HITRAP Facility and Experiments - Status and Future Perspectives

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Haus Hainstein Eisenach

Book of Abstracts

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Session 4 / 1

Study of Highly Charged Ions for the Test of Bound-State QED

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The high-precision measurement of the Zeeman splitting of fine and hyper fine-structure levels can be measured using spectroscopy techniques. The Penning trap ARTEMIS at the HITRAP facility at GSI utilises such a method called Laser-Microwave double-resonance spectroscopy to measure the magnetic moment and to test bound-state QED calculations by the g-factor measurements of heavy, highly-charged ions like Ar13+ and Bi82+. After cooling the stored ion cloud in the trap by resistive cooling, non-destructive detection technique is used to detect the presence of ions. Different ions in the trap are resolved according to their charge-to-mass ratio by fixing the frequency and ramping over a range of voltages. By using Stored Waveform Inverse Fourier Transform (SWIFT) method, Ar13+ ions are isolated from the ion cloud for the g-factor measurements. Studies are also done to determine the phase transition of dense ion cloud due to the discontinuous behaviour of spectral features during cooling.

Session 6 / 2

Clocks based on highly charged ions for tests of fundamental physics

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Highly charged ions (HCI) have many favorable properties. They offer a high sensitivity to test fundamental physics and for the search of new physics, a simplified atomic structure due to a small number of bound electrons, and a low susceptibility to external perturbing fields [1]. Therefore, HCI are also well-suited for next-generation optical atomic clocks, which can in principle operate at record fractional uncertainties of better than 10-18. However, up to recently HCI were not accessible for such type of instruments.

In this talk, I will briefly review how we overcame all previous obstacles by demonstrating Coulomb crystallization of HCI [2], the implementation of quantum logic spectroscopy [3], and ground-state

cooling of weakly-coupled motional modes [4]. With these prerequisites we realized the first optical atomic clock based on an HCI by stabilizing an ultrastable clock laser to the ground-state fine-structure transition in Ar13+ at 441 nm. By comparing this optical frequency to the one of the electric-octupole transition in 171Yb+, we realized a frequency ratio measurement with a fractional uncertainty of about 1x10-16, limited by statistics. We thereby improved the uncertainty of the absolute transition frequency of Ar13+ by about eight orders of magnitude. The systematic uncertainty was 2.2x10-17, dominated by the time dilation shift uncertainty from excess micromotion. Importantly, this level of excess micromotion can be considerably reduced with a new, carefully manufactured ion trap. All other systematic uncertainties are at or below 10-18, demonstrating the potential of HCI as highly accurate atomic references for time keeping and unprecedented tests of fundamental physics. Furthermore, we compared the transition frequencies of the two isotopes 40Ar13+ and 36Ar13+ in order to determine the isotope shift with an improvement of nine orders of magnitude – resolving the QED nuclear recoil contribution.
The experimental approach is universal and thereby generally unlocks HCI for such precision experiments.

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[2] L. Schmöger et al., Science 347 (2015)
[3] P. Micke et al., Nature 578 (2020)
[4] S. A. King et al., Phys. Rev. X 11 (2021)

Session 4 / 3

Characterisation of high-intensity light sources by ponderomotive forces on highly-charged ions

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The ultra-intense X-ray pulses produced by novel free-electron lasers promise many applications, e.g. for protein structure-determination or time-resolved molecular spectroscopy. This requires the pulses to be well-characterised in terms of focal shape, duration and intensity. Providing tools for calibrating these properties is however a difficult task, leading to various approaches utilising different physical effects.
Spatial inhomogeneity in oscillatory electromagnetic fields causes the well-known ponderomotive force to be exerted on charged particles along the negative field gradient. As experiments with focused laser pulses on helium atoms have shown, due to Coulomb attraction, the net drift momentum of bound electrons is transferred to the ionic core, giving rise to a significant center-of-mass acceleration. From measurements on the deflection of atomic beams or trapped highly charged ions one may acquire information on the laser's intensity and gradient, possibly providing an additional tool for calibration.
A numerical implementation and first results showing this beyond-dipole effect for a single-electron system will be presented. As the large spatial extent of the predominantly ionised electronic wave function poses an enormous challenge in terms of computational resources, the solution of the Schrödinger equation is restricted to a one-dimensional model to ensure a high degree of convergence. The motion of the ionic core is obtained by a semi-classical description employing Ehrenfest dynamics via adiabatic coupling. It is found that, depending on the ionisation potential, at certain intensity thresholds the character of the deflection changes, with effects due to the gradient-dependence of the ponderomotive forces being increasingly outweighed by the field's direction at the instance of ionisation.

Session 4 / 4

Angular distribution of Auger electrons following electron-impact excitation of Be-like ions

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Session 1 / 5

Simultaneous storage of ions and electrons in the HITRAP cooling trap

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The HITRAP decelerator facility aims to decelerate and cool heavy, highly-charged ions (HCI) like U^{92+} [1]. After creation of the high charge states at relativistic energies, HITRAP decelerates these ions via a consecutive arrangement of linear deceleration stages and a cylindrical Penning trap. Within this so-called cooling trap, the ions can be cooled to low temperatures before they are ejected and transported to various precision experiments. The used cooling mechanism in the seven-electrode trap is sympathetic cooling with a cold electron plasma in a nested trap configuration.
We present the current status of the cooling trap and the ongoing progress to demonstrate electron cooling of extended amounts of heavy HCI for the first time. For commissioning, the 40 cm long cooling trap can be supplied with HCI from a small EBIT ion source and electrons can be produced externally from a GaAs photo cathode driven by a UV flash lamp. The ions from the EBIT (e.g. Ar^{16+}) are transported through a low energy beamline towards the cooling trap [2]. By appropriate switching of the capture electrodes while the electrons are already stored in a nested potential, simultaneous storage can be achieved. In this configuration, an influence of the ions on the co-trapped electrons could be observed, but so far no energy loss of the ions could be observed.
This work is supported by BMBF under contract number 05P21RDFA1.

