International Symposium on Stored Ions for Precision Measurements

Abstract

Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps

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The four fundamental interactions and their symmetries, the fundamental constants as well as the properties of elementary particles like masses and moments, determine the basic structure of the universe and are the basis for our so well tested Standard Model (SM) of physics. Performing stringent tests on these interactions and symmetries in extreme conditions at lowest energies and with highest precision by comparing, e.g., the properties of particles and their counterpart, the antiparticles, will allow us to search for physics beyond the SM. Any improvement of these tests beyond their present limits requires novel experimental techniques.

An overview is given on recent mass and *g*-factor measurements with extreme precision on single or few cooled ions stored in Penning traps. Among others the most stringent test of bound-state quantum electrodynamics could be performed. Here, the development of a novel technique, based upon the coupling of two ions as an ion crystal, enabled the most precise determination of a *g*-factor difference to date. This difference, determined for the isotopes $^{20,22}Ne^{9+}$ with a relative precision of 5.6×10^{-13} with respect to the g factor, improved the precision for isotopic shifts of g factors by about two orders of magnitude. Our latest results on precision measurements with exotic ions in Penning traps will be presented.

Precision Spectroscopy with Highly Charged Ions in the Dark

Reinhold Schuch

The talk will touch upon the possibilities to perform precision spectroscopy of atomic quantum levels without detecting the emission of photons or electrons. One prominant example is determination of the electron binding energy by high precision mass measurements in Penning traps. Another very different way to the access atomic transition energy is by excitation of bound electrons through resonant coherent excitation of fast ions in crystals, with the following enhanced loss of the excited electrons. This can seen as a kind of collision spectroscopy. Some more examples in that category will be discussed: These are precision measurements of the Q-value in electron capture by, or excitation of, highly charged ions by COLTRIMS. And finally, a very promising tool is the detection of resonances in electron scattering by dielectronic recombination.

Ion trap based mass measurements of short-lived nuclei at ISOLTRAP and SHIPTRAP

Lutz Schweikhard

Mass defects and excitation energies are important properties which reveal the structure of atomic nuclei. Reaching out for the nuclear landscape's boundaries of existence of is a major challenge of modern experimental physics. The high-accuracy mass-spectrometry setups ISOLTRAP and SHIPTRAP, located at CERN/Geneva and GSI/Darmstadt, respectively, allow the determination of precise mass values of exotic nuclei with half-lives down to well below a second. The ions are delivered by the corresponding accelerator facilities and – due to their short lifetimes – have to be investigated “online”.

The experiments are confronted with further challenges. In particular, there are often isobaric contaminants in abundances many orders of magnitude higher than the ions of interest. For precision measurements, these contaminant species have to be removed. Furthermore, very exotic atoms come in only tiny amounts, and the event rates can be as low as just a few ion counts per hour. Nevertheless, ion-trap methods have been developed for dealing with these circumstances, such that either nuclei with lifetimes of only a few tens of milliseconds are accessible or that mass resolving powers exceeding 10 million and relative uncertainties in the 10^{-8} region can be reached.

The investigations are supported by the German Federal Ministry of Education and Research.

EDM Measurement on Laser-Trapped ^{171}Yb Atoms

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The permanent electric dipole moment (EDM) of the ^{171}Yb (I = 1/2) atom is measured with atoms held in an optical dipole trap (ODT). By enabling a cycling transition that is simultaneously spin-selective and spin-preserving, a QND measurement with a spin-state-detection efficiency of 50% is realized. A systematic effect due to parity mixing induced by a static E field is observed, and is suppressed by averaging between measurements with ODTs in opposite directions. The coherent spin precession time is found to be much longer than 300 s. An upper limit on the EDM is determined to be on the order of 10^{-27} e·cm. A ^{171}Yb – ^{173}Yb co-magnetometer is under development. These measurement techniques can be adapted to search for the EDM of ^{225}Ra.

