Winter school on Physics with Trapped Charged Particles

ÉCOLE DE PHYSIQUE DES HOUCHES

Report of Contributions

Contribution ID: **34** Type: **not specified**

MIRACLS - A Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

Collinear laser spectroscopy (CLS) is a powerful tool, with a long and successful history at COLLAPS/ISOLDE, to access nuclear ground state properties such as spin, charge radius, and electromagnetic moments with high precision and accuracy [1]. Conventional CLS is based on the optical detection of fluorescence photons from laser-excited ions or atoms. It is limited to radioactive ion beams with yields of more than 100 to 10,000 ions/s, depending on the specific case and spectroscopic transition. The study of the most exotic nuclides synthesised at ISOLDE consequently demands for more sensitive experimental methods.

Complementary to Collinear Resonance Ionization Spectroscopy (CRIS) [2] or more specialised techniques, e.g. [3], we are currently developing the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS). Supported by an ERC Starting Grant, this novel approach is determined to enhance the sensitivity of CLS by a factor of 20-600. It is centred on an a multi-reflection time-of-flight (MR-ToF) apparatus in which the ions bounce back and forth between electrostatic mirrors [4]. This scheme allows extended observation times and hence higher experimental sensitivity while preserving the high resolution of conventional CLS.

This poster contribution will introduce the MIRACLS concept and will present the current status of the project.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **35** Type: **not specified**

High-precision mass measurements with PENTATRAP

The high-precision Penning-trap mass spectrometer PENTATRAP (1) is currently being commissioned at the Max-Planck-Institut für Kernphysik in Heidelberg. It aims at mass-ratio measurements of stable and long-lived highly-charged ions with a relative uncertainty of below 10^{-11}, a precision so far only achieved for a few relatively light elements (2).
The mass-ratio measurement is carried out by determining the free-space cyclotron frequency in the strong homogeneous magnetic field of a superconducting magnet. A unique feature of PENTATRAP are the five cylindrical Penning traps (3), making simultaneous storage of several ion species, a reduction of the systematic errors and simultaneous in-situ calibration as well as reference measurements possible. Long storage times due to a cryogenic environment and dedicated image current detection systems (4) with single ion sensitivity will lead to high-precision determinations of cyclotron frequencies in all traps.
Mass data at this level of precision have numerous applications, especially for tests of fundamental interactions and their symmetries, among others in neutrino physics research (5) or direct tests of the theory of special relativity (SR) (2, 6). For example, PENTATRAP contributes to the determination of an upper limit of the electron neutrino mass on the 1 eV level within the ECHo collaboration (7) by an independent measurement of the Q-value of the electron capture transition of $^{163}\mathrm{Ho}$ to $^{163}\mathrm{Dy}$. For this measurement an electron beam ion trap is currently commissioned, employing the wire probe injection technique to efficiently inject and produce highly-charged ions of the very rare $^{163}\mathrm{Ho}$ for PENTATRAP. Furthermore, in collaboration with the Insitut-Laue-Langevin in Grenoble (ILL) a direct test of SR in a process where a mass is converted into electromagnetic radiation is planned as in the neutron capture process of $^{35}\mathrm{Cl}$. The mass ratio of $^{35}\mathrm{Cl}/^{36}\mathrm{Cl}$ will be precisely measured at PENTATRAP whereas the photon wavelength is measured by means of crystal Bragg spectroscopy at the ILL.
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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **36** Type: **not specified**

The ALPHATRAP g-Factor Experiment

The ALPHATRAP experiment is a Penning-trap setup dedicated to test bound-state quantum electrodynamics by determining the g-factor of the bound electron in the electric field of highly charged ions (HCI) with ultra-high precision.
The ALPHATRAP experiment is currently in the final stage of commissioning.
The setup exists of a cryogenic double Penning-trap tower in which the HCI can be stored and manipulated for g-factor measurements.
For the production of ions, the setup incorporates an external non-cryogenic compact room temperature Electron Beam Ion Trap (EBIT) for creation of HCI from injected gas, e.g. $^{40}\mathrm{Ar}^{15+}$ or $^{129}\mathrm{Xe}^{25+}$ and a laser ionization source, used for producing singly charged beryllium ions.
A beamline connecting the Heidelberg-EBIT, able to produce HCI up to hydrogen-like $^{208}\mathrm{Pb}^{81+}$, is currently under construction.
In addition to extending measurements of the g-factor of the bound electron into the regime of heavy HCI, a setup for sympathetical laser cooling of the HCI via directly Doppler laser cooled $^{9}\mathrm{Be}^{+}$ ions is currently set up.
With this setup lower ion temperatures could be achieved which is expected to increase the precision of the measurements and reduce unwanted systematic shifts.

An overview and the current status of the project will be presented.

Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **37** Type: **not specified**

Imaging Dark Trapped Ions For Ion-Atom Experiments

Abstract: Low temperature ion-atom interactions have been the object of growing interest over the past decade. Due to the availability of laser cooling for many atoms (Li, Na, K, Rb, Cs, Ca, Sr, Ba, Yb, etc.)[1,2,3] and ions (Ca+, Sr+, Ba+, Yb+ , etc)[4,6,7], the interactions between such ions and atoms have been explored experimentally at mK temperatures[5,7,8]. In the case of optically dark ions (such as Na+, K+, Rb+ and Cs+, for which optical transitions are not accessible via lasers) the ion-atom interactions are at Kelvin temperatures[7,8,9], There is therefore the need to study these dark ion systems at mK temperatures and below, because of the particularly interesting prospect of resonant charge exchange (RCE) interactions, in addition to the elastic collision channel for parent-daughter ion-atom system[10]. Moreover, low mass Alkali ion-atom system have alternate electronic configurations which allow potentials mediating the interactions to be computed with some simplicity.

To investigate these at mK temperatures, we have constructed the experiment described below, which can simultaneously trap Li+ and Ca+ ions. Here we present the results of simulations related to the crystallization of Ca+ and Li+ ion in their common region of stability. We propose a scheme for the characterization of optically dark Li+ ions via extraction on to a microchannel plate.

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Summary

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Contribution ID: **38** Type: **not specified**

Electronic coupling between two ions stored in different traps

The coupling of ions stored in different traps through the charges they induce in a common electrode was proposed in Ref. [1], but it has not been
accomplished yet. The completion of such a system would be an outstanding technological breakthrough in quantum electronics and would pave the
way for the implementation of hybrids systems for quantum information [2]. A pioneer work using radio-frequency traps started at the UC Berkeley several
years ago (see e.g. [3]). With the same technical objective, but now using 7-T Penning traps we started to build the TRAPSENSOR facility at the University of Granada in 2012.
The first scientific aim envisaged is to perform high precision mass spectroscopy utilizing a single, laser cooled, calcium ion as a sensor [4,5]. This will overcome the tradeoffs among precision, number of ions used in the measurement and sensitivity to the target-ion's mass-to-charge ratio existing in current techniques.
To achieve this, the first outstanding goal is to measure the energy transfer between Doppler-cooled ions ($\langle n \rangle \sim 1000$ phonons) stored in different traps [6].
In this contribution we will present the full facility, report on the status of this singular experiment, and present the results obtained in two ion-trapping platforms. The ongoing
work with prospects to reach the single energy quanta exchange level ($\langle n \rangle = 0$) will be also outlined.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **39** Type: **not specified**

Characterization of the nuclear clock isomer ^{229m}Th and search for the optical excitation

The thorium-229 nucleus possesses a unique first excited state at an energy of only about 7.8 eV, coupled to the ground state by a transition with a natural linewidth in the mHz range. This transition can be used as a reference for an optical clock that is highly immune to field-induced frequency shifts and as a sensitive probe of temporal variations of fundamental constants [1]. Despite many experimental efforts, fundamental properties of the isomer were still unknown.
We recently performed the first measurement of the nuclear magnetic dipole and electric quadrupole moments and the mean square charge radius of the isomer [2]. This was achieved via high-resolution laser spectroscopy of the hyperfine structure of trapped ^{229}Th^{2+} ions.
We also plan to investigate the excitation of the nuclear isomer via electronic bridge and NEET processes [3,4], using two-photon laser excitation of high-lying electronic levels in Th^{+} and Th^{2+}.
This work is supported by Horizon 2020 grant agreement no 664732 "nuClock".

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **40** Type: **not specified**

The phase-imaging ion-cyclotron-resonance detection technique used at ISOLTRAP/CERN

The Penning-trap mass spectrometer ISOLTRAP located at the radioactive ion beam facility ISOLDE at CERN performs high-precision mass measurements of short-lived nuclides. This gives access to the study of nuclear structure effects like the location of shell and subshell closures and provides precision β-decay Q-values to test nuclear models and fundamental interactions. For three decades the measurement principle has been based on the time-of-flight ion-cyclotron-resonance (ToF-ICR) detection technique, which is currently reaching its limits for accessible half-lives and relative uncertainties. With the new phase-imaging ion-cyclotron-resonance (PI-ICR) detection technique [S. Eliseev et al., Phys. Rev. Lett. 110 082501 (2013)], experiments can be performed with fewer ions and higher resolving power, providing access to new areas of the nuclear chart. This poster will report on the ion-optical and data-acquisition improvements required for the implementation of the PI-ICR detection technique at ISOLTRAP, as well as results from first on-line measurements in both the high-precision and high-resolution regimes. During a systematic on-line study the Q-value of the ^{88}Sr-^{88}Rb β-decay was determined with an uncertainty of < 130 eV as a validation of the successful implementation of the PI-ICR detection technique with ISOLTRAP. Furthermore, the new detection technique allowed spatial separation of the close-lying isomeric states in ^{127}Cd and ^{129}Cd from which their excitation energy was derived. A mass resolving power $\frac{m}{\Delta m} > 10^6$ was reached for only 100 ms phase-accumulation time.

Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **41** Type: **not specified**

Investigation of two-frequency Paul traps for antihydrogen production

Radio-frequency (rf) Paul traps operated with multifrequency rf trapping potentials provide the ability to independently confine charged particle species with widely different charge-to-mass ratios. In particular, these traps may find use in the field of antihydrogen recombination, allowing antiproton and positron clouds to be trapped and confined in the same volume without the use of large superconducting magnets. We explore the stability regions of two-frequency Paul traps and perform numerical simulations of small samples of multispecies charged-particle mixtures of up to twelve particles that indicate the promise of these traps for antihydrogen recombination.

Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **42** Type: **not specified**

Experimental Cyclic Inter-conversion Between Quantum Coherence and Correlation

Quantum resource theories seek to quantify sources of non-classicality that bestow quantum technologies their operational advantage. Chief among these are studies of quantum correlations and quantum coherence. The former to isolate non-classicality in the correlations between systems, the latter to capture non-classicality of quantum superpositions within a single physical system. Here we present a scheme that cyclically inter-converts between these resources without loss. The first stage converts coherence present in an input system into correlations with an ancilla. The second stage harnesses these correlations to restore coherence on the input system by measurement of the ancilla. We experimentally demonstrate this inter-conversion process using linear optics. Our experiment highlights the connection between non -classicality of correlations and non-classicality within local quantum systems, and provides potential exibilities in exploiting one resource to perform tasks normally associated with the other.

Summary

Here, we illustrated a cyclic scheme where coherence initially in a quantum system A is consumed locally to synthesize an identical amount of discordant correlations with some ancilla B. These correlations are then harnessed to restore coherence in A. Under ideal conditions, this cycle is lossless,
and can be repeated ad-infinitum. We realized one round of this cycle using linear optics, showing explicitly how coherence encoded within a photonic qubit can be converted to discord between it and an ancilla via incoherent operations. By measurement of the ancillary photon, we restored up to 80 percent of the coherence within the original qubit. Our experiment corroborates growing evidence non-classicality in correlations and non-classicality within singular quantum systems are closely connected.

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **43** Type: **not specified**

Study of the antihydrogen ion production in reaction with positronium.

The main goal of the GBAR (Gravitational Behaviour of Anihydrogen at Rest) experiment is to test the week equivalence principle for $\bar{H}$, which has never been measured directly. In order to perform that very complex experiment, ultracold antihydrogen atoms ($\approx 10\mu K$) are needed. As it is impossible to cool down neutrals to required temperature, GBAR is going to produce the antihydrogen ion and measure its free fall after detachment of an extra positron.

Presented poster is describing the ANTION project with the main goal to produce $\bar{H}^+$ for the GBAR, but also to measure antihydrogen atom and ion production cross sections in reactions with positronium, $\bar{p} + ps^* \to \bar{H}^* + e^-$–and $\bar{H}^* + ps^* \to \bar{H}^+ + e^-$. Symmetric reactions to produce H^- are also going to be studied using a proton beam. In order to perform that measurement it is necessary to produce and trap positrons to obtain the high intensity positron pulses (up to a few $10^{10} e^+$/pulse). The accumulated positrons are implemented into a target made of porous silica to form the positronium. Created ps^* cloud is used as a target for (anti)proton, so the (anti)hydrogen production could take place.

In this poster the scheme of the experiment and the current state of its construction and testing will be presented.

Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **44** Type: **not specified**

Breaking Adiabatic Invariance: Energy distribution of a cold positron beam*

Low energy positron beams are used in a variety of applications, including studies of atomic and condensed matter systems.[1] We study here the properties of a magnetically guided cold positron beam (generated in the conventional manner from a 22Na radioisotope source and solid neon moderator [2]) and their relationship to the different magnetic fields along the axis of a 7 m long scattering and annihilation system. Experiments are normally conducted at magnetic fields (˜ 0.6 - 1 kG), where the adiabatic invariance holds well for low positron beam transport energies (˜ 30eV). However, it is found that, for lower magnetic fields and modestly higher initial positron beam energies (˜ 75 eV), adiabatic invariance is broken. Experimental results show deviations from the expected linear dependence of the perpendicular energy ($E_\perp$) distribution with the magnetic field ratio between source and retarding potential analyzer, albeit without violating energy conservation, thus confirming the breaking of adiabatic invariance. The perpendicular energy distribution is uniform across the radial extent of the beam. The implications of this observation will be discussed.

*Work supported by the U. S. NSF, grant PHY 17-02230.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **45** Type: **not specified**

Technological Improvements for Scalable Trapped-Ion Quantum Computing

Recent advances in trapped ion quantum technology have led to impressive results including the demonstration of four qubit GHZ states using subsequent entanglement gates [1] and a dc magnetometer with quantum enhanced sensitivity [2]. We will present the underlying technological advancements, starting with a high-speed multi-channel waveform generator developed in Mainz. The system delivers voltages and waveforms required for high-fidelity gate operations and fast ion transport, splitting and rearrangement of multiple ions. Voltage waveforms are computed using a custom developed software framework, which is capable of automatically generating ideal waveforms for various ion transport operations. In addition, we will discuss improvements of the quantizing magnetic field stability, which is critical for high qubit state coherence times. A permanent magnet setup was developed to significantly improve the stability of the quantizing magnetic field by reducing the effects of temperature drifts on the permanent magnets. Randomized benchmarking is used as a tool to characterize the performance of the setup in quantum information processing.