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Session 4 / 6

QED approach of valence-hole excitations in closed shell systems

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An ab initio QED approach to treat a valence-hole excitation in closed shell systems is developed in the framework of the two-time-Green function method. The derivation considers a redefinition of the vacuum state and its excitation as a valence-hole pair. The proper two-time Green function, whose spectral representation confirms the poles at valence-hole excitation energies is proposed. An contour integral formula which connects the energy corrections and the Green function is also presented. First-order corrections to the valence-hole excitation energy involving self-energy, vacuum polarization, and one-photon-exchange terms are explicitly derived in the redefined vacuum picture. Reduction to the usual vacuum electron propagators is given that agrees in the Breit approximation with the many-body perturbation theory expressions for the valence-hole excitation energy.

Session 2 / 7

Surface modification using slow highly charged ions

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Slow highly charged ions deposit large amounts of their potential energy within the very first monolayers of a material. Depending on material properties, relaxation processes can also lead to permanent nanosized material modifications, e.g. hillocks and craters on surfaces of bulk samples - often in a similar manner as after swift heavy ion impact.
The type of created defect might vary even for a particular material as a function of kinetic and potential ion energy. For CaF2 crystals, for example, two thresholds could already be discovered: only if the projectiles' potential energy exceeds these thresholds, etch-pits and hillocks could be identified post-irradiation, respectively. However, studies so far were mainly limited to potential energies of several tens of keV, as the production of higher charge states together with low kinetic energies and high ion fluences becomes complex. This raises the question whether there are even more types of nanostructures besides the two mentioned above that have not been identified yet. Here, HITRAP offers the optimal possibility to bridge this gap and to expand the studies of highly charged ion induced nanostructuring.
In this contribution I will recap material modification studies using highly charged ions that were performed in the past to outline how HITRAP will help us explore an uncharted territory well beyond the state-of-the-art.

Session 5 / 8

Precision X-Ray Spectroscopy of He-like Uranium using Metallic Magnetic Calorimeters

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Helium-like ions are the simplest atomic multibody systems and their study along the isoelectronic sequence provides a unique testing ground for the interplay of the effects of electron–electron correlation, relativity and quantum electrodynamics. However, for high-Z ions with nuclear charge Z > 54, where inner-shell transition energies reach up to 100 keV, there is currently no data available with high enough resolution and precision to challenge state-of-the-art theory [1]. In this context the recent development of metallic magnetic calorimeter (MMC) detectors is of particular importance. Their high spectral resolution of a few tens of eV FWHM at 100 keV incident photon energy in combination with a broad spectral acceptance down to a few keV will enable new types of precision x-ray studies [2].

We report on the first application of MMC detectors for high-resolution x-ray spectroscopy at the electron cooler of the low-energy storage ring CRYRING@ESR at GSI, Darmstadt. Within the presented experiment, the x-ray emission associated with radiative recombination of stored hydrogen-like uranium ions and cooler electrons was studied. Two MMC detectors developed within the SPARC collaboration [3] were placed at observation angles of 0° and 180° with respect to the ion beam axis. The detectors and their extraordinary capabilities for x-ray spectroscopy will bepresented. Special emphasis will be given to the achieved spectral resolution of better than 90 eV at x-ray energies close to 100 keV enabling for the first time to resolve the substructure of the $K\alpha_1$ and K_2 lines.

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Session 1 / 9

Commissioning of the HITRAP cooling trap with offline ions

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The HITRAP facility is designed to decelerate and cool a bunch of about 10^5 heavy, highly charged ions (HCI). Produced by stripping at high energy, the HCI are decelerated eventually in a linear decelerator down to 6 keV/u and captured within a cylindrical Penning trap. In that trap the HCI can be cooled using electron cooling before being transferred to subsequent experiments [1]. If ions and electrons are stored simultaneously in a so-called nested trap, energy transfer can take place. The electrons cool the transferred energy off by synchrotron radiation in the strong magnetic field of up to 6 T [2].
We present the current status of the HITRAP cooling trap and the next steps of commissioning this setup with offline ions. Recently, a new electrode layout has been installed to improve reliability of the trap operation. Our tests show that the new seven-electrode design is more stable and less error prone than the old 21 electrode design.
We were able to investigate the storage of argon ions in various charge states, delivered by a small EBIT with an energy of 4 keV/q. With the approximately 40 cm long trap it was possible to capture more than 10^5 highly charged ions. Dependencies of the charge state and kinetic energy were observed as they both influence the lifetime of the stored ions. By applying the magnetron frequency of the stored ions to a quartered ring electrode we were also able to excite the ion cloud inside the trap. Moreover, in order to achieve electron cooling it was possible to store ions and electrons simultaneously in this setup, although no cooling effect was observed so far.
The next steps will be the improvement of the trap settings for the simultaneous storage of electrons and ions and the proof of electron cooling of argon ions from the local ion source. Additionally, methods for non-destructive detection of trapped particles will be applied to the setup.
This work is supported by BMBF under contract number 05P21RDFA1.