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Speaker:

Prof. Michael Drewsen, Aarhus University, Denmark

Title:

Search for bosons beyond the Standard Model to atoms through precise isotope shift measurements in Ca^+

Abstract

By combining high-resolution spectroscopy of the 3d $^2D_{3/2}$ – 3d $^2D_{5/2}$ interval with an accuracy of ~20 Hz using direct frequency-comb Raman spectroscopy with isotope shift measurements of the 4s $^2S_{1/2} \leftrightarrow$ 3d $^2D_{5/2}$ transition in all stable even isotopes of $^ACa^+$ (A = 40, 42, 44, 46, and 48), we have been able to carry out a King plot analysis with unprecedented sensitivity to coupling between electrons and neutrons by bosons beyond the Standard Model.
Furthermore, we estimate that by improved spectroscopic techniques available, King plots based on data from spectroscopy on either Ca^+, Ba^+ and Yb^+ ions should be able to produce sensitivity to such potentially new bosons, which surpass other current methods in a broad mass range of 10 to 10^8 eV/c^2.

Perspectives for relativistic many-body and QED calculations for highly charged ions

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Quantum electrodynamics is the best understood quantum field theory and is often used as starting point for tests of the standard model. One can compare highly accurate QED and experimental values for the free electron [1] or muon [2] anomalous magnetic moments for example, or study bound states in few electron ions [3]. Advances in high-precision measurements of transition energies, atomic masses, metastable states lifetimes allow for improving tests of bound state QED. Comparisons of atomic clocks may lead to information in the variation of fundamental constants and the use of highly-charged ions long-lived states could help improve their accuracy [4, 5]. Yet, it is becoming more and more difficult to get relevant accuracy for systems with more than a few electrons. This happens in particular when calculating heavy elements properties needed for astrophysics (see, e.g., [6]), atomic mass measurements (see e.g., [7, 8]), to study long lived metastable states for ions clocks[4], to look at "beyond the standard model" physics [9], to calculate transition energies in highly charged ions or to find optical transitions for super-heavy elements laser spectroscopy [10]. Many calculations become too large to be performed in spite of the huge increase in computer power of the last few decades. I will present a few recent examples to show the limits are encountered even in relatively simple systems, and discuss possible progress.

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Measurement-based cooling of a Trapped Ion

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Measurement-based cooling is a method by which a quantum system, initially in a thermal state, can be prepared probabilistically in its ground state. This is done through some sort of measurement process that heralds the system being in the desired state, without changing it. Here we demonstrate the application of this technique to a trapped atomic calcium ion.

The ion is held in a linear RF blade trap. It is pre-cooled by Doppler laser cooling to a thermal state with a mean excitation of $n \approx 18$ and the measurement-based cooling technique selects those occasions when the ion happens to be in the motional ground state. The fidelity of the heralding process is greater than 95%. This technique could be applied to other systems that are not as amenable to laser cooling as trapped ions.

An optical clock based on a highly charged ion

Highly charged ions (HCI) have long been proposed for the application in optical clocks due to their high sensitivity to fundamental physics and suppressed sensitivity to external field shifts [1]. However, their application as frequency references has long been impeded by the megakelvin temperatures at which HCI are typically produced and stored. In our lab, these obstacles have been overcome by first extracting HCI from a plasma and transferring them to a cryogenic linear Paul trap. There, a single HCI is sympathetically cooled using singly-charged Be^+ ions, enabling quantum logic spectroscopy with Hz-level resolution [2] and cooling of all motional modes to their ground state [3]. This paved the way for the first optical clock employing a HCI, here Ar^{13+}. The evaluation of the experimental setup yielded a systematic uncertainty of 2×10^{-17}, comparable to many other optical clocks. The leading systematic shift is time-dilation from excess micromotion, which will be remedied by a new trap. The frequency of the electric dipole-forbidden transition in Ar^{13+} was compared to the well-known octupole transition in $^{171}Yb^+$. The derived absolute frequency and isotope shift ($^{36}Ar^{13+}$ vs $^{40}Ar^{13+}$) are an improvement of eight and nine orders of magnitude respectively over the previous best result. For the first time, this has enabled to resolve the QED nuclear recoil in a many-electron system [3]. Further atomic parameters can be extracted from the measurements and are in excellent agreement with theoretical predictions. Transferring the applied techniques to other HCI systems is straight forward and we demonstrate this using Ca^{14+}. There we investigated the isotope shift of the transition frequency. These results will be used to test fundamental physics and search for new physics [4, 5].

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Development and Application of Combined Schottky+Isochronous Storage Ring Mass Spectrometry

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Storage of freshly produced secondary particles in a storage ring is a straightforward way to achieve the most efficient use of the rare species as it allows for using the same secondary ion multiple times. Employing storage rings for precision physics experiments with highly-charged ions (HCI) at the intersection of atomic, nuclear, plasma and astrophysics is a rapidly developing field of research. The number of physics cases is enormous. The focus in this presentation will be on the most recent results obtained at the Experimental Storage Ring ESR of GSI in Darmstadt.