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Session Classification: Poster session 2

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Contribution ID: **46** Type: **not specified**

Trapped Ions in Rydberg-Dressed Atomic Media

We report on our hybrid experiment which aims at studying trapped ions interacting with ultracold atoms that are off-resonantly coupled to Rydberg states. Since the polarisability of the Rydberg-dressed atoms can be extremely large, the interaction strength between ions and atoms increases tremendously as compared to the ground state case. Such interactions may be mediated over micrometers and could be used to entangle atoms and ions, to study spin-phonon couplings or to mediate spin-spin interactions [1]. Furthermore, we calculate how to employ Rydberg dressing on a dipole-forbidden transition to generate a repulsive atom-ion potential [2]. This prevents collision-induced heating of the ion due to its micromotion, which is found to limit attainable temperatures in atom-ion hybrids. We discuss our experimental approach for Rydberg dressing of Li atoms as well as a detailed theoretical analysis of Rydberg atom-ion interaction.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **47** Type: **not specified**

Probing frequency shifts induced by external perturbations in ^{171}Yb$^+$ and comparing two single-ion frequency standards

The ^{171}Yb$^+$ ion employed in our single-ion optical clocks features two transitions used for the realization of frequency standards, the $^2S_{1/2}$ to $^2D_{3/2}$ electric quadrupole (E2) [1] and the $^2S_{1/2}$ to $^2F_{7/2}$ electric octupole (E3) [2] transition. The E2 transition frequency shows a significantly higher sensitivity to frequency shifts induced by perturbations from external fields. With quantitative knowledge about the field sensitivity of the E2 relative to the E3 transition frequency, shifts of the E3 transition frequency can be corrected more accurately by analyzing changes in the E2 transition frequency than by measuring the frequency shift on the E3 transition directly. Applying this method to perturbations from electric field gradients, we measured the quadrupole moments of the $^2D_{3/2}$ and $^2F_{7/2}$ states and determined their ratio with a tenfold improvement compared to previous measurements [3, 4]. For the relative uncertainty budget of the ^{171}Yb$^+$ E3 clock, this results in a contribution of 3×10^{-19}.
We verify the successful correction of external influences on the E3 transition frequency by comparing two largely independent single-ion clocks that employ significantly different trap geometries, control software and interrogation sequences. We find an agreement of the E3 transition frequencies within the systematic uncertainties. We also show that improvements in the experimental setup allow for longer interrogation times up to 400 ms and reduce the clocks'instability by a factor of two.
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[3] T. Schneider et al., Phys. Rev. Lett. 94, 230801 (2005)
[4] N. Huntemann et al., Phys. Rev. Lett. 108, 090801 (2012)

Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **48** Type: **not specified**

En route to magnetically confined electron-positron pair plasmas

In contrast to a conventional electron-ion plasma, the electron-positron pair plasma is characterized by the mass balance of the two components. Theoretical studies thus predicted long time ago a fundamentally new insight into plasma physics by studying these plasmas. Only recently experimental activities have become more precise e.g. by the APEX project which aims for the creation of a magnetized low-energy electron-positron plasma in the field of a superconducting levitated dipole. A basic prerequisite for the creation of such plasma is the development of techniques for charged-particle injection into a closed magnetic system and subsequent particle manipulation and confinement. In positron experiments with a prototype dipole trap at NEPOMUC, the world's most intense source of low-energy positrons, these challenges have been addressed.
In this contribution, the current state of research for the APEX project will be presented, including the characterization of the NEPOMUC source, recent results from positron injection, manipulation and confinement experiments and complementary single-particle simulations as well as the development of the superconducting dipole device.

Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **49** Type: **not specified**

Quantum logic inspired cooling and readout techniques for a single (anti-)proton

We present techniques tailored for sympathetic cooling and manipulation of a single (anti-)proton in a Penning trap system. Inside our trap a double-well potential is engineered for co-trapping an atomic ion, which enables for the use of quantum logic spectroscopy inspired cooling and readout schemes [1, 2]. These should allow for preparation at sub-Doppler temperatures and a readout of the (anti-) proton's spin state in less than a second. Within the BASE collaboration [3] these techniques could contribute to tests of CPT invariance with baryons through application to precision measurements of the (anti-)proton's g-factor.

The current status and recent progress made in the setup of the Penning trap apparatus, laser systems, and imaging optics for cooling, manipulation, and detection of the trapped atomic ion are presented.

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **50** Type: **not specified**

A double junction segmented ion trap with integrated optical delivery

INTRODUCTION

Ion traps are a robust and promising platform for quantum information processing and for the implementation of a quantum computer. However, major challenges exist in scaling these systems to the level required for full-scale quantum computing. I will describe work concerned with addressing two of these challenges; namely connecting multiple trap zones in more than one dimension, and integrating laser light delivery into the trapping structures.

MOTIVATION

In the last few decades, the limitations of classical computation have motivated scientists to turn to quantum computation. In the attempt of identifying the key requirements for a quantum system to be a viable quantum computer, the Di Vincenzo criteria were formulated [1]. Trapped ions satisfy all of the Di Vincenzo criteria. There is, however, an important criterion on which research is still open: that the system can be scaled to a large number of qubits while still satisfying all other criteria [2]. One approach towards scalability [3] is that of creating a trap with several trapping regions. This allows gates to be performed on a small numbers of ions, and that gates can be performed in parallel on ions stored in different regions of the processor. In this scenario, linear traps present a limitation: as the ions are arranged in a linear string, it is challenging to arbitrarily entangle two ions separated by a long string of other ions. In order to achieve order switching on a large number of ions and thus transfer of quantum information, junction traps have been proposed [3].