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Session 6 / 10

Open-source Laser System for the Spectroscopy of Highly Charged Ions

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We present a fully open source hardware solution for the next generation of diode lasers for highly charged ion experiments. Our solution, consisting of a laser driver, a temperature controller and a fast servo, provides superior performance in comparison to typical commercial solutions in the field while being more economical and versatile due to its open source platform.

Our laser current driver offers full digital control, sub-ppm drift and the lowest noise in class. Additional features are a high compliance voltage of more than 15 V to drive modern and exotic laser diodes covering UV to to IR and a modulation bandwidth with linear response of more than 1 MHz.

Our temperature controller features best in class noise of <5 µK and stability of <100 µK (@ 25 °C) over several weeks limited only by ambient humidity. Our system offers two channels with independent control and up to 60 W.

Our servo controller, based on the RedPitaya STEMlab platform, features 2 outputs to control both the laser current and the laser piezo with a maximum bandwidth 1.25 MHz.

For all devices, we are in the process of making the hardware and software publicly available under an open source license to allow full customization.

Session 3 / 11

Interaction of slow highly charged xenon ions with metallic surfaces

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Slow single charged ions interacting with solid surfaces dissipate their kinetic energy mainly by nuclear collisions which results in, e.g. defect creation and erosion of material from the surface. Highly charged ions (HCI) are missing a few or even all of their electrons, and therefore carry additional potential energy, which is defined as the sum of the binding energies of all the electrons removed. Such configuration of ions interacting with solids provide unique opportunity for formation of Rydberg hollow atoms (RHA) in fast process of HCI neutralization close to the solid surface. In the RHA a large part of the electrons are in high Rydberg levels (n~30) while some of the inner shells remain empty. Such highly excited atoms quickly decay by Auger electron and x-ray emission. Consequently, their neutralization energy (and part of kinetic energy) is deposited in a small volume close to the surface, eventually leading to the material sputtering and nanostructure formation. The measurement of X-rays and electrons emitted during the neutralization process and the analysis of surface modification give a unique opportunity to study many exotic processes taking place during the interaction of HCI with solid surfaces.
In this talk, I will present the results of experiments carried out at the EBIS facility in Kielce (Jan Kochanowski University, Kielce, Poland), in which we studied the M-X radiation emitted during the neutralization of slow highly charged X^{q+} ions and nanostructures resulting from the deposition of ion energy on metallic surfaces. I will discuss role of such processes as Internal Dielectronic Excitation (IDE), Interatomic Coulombic Decay (ICD) and Two-Electron One-Photon (TEOP) transitions occurring during deexcitation of the RHA. The nanostructure creation process I will interpret using

recently developed micro-staircase model based on the quantum two-state vector model of the ionic Rydberg states population. The model takes into account the neutralization energy, and the kinetic energy deposition inside the solid.

Session 7 / 12

Stringent test of QED in hydrogenlike 118Sn49

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Quantum electrodynamics (QED) is one of the most successful fundamental theories to date. With the *g*-2 measurement of the free electron, QED interaction has been tested rigorously [1]. Using a highly charged ion (HCI), one can similarly test bound-state QED effects. This allows to test the interaction of the electron with the strong electric field present in the vicinity of the nucleus. So far the regime of the heaviest ions has been explored exclusively via Lamb shift measurements of 1<i>s</i>-
and 2<i>s</i>-shell electrons [2, 3]. Similar the bound-electron *g* factor can be measured and compared to
theory to perform tests of QED in heavy HCI [4, 5]. Until now, *g*-factor measurements were limited to low-<i>Z</i> ions, as the production of heavy HCI requires large experimental setups.
Here we present a QED test using a hydrogenlike ¹¹⁸Sn⁴⁹⁺ ion. From an external electron beam ion
trap (HD-EBIT) [6], we inject the HCIs into our Penning-trap setup [7]. A single ion is isolated, and its bound-electron *g* factor is measured with a relative precision of 4.6×10^{−9}, limited solely by the
mass uncertainty of the ¹¹⁸Sn isotope. The comparison with our ab-initio theory calculation allows a
stringent test, matching the stringency of the previous Lamb-shift measurements.

This result marks a key step for *g*-factor QED tests into the high-<i>Z</i> region. Furthermore, our experi-
mental result surpasses the current theory precision by far and thus establishes the basis for order of
magnitude improved sensitivity, once currently ongoing theory calculations succeed.

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Session 4 / 13

Surface modification of gold nanolayers by highly charged xenon ions

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The studies on creation of surface nanostructures on metals, semiconductors and insulators are important for development of new technologies for production of microelectronic devices [1]. Structures of nanometric sizes can be created, for example, in collisions of highly charged ions (HCI) with surfaces of various materials. In this case different parameters of the ion beams, irradiated materials and processing conditions lead to miscellaneous characteristic modifications obtained on a material surface (see [2] and reference therein). In order to fully understand this process systematic measurements of surface modifications using HCI ions under various experimental conditions and with different ions/materials are needed.