The ESR is presently the only instrument dedicatedly utilized for precision studies of decays of HCIs. Radioactive decays of HCIs can be very different as known in neutral atoms. Some decay channels can be blocked while new ones can become open. Such decays reflect atom-nucleus interactions and are relevant for atomic physics and nuclear structure as well as for nucleosynthesis in stellar objects.

Up to now, all investigations of the decays of HCIs were done by employing the time-resolved Schottky mass spectrometry (SMS). The latter relies on the electron cooling and non-destructive monitoring of intensities of the mass-resolved nuclear species of interest. The electron cooling requires at least several seconds and the conventional SMS can be applied to relatively long-lived ions. In the course of the last decade highly-sensitive Schottky detectors were developed enabling us entering the regime of half-lives in several ten milliseconds. Furthermore, the Isochronous Mass Spectrometry (IMS) is employed, which allows avoiding the lengthy cooling processes. In this way the combined Schottky+Isochronous Mass Spectrometry (S+IMS) has been established.

The power of the technique has been verified by measuring the de-excitation of the first excited 0^+ state in ^{72}Ge, which is a pure two-photon decay in the absence of bound electrons.

The reported developments will be put in the context of the present research programs in a worldwide context, where, thanks to fascinating results obtained at the presently operating storage rings, a number of projects is planned.

Present status of the storage-ring mass spectrometer at RIBF

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Atomic masses are one of the most important quantities featuring various effects of nuclear structure, reaction dynamics as well as fundamental physics. Many mass spectrometers have been established in the worldwide facilities. However, masses of exotic nuclei are still a challenge today, and are needed to resolve the mystery of nucleosynthesis, namely, r-process.

Currently, the RI Beam Factory (RIBF) at RIKEN can provide the highest intensities of radioactive beams in the world. Taking the advantage of RIBF, we have recently developed a novel scheme to measure masses of exotic nuclei. The experimental principle is based on the storage-ring mass spectrometry under the isochronous ion-optical condition. We have built a dedicated storage ring, called Rare-RI Ring (R3), lattice structure of which is a weak-focusing cyclotron type to realize a precise isochronous setting [1]. A radioactive ion of interest produced from cyclotron beam is in-flight selected and is injected into the storage ring particle-by-particle at every injection. After a certain period of storage time, the ion is extracted and the total time-of-flight is precisely measured, which is proportional to the mass-to-charge ratio of the ion.

The technical developments of in-flight particle selection scheme and fast kicker magnet system for individual injection are essential to successful operations of the present method. A mass precision of a few hundreds of keV for uranium fission fragments has been achieved. Further improvements are ongoing now. In this contribution we will introduce the technical details and will show the results of commissioning and the latest measurements [2].

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Exploring the Physics at the Schwinger-Limit: Precision Photon Spectroscopy and Polarimetry in the Realm of High-Z Heavy Ions and Atoms

Thomas Stöhlker

Highly charged ions combine extremely strong electromagnetic fields and a simple electronic structure which makes them an ideal testing ground for the electromagnetic sector of the standard model and even for the physics beyond. In this presentation, the focus will be on most recent precision experiments at the ion storage rings of GSI, with particular emphasis on He-like uranium, the simplest multi-electron system at high Z where the interplay between correlation, relativity and QED is a particular challenge for theory. One may note that until now practically no precise experimental data for He-like heavy ions has been available (beyond nuclear charge of 60). More specifically, Bragg spectrometer-based studies of the 3P2-3S1 intrashell transitions will be discussed [1], as well as measurements of the Kα ground-state transitions based on the application of metallic magnetic micro-calorimeters [2]. Complementary studies will be addressed in addition, where elastic scattering of high-energy photons is subject of the research [3]. The goal of these studies is to provide detailed insights into the higher-order QED process of Delbrück scattering, where energic photons are elastically scattered by the virtual electron-positron pairs in the extreme electro-magnetic fields of heavy nuclei [4].

