Besides, strong toroidal effects gives rise to interesting nonlinear collective dynamics which will be discussed in this paper.

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Development of quantum repeater based on trapped ions at SK telecom

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One of the biggest challenges in applying the current quantum key distribution (QKD) system to large area networks is that the current commercial QKD system cannot connect remote nodes separated by long distances purely in quantum states due to the inevitable attenuation in the fibers. At SK telecom, in addition to a commercial QKD system, we are also developing a quantum repeater based on trapped ions so that a QKD system can be eventually implemented completely in the quantum domain independent of the size of the network.
To build scalable quantum repeater nodes, we have been developing micro-electro-mechanical system (MEMS) fabrication processes for ion trap chips. Using these chips, we trapped both isotopes of 171 and 174 Yb ions, and confirmed that we can shuttle these ions. We can also induce Rabi oscillations with a single 171 Yb ion. In this poster, we will present our on-going research towards the implementation of quantum repeaters at SK telecom.

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Doppler-free two-photon spectroscopy of trapped HD+ ions

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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 we are now implementing 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. From these simulations sub-Doppler lines with a width 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 experimental results at that level with state-of-the-art HD^+ level structure calculations may lead to the most stringent test of molecular QED at the level of $4{\times}10^{-11}$ [3]. Moreover, it will provide a new value of the proton-electron mass ratio with a relative uncertainty of ˜10^{-10}, and enable searches for possible fifth forces ensuing from rolled-up higher dimensions with improved sensitivity [4].

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Towards strong coupling in an ion-trap fiber-cavity apparatus

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With atoms coupled to optical cavities it is possible to build up quantum interfaces between stationary and flying qubits. A quantum network based on these interfaces offers a compelling solution to

the challenge of scalability in quantum computing. By using fiber-based cavities, we expect to reach the strong coupling regime of cavity quantum electrodynamics with single ions.

To that end, we further developed the laser ablation of fiber facets and produced them in a collaboration with the group of Jakob Reichel. The fiber facets are then coated to produce high-finesse fiber mirrors. Specifically, we plan to produce cavities of about 8 µm mode waist and 500 µm in length for use in our integrated ion-trap cavity setup. In parallel, we are currently building a new miniaturized calcium ion trap in the "Innsbruck"linear design.

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A.E.G.I.S. experiment - Antimatter laser cooling part

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The AEGIS collaboration aims to create atoms of anti-hydrogen ($\bar{H}$) and to study the impact of gravity force on it.
In a penning trap, a 3-body-reaction between an anti-proton and an atom of Positronium (Ps=e+ + e-) forms an $\bar{H}$. Then, $\bar{H}$ beam is horizontally accelerated to exit the trap and gravity measurements are performed via a deflectometer.

To improve the reaction efficiency and the gravity measurements, we are interesting in manipulating cold antimatter particles. We studied some ways to laser cool antimatter, and present in this poster two main simulations results:

- Positronium laser cooling? The main issue for cooling Ps is the short lifetimes which are involved: the fundamental triplet state of Ps (called ortho-Ps) has a lifetime of about 142ns. We performed 3D Doppler laser cooling simulations, and results seem to be encouraging!
- pbar and laser cooling? We also studied the possibility of sympathetic cool antiprotons via laser-cooled negative ions that are simultaneously confined in the same ion trap.
We present here simulations results of laser cooled molecular anions (C_2^- species).

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Tutorial 2 Penning Traps

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ARTEMIS: Bound-Electron �-Factor Measurements by Double-Resonance Spectroscopy

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Magnetic moments of electrons bound in highly charged ions provide access to effects of quantum electrodynamics (QED) in the extreme fields close to the ionic nucleus. The cryogenic Penning trap setup ARTEMIS is dedicated to determine the electronic g-factors of highly charged ions such as boron-like argon (Ar^{13+}) via the method of double-resonance spectroscopy. A closed cycle between the fine-structure levels $2^2P_{1/2}$ - $2^2P_{3/2}$ is driven by a laser whereas microwaves are tuned to excite transitions between Zeeman sublevels. With this Larmor frequency and the measurement of the ion cyclotron frequency the g-factor can be determined with an expected accuracy of 10^{-9} or better. Such measurements are also able to resolve higher-order contributions to the Zeeman effect. In this poster we report the commissioning of the novel half-open double trap with in-trap ion creation, characterization of the trap and first measurements performed at ARTEMIS which is part of the experimental program of the HITRAP facility. The double-resonance method can also be applied to g-factor measurements of the hyperfine structures of heavy hydrogen-like ions.