Our work focuses on pursuing the scalability requirement, by the creation of a double-junction ion trap. The trap geometry and the electric fields provide control over the motion of the ions, while laser light is used to perform quantum gates and state detection. Our trap introduces new features to improve both the ion motion control and the ion manipulation.

TRAP DESIGN

The trap is made of a stack of silica glass wafers: two host the junction trap structure, the middle wafer is used for optical integration and outer wafers hold shim electrodes for stray electric field compensation. There are three experimental zones and a total of 145 electrodes. With an electrode to ion distance of 185 μm, driving the trap at 90 MHz allows us to achieve secular frequencies of 3.7 (Ca) and 16 (Be) MHz. Tapered electrodes allow for an optical access angle of 45°.

We concentrate our design efforts on the junction region. Here, we find that open bridges, as well as closed bridges, can be used to minimise the residual axial field (axial presudopotential barriers), which the ions encounter when approaching the junction. We are able to optimise the junction geometry to achieve pseudopotential barriers below 0.2 eV. We also investigate the excess micromotion contribution from the finite size of electrodes and from electrode gaps. We find that gaps create a residual oscillatory axial electric field, with amplitude of 200 V/m, which is attenuated when the segmentation is only present on the dc fingers.

There are two main novel features in our design: first, the use of selective subtractive 3D printing technology to fabricate the wafers. This technology offers a way of incorporating the alignment of the wafers into the trap structure, minimising misalignment and providing a way to create larger arrays of traps. Secondly, the integration of optical delivery via micro-lensed optical fibres to achieve focused beam spots$<20\mu$m at a working distance of 400 μm. An integrated shim electrode will compensate for their charging.

SUMMARY

We are finalising the design and fabrication of a novel segmented 3D ion trap featuring two X-Junctions and delivery of light integrated within the trap wafers. This work will be useful in investigating approaches to scalability of quantum computers.

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Summary

We are finalising the design and fabrication of a novel segmented 3D ion trap featuring two X-junctions and delivery of light integrated within the trap wafers. This work will be useful in investigating approaches to scalability of quantum computers.

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **51** Type: **not specified**

Numerical simulation of He+ and Be+ in a linear Paul trap for Ramsey-comb spectroscopy

Bound state quantum electrodynamics is one of the most thoroughly tested theories in physics, but was recently challenged by measurements done on muonic atoms, where a discrepancy of >5σ was reported between the nuclear charge radii extracted from spectroscopic measurements on muonic hydrogen and electronic hydrogen [1-4]. To gain new insights into the "proton radius puzzle"we aim to measure the 1S-2S transition in He+ with kHz accuracy using Ramsey-Comb spectroscopy [5], and compare it to measurements of the 2S-2P transition in muonic He+ performed by the CREMA collaboration. We will combine a 790 nm photon with one at 32 nm (obtained by high-harmonic generation) to excite the transition. For this experiment a single helium ion will be trapped in a linear Paul trap together with a beryllium ion. The latter is used to sympathetically cool He+ and for reading out its quantum state to perform spectroscopy.

To explore the dynamics between the ions and to optimize cooling parameters we performed simulations. Finite element calculations of the trap were carried out and fitted with a multipole expansion to estimate higher-order field contributions. By including these field corrections in the molecular dynamics simulations of the ions, the experimental cycle of loading the trap, cooling and manipulation of both ions, and the dynamics during spectroscopy is investigated.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **52** Type: **not specified**

Testing QED and the Proton Radius Puzzle with Ramsey-comb spectroscopy on H_2 and He^+

Quantum electrodynamics (QED) is one of the best tested theories in physics [1]. However, energy levels in atomic hydrogen have been determined with much higher accuracy than what QED theory can provide, because it is hampered by the uncertainty in the experimentally determined proton charge radius. Therefore, spectroscopic measurements on muonic hydrogen (μH) were performed which improved the accuracy of the proton charge radius by a factor of 10, but showed a 5-7 σ discrepancy with the CODATA-2010 value [2]. This problem is now known as the proton radius puzzle. Recently the proton radius obtained from 2S-4P spectroscopy [3] in electronic hydrogen confirmed the muonic value and this confusing state of matters requires further tests.

We pursue two possibilities to help unravel the puzzle. One is precision spectroscopy of molecular hydrogen on the two-photon X-EF band to extract a proton radius and to test molecular quantum theory. The other is based on 1S-2S spectroscopy in electronic helium ions, to be compared with spectroscopy on the 2S-2P transition in muonic helium ions performed by the CREMA collaboration. This will provide new information on the proton radius puzzle by a comparison of the alpha particle charge radius [2], and could potentially also lead to a better bound-state QED test. In both experiments we need short wavelengths that require high power laser pulses for nonlinear upconversion.