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Recent advances in QED and collision dynamics using highly charged ions at CSR

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Two aspects concerning the progresses at the cooler storage ring CSRe in Lanzhou will be reported. Firstly, the recent experimental results on QED test using F-like nickel ions via dielectronic recombination spectroscopy, fully differential cross section of helium ionization by 120 MeV/u Fe^{26+} ion using reaction microscope, and simulation of laser cooling dynamics at storage ring. Secondly, future aspects will be presented, including the experimental plans of precision spectroscopy and relativistic collisions dynamics at CSRe in next three years, and the progress of HIAF project in Huizhou, Guangdong province, and the atomic physics plans.

Low-Energy Nuclear Reactions with Stored and Cooled Radioactive Beams

Jan Glorius

In the past decade, research into low-energy nuclear reactions has entered a new era in heavy ion storage rings. At the GSI storage rings ESR and CRYRING we are now able to conduct reaction cross section measurements with decelerated radioactive beams. In this talk I will give an overview of the different experimental campaignes that address astrophysical issues in this context.

One of these initiatives is the proton-capture campaign in the ESR, aiming to directly measure proton-induced reactions of key importance for explosive nucleosynthesis. In the latest experiment, we successfully applied this technique to a radioactive beam for the first time.

Further, there is the NECTAR project, which targets neutron-induced reactions using the indirect surrogate technique to constrain reaction theory in cases where measurement by traditional methods is impossible. The proof-of-principle experiment has been recently accomplished, and there are ongoing plans to extend the method.

Lastly, the CARME setup has recently been installed and commissioned in CRYRING. This versatile array of Si-detectors surrounding the internal gas target enables a wide range of low-energy studies with radioactive beams to be pursued.

Recent results and developments as well as future plans within those projects will be discussed.

High-resolution Laser spectroscopy on the cooled and bunched radioactive ion beams

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Taking the full advantages of the cooled and bunched radioactive ion beams delivered from a gas-filled linear Paul trap, collinear laser spectroscopy experiment could reach a higher resolution and sensitivity to access the ground-state properties (spins, electromagnetic moments and charge radii) of the radioactive nuclei [1]. These nuclear properties allow for a more detailed investigation and understanding of the exotic nuclear structure, e.g. shell evolution, nuclear magicity, and deformation [2-3]. Additionally, as the basic properties of the atomic nuclei, they also offer a prominent test of the advanced nuclear many-body methods and nuclear interactions [2-4].

In this talk, high-resolution laser spectroscopy experiments and the recent results on the properties and structure of neutron-rich nuclei (e.g. 46-49Sc and 81-82Zn) in the calcium and nickel regions will be presented and discussed [4,5]. Furthermore, recent progress and near-future plan on the development of high-resolution laser spectroscopy together with the RFQ ion trap in China will be introduced.

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Precision Spectroscopy of Helium Atoms

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Precision spectroscopy in few-body atomic systems, like hydrogen and helium, enables the testing of the quantum electro-dynamics (QED) theory and determination of the fundamental physical constants, such as the Rydberg constant, the proton charge radius, and the fine-structure constant. It also sets constraints on new physics beyond the standard Model (BSM). High precision spectroscopy of atomic helium, combined with ongoing theoretical calculations for the point nucleus may allow an alternative determination of the helium nuclear charge radius, which could be more accurate than from the electron scattering. Moreover, the comparison of results from electronic and muonic helium will provide a sensitive test of universality in the electromagnetic interactions of leptons.

Our group has performed laser spectroscopy measurement of the 2^3S-2^3P transition of helium atoms, in the past decade [1,2]. Recently, we updated our atomic beam setup, adding a Zeeman deceleration system, we implemented a new metastable atomic helium beam with high brightness and adjustable speed [3]. In this setup, the influence of first-order Doppler effect can be significantly reduced. At the same time, we have improved the probe laser system, by using a switching traveling wave field instead of the standing wave field that used in the original experiment, to probe the atomic beam [4]. This improvement effectively reduces the light force induce shift in our previous measurement [5]. Based on that setup, the issue of post-selection in precision spectroscopy of the 2^3S-2^3P transition of 4He has first revealed. We experimentally observed a discrepancy between the results with and without post-selection, which is validated by our simulations and theory. Our findings reveal the extra bias of weak signals when applying WVA and indicate a correction of previously experimental results obtained under post-selections. Our work highlights the significance of quantum mechanics and technologies in modern precision measurement and appeals to more attention to evaluate and interpret experiments in the framework of quantum optics and quantum metrology.