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Cryogenic Penning Trap at VECC

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The development of Cryogenic Penning trap at VECC has reached an advanced stage and the system would soon be commissioned. In this work, we shall describe the simulation, design, and fabrication of a Cryogenic Penning trap system and study its applications. The Penning trap assembly and its associated electronics will be housed in the liquid helium filled bore of a 5-Tesla superconducting solenoid magnet. The Penning trap assembly will comprise a 5-pole open end-cap, orthogonalized, cylindrical Penning trap, associated electronics and its corresponding hanging assembly. A cloud of electrons will be trapped and the eigen-motions of the electrons will be detected by Fourier Transform-Ion Cyclotron Resonance (FT-ICR) method for successful commissioning. The feasibility of trapping high energy electrons in a Penning trap and to measure the relativistic mass increase of such electrons to determine the kinetic energy of individual electrons with very high precision has been studied. The work has the potential to improve the present accuracy of measuring kinetic energy of the end-point of a beta decay spectrum and thus increasing the sensitivity of the electron-antineutrino mass measurement. The idea and technical challenges in experimental realization, to trap and measure the mass of the high energy electrons in VEC-TRAP has been discussed in this work.

Summary:

We have presented the status of Cryogenic Penning Trap at VECC. Various challenges taken up in the process of development has been discussed. The idea of trapping high energy electrons in a Penning trap and to measure the relativistic mass increase of such electrons to determine the kinetic energy with very high precision has been described briefly.

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Compact optical clock with trapped charged particles

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The purpose of this work is to design and realize an optical atomic clock based on the 435,5nm quadrupole transition of the 171Yb+. The study aims at obtaining a frequency stability of 10-14 at one second of integration time in a complete setup volume of less than 100 liter.
To achieve this performance, the Ytterbium ions will be laser-cooled and trapped by electrodynamics fields. In order to satisfy the volume constraints we will design a micro-fabricated surface-electrode (SE) trap and a reduced vacuum chamber for the charged particles. We will also use fibered optical components whenever possible.
SE traps are usually used in quantum information processing setups. The use of such a device in a metrological experiment should also allow the fine characterization of the trap characteristics, such as heating rates and coherence times.

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Near-field microwave operations with 43Ca+ qubits

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Our recent work on performing near-field microwave qubit operations using $^{43}Ca^{+}$ ions will be reported.

Using intermediate-field "atomic clock"states, we have demonstrated single-qubit preparation, gates and readout each with 99.9% fidelity or better, with operation times much less than the qubit coherence time of $T_2^* = 50$s 1. These results were achieved in a room-temperature surface trap incorporating integrated microwave waveguides and resonators, using near-field microwaves to drive the qubit gates [2]. We have also used the same trap to implement two-qubit gates with approximately 90% fidelity, the best ever achieved using microwaves [3].

In a separate experiment, we have designed and fabricated a surface trap to implement scalable independent qubit addressing using near-field microwaves [4]. We drive qubit rotations with microwaves in one trap zone while nulling the microwave field in a neighbouring zone (1mm distant), achieving spin-flip addressing errors of order 10^{-6}.

We have also been working on improving the stability of our 146G magnetic field. This is the most significant source of error in our state preparation and readout in the intermediate-field scheme, and it also limits the quality with which diagnostics and characterisations can be carried out. We expect to be able to achieve a stability of below 1mG rms. Our progress will be reported.

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27

Measurement of the charge exchange cross sections between positronium and (anti)proton and (anti)hydrogen

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The antiprotons will be provided by the ELENA facility at the Antiproton Decelerator, at CERN. They will then be slowed down to 1-10 keV by a decelerator device and focused on a dense positronium cloud, where reactions (1) and (2) will take place . To produce this target cloud, we will use an intense source of positronium that we are developing for the CERN GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment. A low energy linac-based slow positron generator loads a positron accumulator - a multi-electrode Penning- Malmberg trap with 5 T magnetic field. Positrons are cooled by a cold electron plasma, and collected in a potential well. An intense positron pulse is then ejected from the trap onto a converter target made of porous silica, in which positronium will be produced in a cavity with reflective walls, at low kinetic energy. It will be then excited by a pulsed laser beam to its 3d and 2p levels to enhance antihydrogen (ion) production. 3d excitation will be done with an existing laser setup (developed by LKB), using a Doppler-free two-photon reaction induced by two 410 nm laser pulses. For the 2p excitation a 243 nm pulsed laser will be built.

Before working with antimatter, we will measure the production cross section of hydrogen via the charge exchange reaction between protons and excited positronium: $p + Ps \rightarrow H + e^+$ (3), and the subsequent four-body reaction $H + Ps \rightarrow H^- + e^+$(4). In this experiment a proton source will be used. The cross sections determined by the experiment will be compared with the theoretical predictions.

Summary:

We will measure the production cross section of an antimatter ion, the antihydrogen ion. It will be produced by means of a two-step reaction: first the charge exchange reaction $\bar{p} + Ps \rightarrow \bar{H} + e^-$ (1) and then $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ (2), in which antihydrogen produced in the first reaction interacts with another positronium to create an antihydrogen ion.
The results of the experiment will be an important step towards the gravitational measurement of antihydrogen atoms (GBAR project), since the apparatus developed is an essential part of the GBAR instrumentation.