We developed a method that combines high power with high precision, called Ramsey-comb (RC) spectroscopy [4], based on excitation with different pairs of amplified and upconverted frequency comb laser pulses. With this method we measured the two-photon EF-X transition (v=0, J=1) at an accuracy of 10^{-11} [5], using counter-propagating 202 nm pulses to suppress the Doppler effect. The accuracy is nearly 2 orders of magnitude better than previous measurements, and further improvements are envisioned to be able to extract a proton radius. This result also shows that the RC method is very promising for the 1S-2S He^+ experiment. There we will combine a 790 nm photon with its 25th-harmonic to perform two-photon RC spectroscopy with unequal photons to significantly increase the transition probability. He^+ will be trapped in a linear Paul trap and sympathetically cooled with Be^+. We are now testing the combination of the RC technique with high harmonic generation, by exciting xenon with a pair of upconverted pulses at ˜113 nm. The current status of all three experiments will be presented.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **53** Type: **not specified**

High Precision Mass Measurements on Light Ions

The former g-factor experiment located in Mainz performed various g-factor measurements on highly charged ions, resulting in tests of bound state QED [1] and the most precise value for the atomic mass of the electron [2]. These measurements will be continued within a new experiment at the MPIK with access to heavier highly charged ions. Meanwhile the follow-up experiment in Mainz, which is presented here, shifted its focus to high-precision mass measurements of light ions.
Light nuclei play a fundamental role in physics. The proton and the neutron, together with the electron make up all matter we encounter in our everyday life, making their properties highly interesting for metrology.
Another application is the determination of the electron-antineutrino mass at KATRIN˜[3], where the mass difference of tritium and helium-3 is required.
Our setup is dedicated to mass measurements of light ions by means of Penning-trap mass spectrometry. One highlight is a newly developed doubly compensated Penning trap, which has a harmonicity at least one order of magnitude better than all Penning traps described in the literature so far. We recently measured the proton mass at a relative uncertainty of 3×10^{-11} by comparing the cyclotron frequencies of a proton and a $^{12}C^{6+}$-ion [4]. The usage of two independend tank circuits connected to the measurement trap with their frequency ratio carefully tuned to the ratio of the charge-to-mass ratios of the ions allowed a rapid nondestructive measurement in the exact same field configuration. The optimized measurement scheme and the use of a phase-sensitve measurement technique yield a relative statistical uncertainty of 1.8×10^{-10} with a single measurement cycle.
As a next step we will focus on the mass of the deuteron, in order to extract the mass of the neutron using an improved value for the binding energy currently being measured at the ILL. At the same time, we are taking steps to push our uncertainties down to the 10^{-12}-regime

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **54** Type: **not specified**

Recent nuclear binding-energy studies with ISOLTRAP

The trends of nuclear binding-energies, obtained from high-precision atomic mass values, are sensitive to a wide range of nuclear structure phenomenon such as shell effects or onsets of collectivity. Hence, binding energies enable to track down the evolution of nuclear structure in yet unexplored region of the nuclear chart, also providing essential inputs to many nuclear models.

Three decades ago, the ISOLTRAP mass spectrometer [1], located at the radioactive ion-beam facility ISOLDE/CERN, pioneered the technique of on-line Penning-trap mass spectrometry of short-lived isotopes. Ever since, ISOLTRAP's research effort has been dedicated to the study of exotic nuclear species in key regions of the nuclear chart. This poster will present results from two of the most recent measurement campaigns performed with ISOLTRAP. First, the persistence of the neutron N=28 shell closure in the Argon isotopic chain will be addressed in the light of very recent measurements of the atomic mass of $^{46-48}$Ar. Results from a measurement campaign dedicated to the neutron-rich $^{58-63}$Cr isotopes will also be presented. The latter measurements provide new insights into the development of ground-state collectivity towards the region of nuclear deformation around N=40.

[1] Mukherjee et al., Eur. Phys. J. A 35, 1-29 (2008).

Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **55** Type: **not specified**

Towards inelastic collision rate coefficients of OH+ with He via photodissociation

Cooling internal degrees of freedom by inelastic collisions is a widely applied method in cold molecule physics, especially for species that lack the possibility of laser cooling. [1] Despite this, the state specific rate coefficients are commonly unknown. Experimental data for ions at low temperatures, of the order of a few Kelvin, is particularly sparse. Our group has previously reported rotational state-to-state rate coefficients for the hydroxyl anion, OH-, in collisions with helium, He. [2] The Langevin capture rate which is commonly used as an estimate in ion-neutral collisions was found to overestimate the rates by an order of magnitude, demonstrating the elasticity of the system.

We now aim to measure the inelastic collision rate coefficients for trapped hydroxyl cations, OH+, with He buffer gas using photodissociation as a state-specific probe.

OH+ has been observed in numerous regions in space and is of special astrophysical interest because it could function as a tracer for cosmic and X-ray ionization rates besides serving as an initiator in the oxygen chemistry. [3] The photodissociation of OH+ also plays an important role in astrochemistry [4] and has interesting dynamics by itself. For excited vibrational levels in the A state, dissociation can occur via coupling between bound and dissociative excited electronic states or by tunnelling, and dissociation into both of the quasi degenerate channels O++H and O+H+ has been observed. The cross section and the branching ratio were found to be highly state specific. [5, 6]

Our experimental studies, in combination with quantum chemical theory [3, 7] , aim to give a fundamental understanding of collisions including quantum effects which can have a significant contribution when low masses collide at low temperatures. Open shell species like the OH+, are particularly interesting as collisions can induce changes in the electronic spin as well as the nuclear rotation.