Key words: Helium Spectroscopy, Post-Selection, Weak Measurement, Isotope Shift, Nuclear Charge Radius

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Atomic structure calculations of np^3, nd^6, and nd^8 highly charged ions

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The rich energy configurations of highly charged ions (HCIs) offer numerous optical transitions between the ground state and the low-lying excited states, which have wide applications for astronomy, plasma, frequency metrology, and precision measurements. Generally, the compact size of the HCIs makes them insensitive to external fields. Strong relativistic effects and high ionization energies make the HCI clock transitions highly sensitive to variation of the fine structure constant and dark matter searches [1-3]. In this talk, we will introduce our investigation of energies and spectroscopic properties of the neutral atoms P through Mc belonging to Group-15, singly ionized atoms S^+ through Lv^+ of Group-16, and doubly ionized atoms Cl^{2+} through Ts^{2+} of Group-17 [4]. These ions have the np^3 configurations, and their forbidden transitions among the low-lying fine-structure splitting states are found in the optical region. The high-accuracy calculation of atomic properties such as lifetimes, Landé g_J factors, and magnetic dipole (A) and electric quadrupole (B) hyperfine structure constants of the fine-structure partner states with np^3 configurations are reported. We will discuss d^6 and d^8 open-shell highly charged Ions as distinguished candidates of ultra-stable optical clocks [5]. We have examined the energy level-crossing rule of the low-lying states of the nd^6 and nd^8 HCIs. They offer at least two sets of clock transitions with quality factors about 10^{16-18} and fractional uncertainties due to major systematics effects are below the 10^{-19} level. These clock transitions also show very sensitivity for probing fundamental phenomena like possible temporal variation of the fine structure constant and local Lorentz symmetry invariance. Various spectroscopic properties of the np^3, nd^6, and nd^8 highly charged ions reported by using atomic structure calculations based on three different relativistic many-body methods can be useful in guiding experiments to measure them in the future and probing the potential of the methods employed.

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Progress on Ni^{12+} based highly charged ion clocks

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Abstract:

Highly charged ions (HCIs) have promising clock transitions with potential accuracy below 10^{-19}, Furthermore, they are sensitive to fine structure constant α and can be used to explore new physics beyond the standard physical model[1,2,3,4]. we utilized the Shanghai-Wuhan Electron Beam Ion Trap (SW-EBIT) [5] to perform a high-precision measurement of the M1 transition of Ni-HCI. Our approach involved an improved calibration scheme for the spectra, utilizing auxiliary Ar^+ lines for calibration and correction. Our final measured result of the M1 transition wavelength demonstrate a five-fold improvement in accuracy compared to our previous findings[6], reaching sub-picometer level accuracy[7]. In addition, High energy HCI bunches were slowed down[8] to the ion trap and cooled in a room temperature ion trap by means sympathetic cooling through the laser-cooled Be^+ ions. The Ni-HCIs temperature were decreased to hundred millikelvin level from megakelvin.

Table I. Error budget: The final result and main error sources to the wavelength measurement

Source of error	Shift (pm)	Error (pm)
Line centroid determination	511582.05	0.21
Calibration system	/	0.33
Isotope shift	0.06	0.06
Stark shift	/	<0.01
2nd -order Zeeman effect	/	<0.01
Total	511582.11	0.40

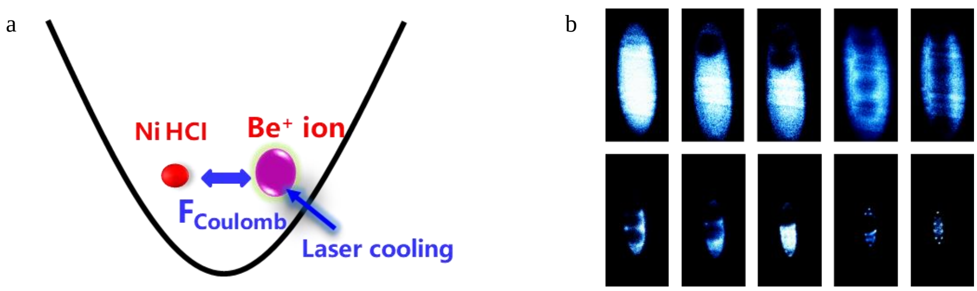

Fig. 1. The sympathetic cooling of HCIs. a: Sympathetic cooling Schematic Image; b: Coulomb crystal of Be^+ and Ni HCI(the dark circular shapes) --The process of HCI from being injected and trapped and subsequently lost one by one.

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