In this work surface modifications caused by irradiation of 100 nm gold nanolayers using highly charged Xe^{q+} (q+=25, 30, 35, 36, 40) ion beams have been studied. The samples were irradiated at the Kielce EBIS facility (Jan Kochanowski University, Kielce, Poland) [3]. The AFM images of irradiated surfaces allowed for the first time to unambiguously identify nanostructures in the form of craters and hillocks on the gold surfaces [4, 5]. The experimental results were compared with the theoretical calculations using: micro-staircase model [6], the inelastic thermal spike (i-TS) model [7], molecular dynamics (MD) simulations [8], and compared with the experimental data obtained for slow single ionized Xe^{+} hitting Au surface [9]. Predictions of the micro-staircase model clearly showed that both the kinetic energy and the potential energy of the HCI have an influence on the type and size of nanostructures obtained on metallic surfaces. In this model interplay of these two energies is described by the critical ionic velocity. For the ionic velocities lower than the critical one the model assumes an appearance of the hillocks, while for the larger velocities a dominant surface structures are craters.

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Session 1 / 14

ESR as a Decelerator of Heavy Ions for HITRAP – Status and Recent Developments

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Deceleration of highly charged ions is a mode for the operation for the ESR storage ring at GSI which is required for various types of experiments. The special requirement for HITRAP is the deceleration down to an energy of 4 MeV/u precisely, which is close to the minimum design value, in combination with fast extraction. The deceleration can start from any injection energy, but for efficient production of highly charged ions or RIBs an injection energy of 300-400 MeV/u is favorable. Consequently, the beam has to be decelerated by up to a factor of 100 in energy. Fast and efficient deceleration is crucial to provide experiments at HITRAP with sufficient average intensity. The delivered intensity is presently mainly limited by the vacuum of the ESR which determines the beam lifetime and the losses at the lower energies. The present status of the ESR and some recent development which are relevant for the operation as decelerator for HITRAP will be discussed.

Session 2 / 15

Perforation of 2D-structures by impact of highly charged ions

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See Attachment (Abstract in better format)

In the past two decades it has become possible to isolate monolayers of bulk materials. These new types of target materials are effectively 2-dimensional (2D) and as such have opened up new possibilities for material research. In particular, we are interested in the response of these targets to strong fields when irradiated with highly charged ions (HCI) often leading to pore formation in the layer. A complete description of the interaction of HCIs impinging on 2D materials is clearly out of reach as the interaction is governed by multi-particle processes such as the polarization of the layer ensuing the acceleration of the HCI by the 2D equivalent of its image charge, the charge transfer dynamics between HCI and the 2D material at smaller distances, the nuclear stopping upon impact on the target layer, and the neutralization dynamics of the charge depleted area left by the HCI around the impact point. To make the problem accessible we have set up a Monte-Carlo simulation combining a molecular-dynamics simulation for the target atoms with hole-hopping conduction after extraction of electrons by the impinging HCI. Depending on the conductivity of the simulated material (free parameter in simulation) we observe pore formation in qualitative agreement with experiment.

While charge transfer and surface damage after impact of HCI on solid surfaces has been investigated in detail, both of which could be well described by the classical-over-the-barrier (COB) model and classical molecular-dynamics simulations, similar interaction systems, however, are not yet well understood for 2D target materials. Due to the limited conductivity of the layer which results in a reduced total number of electrons available for charge-exchange processes for the neutralization of the HCI and, following this charge

transfer to the projectile, the neutralization of the impact area are expected to proceed slower increasing the time available for Coulomb explosion.
We have combined the COB model for the electron transfer from the target layer to the HCI with a charge hopping model for charge conduction within the 2D material. These two models are integrated into a molecular-dynamics simulation for the motion of the target atoms. To model the nuclear dynamics we use a Stilling-Weber potential valid for graphene layers with a varying number of carbon rings around the impact point. Depending on the conductivity (i.e. hopping time) chosen for the simulation, different target sizes had to be used in order to achieve convergence of the numerical results.
As free parameters in the simulation we vary the initial charge state Q_{in} of the HCI as well as the hopping rate $f_h = t_h^{-1}$
(mobility) of positive hole charges. Diffusion con-
stants (hopping rates) for different targets have been estimated from the band structure of the materials. Certainly, hopping conduction is not a suitable model for (semi-)metallic conduction as in ground-state graphene but can be used for any material with (small) band gaps as can be expected to be induced also in graphene in the Coulomb field of the approaching HCI. Other materials such as, e.g., MoS2 (large band gap) or Fluorographene with a conductivity depending on the degree of fluorination are well described by hole hopping models.
We determine regions of stability (blue) and pore formation (pink) of the target as a function of Q_{in} and t_h (Fig. 1) with the release of a single target atom defining the limit of stability. The functional dependence of the line separating regions of stability and instability is well fitted by $Q_{in} \sim (t_h - \tau_c)^{-\frac{1}{2}}$. Qualitatively, our simulation reproduces available experimental data, i.e., we find pore formation for MoS2 (well in the pink area for all charge states) and stability for graphene (on the left border of Fig. 1). Experiments of Fluorographene layers as target and HCI with a wide range of initial charge states Qin were recently performed. To examine the transition region, comparisons to the Fluorographene experimental data will allow us to benchmark and further improve our simulation.
Future experiments exploiting the capabilities of HITRAP to provide very highly charged ions at very small kinetic energies (long interaction times) will allow to test the stability of graphene in this extreme region of interest. Based on our simulation we will be able to assess the electronic properties of graphene under extreme conditions.