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **56** Type: **not specified**

Double-trap Measurement of the Proton Magnetic Moment at 0.3 Parts Per Billion Precision

Precise measurements of the fundamental properties of the proton such as its mass, lifetime, charge radius, and magnetic moment are important for our understanding of the physics of atomic and nuclear structure as well as for tests of fundamental symmetries. As one of very few particle-antiparticle pairs which are directly comparable, the proton and antiproton serve as an important laboratory for tests of charge parity time-reversal (CPT) symmetry and the weak equivalence principle.

Here we present our latest direct measurement of the proton magnetic moment with a relative precision of 3×10^{-10} [1]. This improves our previous measurement by a factor of 11 [2] and is 33 times more precise than measurements based on MASERs. A comparison with our recent measurement of the antiproton magnetic moment [3] constitutes one of the most precise tests of the CPT symmetry in the baryon sector.

The advancement was achieved by application of an improved double Penning-trap technique. An optimized Penning-trap geometry with a more homogeneous magnetic field in the measurement trap and the application of a self-shielding coil allowed stabilization of magnetic field (cyclotron frequency) fluctuations by an order of magnitude. Together with a carefully optimized spin-flip drive this led to a significantly reduced line width of the g-factor resonance. An improved superconducting cyclotron resonator increased the cooling rate by a factor of 4, cutting measurement times in half and greatly increasing statistics.

These crucial developments, applied to this improved measurement of the proton magnetic moment, will be presented in this poster.

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **57** Type: **not specified**

Three-photon coherent population trapping for high resolution spectroscopy

A cloud of trapped ions, represented here by a four level atomic system $\mid S_{1/2}>, \mid P_{1/2}>, \mid D_{3/2}>$ and $\mid D_{5/2}>$, is probed by the collection of photons from the transition $\mid P_{1/2}>$ to $\mid S_{1/2}>$.

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Figure : Four level atomic system of Ca+ ions

The lambda configuration with lasers at 866nm and 397nm allows for a two-photon dark state to take place. If the $\mid S_{1/2}>$ state is coupled with the $\mid D_{5/2}>$ state (which we are going to refer to as $\mid S>$ and $\mid Q>$) a three photon dark state is to be expected 1. Indeed the transition at 729nm is weakly coupled and the sub-system is diagonalizable:

\begin{equation}
\mid S_{Q}>=N_{1}(\mid S> + \alpha\mid Q>) ~~and~~ \mid Q_{S}>=N(\mid D> - \alpha \mid S>)
\end{equation}

with a normalisation factor N_1, and $\alpha = \Omega_C/2\Delta C$, we achieve a new lambda-shaped system with a dark state written as:

\begin{equation}
\mid \Psi_{dark}> = N_{2} (\varepsilon \mid D> + \mid Q_{S}>)
\end{equation}

With $\varepsilon = \alpha\Omega_B/\Omega_R$ and a normalisation factor N_2. The condition for this state not to be coupled to the rest of the system is:

\begin{equation}
\Delta R + \Delta C - \Delta B + \alpha \Omega _{C} /2 =0
\end{equation}

To achieve a stable 3-photon coherent population trapping experimentally, one has to reduce the relative phase fluctuations of the three lasers. In order to do so, two lasers are phase-locked onto a frequency comb which is himself locked onto the 729nm laser. This 729nm ultra-stable Ti:Sa laser was built within the laboratory and has a frequency stability of better than 5×10^{-14} for one second. For this 3-photon resonance, the phase matching condition: $\vec{K}_R + \vec{K}_C - \vec{K}_B = \vec{0}$ cancels out the first order Doppler Effect.

Recent experimental results will be presented.

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **59** Type: **not specified**

Progress towards precision spectroscopy of antihydrogen in the ALPHA experiment

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Antihydrogen offers a unique way to test matter/antimatter symmetry. Antihydrogen can reproducibly be synthesised and trapped in the laboratory for extended periods of time 1[2], offering an opportunity to study the properties of antimatter with high precision. The ALPHA collaboration at CERN has developed an experiment capable of accumulating several tens of trapped antihydrogen atoms [3], and interrogating the bound state energy structure using resonant microwaves [4] and laser light [5]. These recent results demonstrate that spectroscopic measurements of trapped antihydrogen are possible, and the collaboration is firmly en-route towards high precision measurements. Here, I present an overview of the ALPHA apparatus and the techniques which have been developed for measuring the spectrum of antihydrogen.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **61** Type: **not specified**

Sympathetic Cooling of Protons and Antiprotons with a Common Endcap Penning Trap

Nearly complete quantum control of individual trapped ions has become commonplace in many precision spectroscopy, metrology, and quantum information experiments. However, while measurements of the properties of fundamental particles for CPT tests have had remarkable recent successes [1, 2, 3], they have been limited to 0.3 ppb precision by long measurement times and particle temperatures on the order of 10 K. Unfortunately, the lack of an electronic structure has excluded laser cooling and made older techniques such as resistive cooling with tuned circuits still viable and necessary. In the context of an improved measurement of the proton magnetic moment in a Penning trap, our collaboration has developed a new apparatus that will allow us to sympathetically cool individual protons and, eventually, antiprotons. By coupling to laser cooled beryllium ions we will be able to achieve an unprecedented level of control of individual particles can, ultimately yielding an improved test of CPT invariance in the baryon sector.