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Towards a measurement of the electron's electric dipole moment using trapped molecular ions

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Trapped molecular ions have the potential to provide several significant advantages in precision measurement experiments due to the ease with which they can be trapped and the long coherence times possible in ground or metastable states. Here we demonstrate precision spectroscopy using clouds of HfF^+ confined in a Paul trap for stringent tests of time-reversal symmetry by measuring the permanent electric dipole moment of the electron (eEDM). In this experiment, we perform Ramsey spectroscopy between magnetic sub-levels of the metastable $^3\Delta_1$ electronic state with a coherence time in excess of 500 ms. We will present our techniques for state preparation and detection, and application of rotating electric and magnetic bias fields. We will also present the results of initial systematic error investigations, and a preliminary eEDM measurement.

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Status of the Canadian Penning trap mass spectrometer at CARIBU

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The Canadian Penning trap (CPT) is currently located at Argonne National Laboratory in the CARIBU facility where intense beams of neutron-rich nuclei are produced from the spontaneous fission of ^{252}Cf. The focus of the current CPT campaign is to provide precision mass measurements of nuclides involved in the astrophysical r-process. To date more than 110 nuclides have been measured to an average mass precision of $\delta m/m \approx 10^{-7}$ using the time-of-flight ion-cyclotron-resonance method. At CARIBU this technique only allows the CPT to probe nuclides with half-lifes longer than $\sim$ 200ms and fission branches larger than 5×10^{-4}%. An upgrade of the CPT detector system to a phase-imaging technique is currently underway which will shorten measurement cycles by a factor of 5-10, allowing us to probe nuclei 1-3 neutrons further from stability than is currently possible.

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Enhancing the control over the ion energy in a hybrid atom-ion experiment

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We investigate the interaction of a laser-cooled trapped ion (^{138}Ba$^+$, ^{87}Rb$^+$ or ^{87}Rb$_2^+$) with an ultracold cloud of optically confined ^{87}Rb atoms. The ion is held in a linear Paul trap and is immersed in the center of
the cold atomic cloud.
By controlling a set of parameters, like changing the micromotion energy, we can manipulate the atom-ion collisions and investigate elastic and inelastic collision phenomena. Using the cold atom gas we can achieve sympathetic cooling of the ^{138}Ba$^+$ to sub-Doppler temperatures (sub mK).
To be able to measure the energy after collisions precisely we are setting up a resolved sideband system for the ^{138}Ba$^+$ ion which I will present.
Another project is to implement a dipole trap at 493 nm for the ^{138}Ba$^+$ ion and to switch off the Paul trap during the atom ion interaction in order to remove the micromotion completely.

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Linear Paul Trap Design for Scalable Quantum Information Processing

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In the Ion Trap Quantum Computing group at Oxford we are working towards demonstrating the building blocks of a scalable quantum computer. Using hyperfine states of ^{43}Ca ions confined in a linear Paul trap we have demonstrated state preparation, state readout, single qubit operations, and two-qubit entangling gates, all below the fault-tolerant error threshold. An important ingredient for a freely scalable architecture is a remote entangling link. We plan to implement this by linking together two multi-ion traps using a photonic interconnect.

This poster presents some design details for a macroscopic linear ion trap which will be used to implement this photonic interconnect. The trap has been reduced in size from the previous design by nearly 50% while still maintaining the same ion-electrode distances, requiring careful design choices to minimise manufacturing tolerances. We have also identified some key technical limitations which have contributed to the two-qubit gate error, and optimised the design to further reduce these errors.

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High fidelity two qubit gates with trapped ions

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In order for quantum computation to become useful for practical purposes, it is necessary to be able to perform two-qubit entangling gates with fidelities high enough that quantum error correction can be applied. Therefore we have performed a careful analysis of the error sources of our system and by identifying the leading error sources we have decreased our two-qubit gate errors by nearly an order of magnitude and got closer to the fault tolerant regime. With a Bell state fidelity of 99.75(7)% we have observed the best two qubit gate fidelity reported so far. Our gate operations are driven by Raman lasers acting on two $^{43}Ca^{+}$ ions trapped in a linear Paul trap. To explore possibilities of coupling to photonic qubits and thus link several traps with each other, we have performed the same gate on two ions of different species (^{43}Ca & ^{40}Ca) and achieved gate fidelities >99%. We have performed tomography on the created Bell state and have violated the CHSH-type Bell inequality by 23 standard deviations (S=2.23(1)).

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Optimized Cooling of Ions by Collisions with Cold Parent Atoms

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We present a combined ion-atom trap which consists of a linear Paul trap and a magneto optical trap (MOT). It traps ions and atoms simultaneously with spatial overlap, and enables us to study interaction between the trapped ions and cold atoms.1
In the experimental configuration described above, cooling of ions has been unambiguously established even for equal mass of ion and the atom due to the localized MOT atom distribution leads to cooling of ions.[2] A single ion-atom resonant charge exchange collision bringing a fast ion to a complete stop will be discussed. The experimental conditions, when such collisions are favorable,

are enumerated. The ion cooling processes have to be numerically computed in the quantum collisions framework for low temperatures.
It has been shown that this cooling of the ions is limited by the micro-motion of ions in the trap in such systems.[3] Numerical calculation and efficient trap designs for minimizing the radio frequency heating and micro-motion effects and there by optimizing the collisional cooling of ions will be presented. Finally the utility and future prospects of this method [4] are discussed.