Session 6 / 16

Total binding energies and prediction of very long-lived metastable states for ion trap experiments

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The accuracy of quantum electrodynamics tests in strong fields has been tested up to now by measuring transition energies in highly-charged ions, using accelerator facilities and ion sources (see, e.g., [1] and Refs. there in). New applications like atomic mass measurements with 10-11 relative accuracy, performed using advanced ion traps, require the evaluation of total binding energy differences between the ion measured and the neutral atom for which the total mass must be provided [2, 3]. Such accurate masses can be used in a variety of applications like the measurement of the neutrino mass. This high precision also allows to detect long-lived metastable with only a few tens of eV above the ground state [4]. In my talk I'll describe the evaluation of mass differences between highly-charged ions and the corresponding neutral atom. I will also describe examples of metastable states that can be detected in ion traps and provide their lifetimes, including effects like hyperfine quenching [5], to see if one can hope measuring also their lifetimes in the trap. Such metastable states are usually the result of changes of level orders due to relativistic effects [6, 7]. Such metastable states could be the building blocks for future high-precision atomic clocks.
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Session 4 / 17

Two-electron processes in relaxation of hollow atoms

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The M-X-rays emitted from Rydberg (n~30) hollow atoms (RHA) created in collisions of highly charged Xe^{q+} ions (q=23-36) with Be surface were measured and interpreted in terms of the MCDF calculations [1] as a cascade of nf-3d electric dipole X-ray transitions, including their M-shell hypersatellites. The measured X-ray spectra indicate the importance of two-electron processes, in particular the Internal Dielectronic Excitation (IDE) [2] and Two-Electron One-Photon (TEOP) transitions in relaxation of studied RHA. In fact, the observed M-X-rays for Xe^{26+} ions, that have no initial vacancies in 3d subshell, result from filling 3d vacancies formed exclusively by the IDE. We found a sharp cut-off for X-ray cascade at n~10-20, which supports the idea that for higher n-states the relaxation proceeds via the Interatomic Coulombic Decay (ICD) [3]. We demonstrate that present observations explain why the relaxation of RHA can proceed in the ultrafast timescale.

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Session 9 / 18

Nonlinear isotope-shift effects in highly-charged ions

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Precision isotope-shift spectroscopy of ions provides a very promising tool to probe the fundamental limits of Standard Model and to search for hypothetical "fifth-force" interactions. The analysis of the isotope-shift experimental and theoretical results can be performed most conveniently by means of the so-called King plot (KP). In this plot, the normalized frequency shifts of two (or even more) atomic transitions are displayed against each other for a series of isotopes of the same element. While KP is linear to the leading order, its non-linearity can be attributed to higher-order Standard Model effects or to a fifth-force interaction, or to a combination of both. The separation of these two contributions to the KP non-linearities remains an open and very challenging question. In order to attack it, one has to understand well the higher-order Standard Model corrections to the electronic structure of ions. In my presentation I will review recent theoretical advances in the analysis of (higher-order) field-shift and recoil isotope-shift corrections. Special attention will be paid to robustness of the KP analysis to the uncertainties of these theoretical predictions.

Session 3 / 19

X-ray Spectroscopy of Charge Exchange at Ultra-Low Collision Energies

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Charge exchange (CX), the atomic process in which a bound electron from a neutral atom or molecule is tranferred into a highly excited state of a highly charged ion (HCI), results in the emission of a complex characteristic x-ray spectrum. Relative line intensities in this spectrum depend on the donor and acceptor species, as well as their relative velocity.

CX contributes to spectra of astrophysical plasmas observed with x-ray observatories and can provide information about their compositions, temperatures and densities. However, how much of this information can be reliably deduced from spectra is currently limited by our incomplete understanding of the capture process and the subsequent radiative cascade. With the high-resolution microcalorimeter instruments onboard the next generation of x-ray observatories, better models are urgently needed. Such models have to be benchmarked by laboratory experiments.

HITRAP provides an excellent environment to study CX with ultra-slow HCI in a wide range of elements and charge states, for many of which very little or no experimental data is available. Experiments could explore the regime of high-Z ions undergoing CX at collision energies well below 10 keV/u, in which many commonly used approximations are expected to not be applicable anymore.
X-ray and UV spectroscopy combined with ion time-of-flight measurements at the HITRAP pulsed gas target would make unique systematic studies possible, which will directly impact the interpretation of astrophysical x-ray spectra and give insights into fundamental aspects of ion-atom interactions.

Session 5 / 20

Studying quantum-dynamics in collision involving highly charged ions

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While the study of the dynamics in scattering reactions between ions and atoms or molecules is a research field with a very long tradition, there are still many interesting and new aspects that are presently investigated. As compared to other projectile species such as electrons or photons, ions are particularly attractive because the allow to generate the shortest (down to zeptoseconds) and most intense electromagnetic pulses (well above 10^{20} W/cm^2) that can be created laboratories today. The present and planned accelerator facilities available at FAIR provide the ideal experimental tools to study the interaction of target systems with these pulses even in domains that were previously not accessible. In this presentation, some examples on recent advancements in the study of ion collision dynamics will be introduced and prospects for experiments at FAIR will be discussed

Session 4 / 21

Two-loop self-energy corrections to the bound-electron g-factor: Status of M-term calculations