Inspired by ideas from the early days of laser cooling [4], we plan to couple single particles to Doppler cooled ions through image currents induced in a macroscopic endcap electrode, connecting two Penning traps. Our calculations show that we will be able to prepare single particles with nearly Doppler limited energy in the axial, and subsequently cyclotron, modes on a time scale of tens of seconds. Once successfully implemented, we will be able to deterministically resolve individual spin states with high fidelity, nearly an order of magnitude faster than with current techniques. Shown here is the early progress of the new experiment with an outlook toward an improved measurement of the proton and antiproton g-factors.

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Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **62** Type: **not specified**

Laser Cooling of Molecular Anions for Ultracold Antiprotons

Several experiments at CERN aim at testing the CPT-theorem and weak equivalence principle using antimatter, among them the AEgIS experiment. Here, antihydrogen - produced via resonant charge exchange - will be used for precision measurements where the achievable sensitivity is determined by the temperature of the
antiprotons.

We are investigating laser-cooling of anionic molecules to sympathetically cool antiprotons. A test setup to produce cold C2- molecules is currently being commissioned. This will be presented together with theoretical studies on the feasibility of several laser-cooling schemes.

The unprecedented laser-cooling of anions would also enable sympathetic cooling of any other negatively charged species, opening new opportunities in a variety of research areas.

Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **63** Type: **not specified**

Improvements and Stabilisation of the BASE Apparatus for High-Precision Measurements of the Antiproton

A number of upgrades and stabilisation techniques to the BASE apparatus 1, motivated by improving upon the recent 1.5 ppb measurement of the antiproton g-factor [2] and other fundamental properties of the antiproton, are presented.

A new modified-cyclotron mode detection system has been commissioned and installed into the BASE apparatus. The primary function of this instrument is to resistively cool the modified-cyclotron mode, necessary to resolve single spin-flip transitions with high fidelity [3] – itself an integral part of g-factor measurements. This device also allows direct observation of the modified-cyclotron frequency, which in turn permits high-resolution measurements of the magnetic field.

Pressure stabilisation is also a new addition to the BASE experimental setup and has been added to keep both the pressure inside the apparatus, and the flow out of the cryogenic liquid reservoirs, as constant a possible. This has had a significant impact on the frequency stability of sideband measurements, improving from > 5 ppb to 1.7 ppb in terms of fractional precision.

A further stabilisation improvement is the implementation of a new self-shielding solenoid, centred over the Precision Trap (PT). The intention of such a device is to suppress the effect of external magnetic field fluctuations induced by the Antiproton Decelerator (AD) on the trapped particle. A self-shielding factor of 100 has been determined for this new instrument, corresponding to a 10-fold improvement compared to the device used in a previous charge-to-mass ratio measurement [4].

With a significantly upgraded experimental apparatus and improved methods and techniques, a sub-ppb measurement of the antiproton magnetic moment is anticipated.

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Summary

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Session Classification: Poster session 2

Track Classification: Poster Session 2

Contribution ID: **64** Type: **not specified**

Ground State Cooling of the Radial and Axial Modes of a Single Ion in a Penning Trap

Following results of laser cooling a single ion of $^{40}Ca^{+}$ to its motional ground state ($\bar{n}_z = 0.02(1)$) in the axial domain of a Penning trap 1, we report simultaneous sideband cooling of both radial modes to near their ground state in the same apparatus. Sideband cooling is performed on the $S_{1/2} \leftrightarrow D_{5/2}$ electric quadrupole transition at 729 nm, and average phonon numbers for the magnetron and modified cyclotron modes are found to be $\bar{n}_- = 0.7(2)$ and $\bar{n}_+ = 0.3(1)$ respectively. The observation of Rabi oscillations in both the axial and radial domains shows that the electronic state of the ion can be coherently manipulated.

Summary

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Session Classification: Poster session 1

Track Classification: Poster Session 1

Contribution ID: **65** Type: **not specified**

Increasing antihydrogen trapping efficiency at ALPHA using laser-cooled positrons

Antihydrogen, the bound state of a positron and an antiproton, is being studied by the ALPHA collaboration at CERN so that it can be compared to its matter counterpart, hydrogen. Antihydrogen is synthesised by merging plasmas of antiprotons and positrons in a magnetic trap, allowing a small fraction of the antihydrogen atoms created, the coldest, to remain trapped.

Decreasing the temperature of the antihydrogen when it is formed would in turn increase the trapping rate, allowing measurements to be performed with better systematics and in shorter periods of time. By introducing a cloud of beryllium ions into the positron plasma, it would be possible to laser-cool the beryllium ions, allowing them to sympathetically cool the positron plasma. This laser-cooled positron plasma could then be used for antihydrogen formation, potentially allowing for order of magnitude increases to the antihydrogen trapping rate.

Summary

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Session Classification: Poster session 1

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