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The theoretical uncertainty of the bound-electron g-factor in heavy hydrogen-like ions is dominated by uncalculated QED Feynman diagrams with two self-energy loops. Precision calculations of these diagrams in which the interaction between electron and nucleus is treated exactly are needed to improve the theoretical accuracy of the bound-electron g-factor in the high-Z regime. Results of such calculations are highly relevant for ongoing and future experiments with high-Z ions at the ALPHATRAP and HITRAP facilities, as well as for an independent determination of fundamental constants such as the electron mass m_e and the fine structure constant α from the bound-electron g-factor [1,2]. Furthermore, comparisons of theory and experiment for heavy ions can serve as a probe for physics beyond the Standard Model after an improvement of the theoretical accuracy through the completion of two-loop calculations [3].
Due to the presence of ultraviolet divergences, two-loop self-energy Feynman diagrams need to be split into the loop-after-loop (LAL) contribution and the so-called F-, M- and P-terms which require different analytical and numerical techniques. The F-term corresponds to the ultraviolet divergent part of the nested and overlapping loop diagrams with free electron propagators inside the self-energy loops. The M-term corresponds to the ultraviolet finite part of nested and overlapping loop diagrams in which the Coulomb interaction in intermediate states is taken into account exactly. In our previous work, we have obtained full results for LAL and the F-term [4]. In this work, we present our results for the M-term contribution. P-term contributions correspond to diagrams which contain both bound-electron propagators inside the self-energy loops as well as an ultraviolet subdiagram and will be considered in a future work.

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Session 4 / 22

HILITE - Compact Penning trap for High-Intensity-Laser Experiments

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The influence of relativistic effects on tunnel ionisation of electronic systems was described in detail by theory. For hydrogen-like ions of atomic charge Z and laser radiation intensity I these effects become significant for $Z > 45(I/I_0)^{0.1}$, with $I_0 = 10^{22}\,\mathrm{W/cm}^2$. This motivates the use of highly-charged ions to investigate ionisation. Suitable candidates are hydrogen-like ions, such as O^{7+} or Ne^{9+}, as the average electric field over the 1s orbital is comparable to the electric fields of current laser systems.

To prepare a target of highly charged ions we have devised the HILITE (High-Intensity Laser Ion-Trap Experiment). The setup can store several thousand ions in a controlled ion cloud using a Penning trap. The whole setup is transportable to be used at high-power laser facilities. It includes an Electron-beam ion trap (EBIT) which can create a wide range of highly-charged ions. The produced ion bunches with a kinetic energy of about 2 keV/q are deflected by a 90° electrostatic detector. It includes two sikler lenses to compensate for the stray magnetic field of the 6 T magnet. The beamline also contains three non-destructive image charge detectors to track the ions bunches. The ions are decelerated using a two stage deceleration system and captured dynamically.
To manipulate and detect the stored ion cloud we use common procedures, such as resistive cooling, SWIFT, FT-ICR and the rotating wall technique.

We present the setup and characterisation measurements with stored Ne^{7+} ions and we will give an outlook on the planned laser-ion experiments at the Jena high-power laser system JETI200.

Session 8 / 23

Strong-field QED and beyond in highly charged ions

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In this contribution, we discuss the quantum electrodynamic (QED) theory of strongly bound atomic systems. The ionic g factor can be measured nowadays to high precision with the combination of Penning traps and electron beam ion traps. The collaboration of theory and experiment enables impactful and detailed tests of QED in a strong background field, and a competitive determination of fundamental constants [1] and nuclear properties [2]. Very recently, we have shown that such studies also allow to test certain extensions of the Standard Model of particle physics, and set bounds on the strength of a hypothetical fifth force [3,4]. We summarize our ongoing calculations of radiative corrections in the non-perturbative Coulomb potential, which are necessary for further improvements in this field.

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Session 4 / **24**

Experimental study of the laser-induced ionization of heavy metal and metalloid ions: Au^{+} and Si^{2+}

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We implement a liquid metal ion source\,(LMIS) in a 3D coincidence momentum spectroscopy setup for studying the interaction of ionic targets with intense laser pulses. Laser intensities of up to $4{\cdot}10^{16}$\,W/cm^2 allow for the observation of up to 10-fold ionization of Au^{+}-ions and double ionization of Si^{2+}-ions. Further, by utilizing two-color sculpted laser fields to control the ionization process on the attosecond time scale, we demonstrate the capability to resolve the recoil ion momenta of heavy metal atoms. Simulations based on a semiclassical model assuming purely sequential ionization reproduce the experimental data well.This work opens up the use of a range of metallic and metalloid ions, which have hardly been investigated in strong-field laser physics so far.

Session 3 / **25**

Photon counting detectors for laser spectroscopy experiments at SPECTRAP

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GSI has an active program of laser spectroscopy experiments with highly charged heavy ions. The focus of the measurements is on the study of fundamental interactions in extreme electric and magnetic fields, like they are available in few electron configurations of these heavy ions. The applied experimental methods comprise on the one hand laser spectroscopy of relativistic ions in storage rings and on the other hand high-precision laser spectroscopy of ions stored at cryogenic temperatures in Penning traps.
Especially in trap measurements, where one cannot make use of the Doppler effect to shift emitted fluorescence photons to an advantageous wavelength region as is possible in a storage ring experiment, the transitions of interest span a wide wavelength range from the UV to the near infrared.

It is therefore necessary to develop different detection systems adapted to the actual experimental situation and able to reliably detect lowest rates of emitted fluorescence photons at the given wavelength.

The talk will give an overview of the different detection systems developed or procured at the university of Münster for laser spectroscopy experiments at SPECTRAP.
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Session 8 / 26

ARTEMIS: Toward Measurement of Magnetic Moments in Heavy, Highly Charged Ions

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In ARTEMIS[1] laser-microwave double-resonance spectroscopy[2] will be used to measure the intrinsic magnetic moments of both electrons and nuclei in heavy, highly charged ions (HCIs). The extreme field strength of the nearby nucleus in such heavy HCIs enhances the effect of bound-state QED and nuclear interactions with the orbiting electron. Figure 1 shows the level scheme for hydrogen-like bismuth and the transitions used for the measurement.

The ARTEMIS Penning trap (Figure 2) has two sections: the spectroscopy trap (ST) and creation trap (CT). The ST uses a half-open design for optical and ion access[3]. On the closed side spectroscopic access is provided by a transparent endcap electrode with a conductive indium-tin-oxide coating. This provides ≈ 2 sr conical access to the trap center for irradiation and detection of fluorescence light but maintains a well-defined trap potential. On the open side HCIs can be injected from the adjacent CT, where they can be created *in situ* via electron impact ionization or captured from an external source. The cryogenic fast-opening valve allows injection of ions from the HITRAP facility while maintaining ultra-low residual gas pressure in the trap region. Temperatures as low as 8.5 K and lifetimes greater than 22 days have been observed for O^{4+} since the beamline was connected. Stored ions are monitored non-destructively by their induced image currents, which also brings the ions into thermal equilibrium with the cryogenic environment [4]. Attempts at ion injection from the SPARC EBIT are currently underway. Simulation driven design of a bunching pulsed drift tube and position sensitive, non-destructive charge counter that will improve the injection tunability and transmission will also be presented.

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Session 2 / **27**

S-EBIT II, a local ion source for HITRAP

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The demand for beamtime at GSI infrastructures like ESR, CRYRING or HITRAP has increased over the last years and cannot be fully covered by the GSI accelerator infrastructure. Local ion sources play an important role to close this gap and allow for 'offline operation' of experiments at GSI [1].
Electron Beam Ion Traps (EBITs) are widely known as a versatile tool for spectroscopic studies of partially ionized atomic systems. Furthermore, they can be used as small stand-alone ion sources, capable of producing beams of heavy highly charged ions of a certain charge state at reasonable intensities. The Jena S-EBIT facility are two EBITs, the former R- and S-EBIT from Stockholm [2], which both are suitable for x-ray spectroscopy studies and ion extraction.
The S-EBIT I has been used as a tool for x-ray spectroscopy, including the testing of newly developed x-ray detectors, like the magnetic metallic microcalorimeter maXs30 [3]. In addition, the setup was recently expanded by a short testing beamline, to evaluate the potential of the S-EBIT I as an ion source.
The S-EBIT II is currently in commissioning for operation as a standalone ion source for HITRAP in the near future. This will provide new opportunities for local experiments, like the ARTEMIS experiment, independently from the GSI accelerator infrastructure.

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Session 8 / **28**

Theory of bound-electron g-factors

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I will describe the basics of bound-state Quantum Electrodynamics (QED). I will focus on the interaction of a bound particle with an external magnetic field, parametrized by the g-factor. Recent developments in the theory of g-factors in low-Z ions will be described. Some developments in medium-Z and high-Z ions will also be discussed.

Session 3 / **29**

Interaction of Highly Charged Ions with Surfaces - Two Decades of Research at the HZDR Ion Beam Center

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Investigations of the interaction of highly charged ions (HCI) with solid surfaces started back almost 20 years ago at the HZDR Ion Beam Center (IBC). In particular, first experiments focused on the determination of channels for potential energy dissipation in solids [1].

Successively, systematic studies on HCI induced modifications of surface topography on the nm scale were conducted [2,3]. Those were accompanied by determination of secondary electron emission mechanism during the HCI impact. More recently, studies were extended to the interaction of HCI with ultra-thin foils and 2D-Materials [4,5].

In this talk we will give a summary on the outcome of these activities, draw conclusions and discuss open issues. Furthermore, we will report on recent and ongoing activities. In particular, we will present (a) a new experimental setup for the investigation of the interaction of slow HCIs with gas targets as well as (b) a new low energy ion laboratory.

The latter one will contain two sources for highly charged ions in conjunction with state-of-the-art equipment for surface modifications and characterization, combined in a common ultra-high vacuum system. Planned HCI and other activities at this unique facility will be discussed.

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Session 5 / 30

Theoretical predictions of the structure of heavy muonic atoms and searching for an elephant in the room

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When coming close to an atom, a muon can be captured by the nucleus and form a hydrogen-like muonic ion, which is typically also surrounded by atomic electrons. This atomic system is commonly referred to as a muonic atom. Due to the muon's high mass, it is located much closer to the nucleus; and, especially for heavy nuclei, this results in big nuclear size effects and a strong dependence of the muon bound-state energies on the nuclear charge and current distributions, as well as in large relativistic effects [1, 2]. A combination of the knowledge about the level structure and experiments measuring the transition energies in muonic atoms enabled the determination of nuclear parameters like charge radii, electric quadrupole and magnetic dipole moments [3].
Theoretical predictions of the fine-, hyperfine structure, and dynamical splitting of muonic atoms, based on rigorous QED calculations will be presented. State-of-the-art techniques from both nuclear and atomic physics are brought together in order to perform the most comprehensive to date calculations of the quantum-electrodynamics and nuclear contributions. A long-standing problem of

fine-structure anomalies in muonic atoms will be revisited in the light of the last improvements on nuclear-polarization [4] and self-energy calculations [5].
Finally, we will discuss the currently used tabulated values of the rms radii based on their extraction from the muonic spectra and possible further development in this direction.

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Session 4 / 31

Superconducting toroidal resonator at ARTEMIS in HITRAP

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ARTEMIS (AsymmetRic Trap for measurement of Electron Magnetic moment in IonS) is a Penning trap-based experiment at HITRAP in GSI, Darmstadt, which is aiming to measure the g-factor of heavy, highly charged ions (such as U91+) as one of the most stringent tests of quantum electrodynamics. These ions in the magnetic and electric fields of the Penning trap demonstrate a distinctive motion that can be broken down into three individual components. In order to measure the g-factor of the ions in the trap, a crucial part is to measure the frequencies associated with the charged particle of each of these individual motions independent of each other. This is done using the image current generated across the trap electrodes taking into account the self-capacitance of the trap electrodes. We present the use of an RLC circuit in the form of a toroidal superconducting resonator made of NbTi with a copper housing along with the associated designing principles taking into consideration the operating working conditions of 7T and 10-13 mbar. This is followed by the recent test results of a superconducting toroidal resonator with a Q factor ≈ 4500 at an operating eigenfrequency ≈ 2.4 MHz. Further plans include the study of changing designing parameters and their influence on the Q factor.

Session 9 / 33

SpecTrap

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SpecTrap is part of the experiments located at HITRAP and aims at precision measurements of optical transitions in few-electron highly charged ions as a means of testing QED predictions in the regime of extreme electromagnetic fields. Particularly, focus is on spectroscopy of hyperfine transitions in hydrogen- and lithium-like ions that are cooled and confined in the cryogenic Penning trap. I will briefly discuss the motivation of the experiment, previous results on ion cooling, its current status, and immediate next steps.

Session 9 / 34

Atomic processes and cascades: News from the JAC toolbox

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The Jena Atomic Calculator (JAC) provides an easy-to-use but powerful toolbox to extent atomic theory towards new applications. It has been designed to be equally accessible for working spectroscopists, theoreticians and code developers. In this talk, I shall discuss the recent progress in developing these tools towards different cascade and second-order processes which are relevant for highly-charged and inner-shell excited ions.

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Modification of the configuration interaction plus many-body perturbation theory approach for calculations of atomic structure of ions with partly filled d and f shells

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At present, there are several methods for relativistic calculations of atomic structure and properties, such as multiconfiguration Dirac-Fock, coupled cluster, configuration interaction (CI), many-body perturbation theory (MBPT), their combination, and others. Generally, these approaches can provide accurate and reliable results for atoms and ions with a small number of valence electrons. Calculations of the spectra of ions with many valence electrons, like lanthanides and actinides, are very difficult and usually not so accurate. To account for strong electron correlations in these species a very large configuration space is required. Such a huge configuration space makes calculations very expensive.

The proposed modification of the original CI+MBPT method [1] uses different splitting of the problem into the CI and MBPT parts [2]. In particular, it is suggested to account for double excitations from the valence subspace to virtual using the MBPT and to include single excitations in the CI space. Moreover, the same idea of dividing into parts with single and double excitations, which are then handled differently, can also be used for treating the core-valence correlations.

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Registration

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Workshop Event - Wartburg Excursion

Session 3 / 38

CRYRIMS - The COLTRIMS-Reaction-microscope for CRYRING

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With its roots in collision physics, back in the late 1980, COLTRIMS-setups (COLd Target Recoil Ion Momentum Spectroscopy) or Reaction microscopes, as they are also termed, are widely used in modern AMO-physics. Technically they consist of a super sonic gas jet, the imaging spectrometer and position and time-sensitive detectors. The super sonic gas jet provides the target, covering basically everything that can be brought into the gas phase. Gas jet and ionizing radition, here the CRYRING-beam, are crossed at right angle. Charegd particles (electrons and ions), which are set free in the interaction are projected with weak elektric and magnetic fields onto position and time-sensitive detectors, allowing the determination of each particle's momentum in coindice with the others. Here we report on the planned versatile setup, that will be part of the CRYRING Instruments.

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Introduction

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Final Discussion

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HITRAP Decelerator Status

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HITRAP Decelerator Status

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Relativistic effects in highly charged heavy ions

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In electron-electron interactions in electromagnetic systems, retardation in the exchange of a virtual photon is essentially important as the first-order quantum electrodynamics correction. However, the retardation effect is generally so small that it is buried in unretarded electric and magnetic interactions and thus has yet to be directly probed. Here, we present a giant contribution of the retardation effect in an electron-electron interaction via observing strong electric-dipole-allowed radiative transition rates.
In this talk, we also present the investigation on the linear polarization of K-shell radiative recombination (RR) to highly charged bare and hydrogenlike ions. In particular, the spin-flip contribution on the polarization is studied through relativistic theoretical calculation. The experimental polarization obtained for Kr shows a better agreement with the simulation including the spin-flip contribution. It indicates that the spin-flip effect on the polarization of RR x-ray photons could be identified with the lightest element hitherto.

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Trip to Jena