20th International Conference on the Physics of Highly Charged Ions

HCI 2022 MATSUE

Aug. 29 - Sep. 3, 2022, Matsue, JAPAN

Book of Abstracts

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ABOUT

HCI 2022 is the 20th in a series of International Conferences on the Physics of Highly Charged Ions. The conference covers the following topics on highly charged ions: Fundamental aspects; Structure and Spectroscopy; Collisions with Electrons, Ions, Atoms and Molecules; Interactions with Clusters, Surfaces and Solids; Interactions with Photons, Plasmas and Strong Field Processes; Production, Experimental developments and Applications.
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SCIENTIFIC PROGRAM

Day1: Aug 29th (Mon)

9:10		Opening
9:30	RL-1	Kyoko Matsushita X-ray observations of cosmic plasmas
10:15	ST-1	Yang Yang First Laboratory Verification of Magnetic-field-induced Transition Effect in Fe X
10:35	Coffee	
11:05	PR-1	Jyoti Rajput Addressing Molecular Dissociation using Ion Impact
11:35	PR-2	Alba Jorge On the importance of dynamical screening in mean-field calculations involvingmany-electron systems
12:05	ST-2	Lokesh C Tribedi First observation of giant quadrupole plasmon resonance in C_{60} in high perturbation HCI collisions
12:25	Lunch	
14:00	PR-3	Zhimin Hu Relativistic effects on radiative properties and electronic collisions of highlycharged heavy ions
14:30	ST-3	Naoki Kimura Lifetime measurement of the microsecond-order electric-quadrupole transition: Application of plasma-assisted laser spectroscopy
14:50	ST-4	Dipti Analysis of E3 transitions in Ag-like high-Z ions observed with the NIST EBIT
15:10	ST-5	Sophia Strnat Elastic x-ray scattering by highly charged ions
15:30	Coffee	
16:00	PR-4	A. Niggas Charge exchange dynamics of highly charged ions with atomically thin materials
16:30	PR-5	L. Skopinski Particle emission from 2d materials induced by highly charged ion impact

17:00	ST-6	Asghar N Kayani Radiative Double-Electron Capture by Highly-stripped Ions on Graphene
17:20	ST-7	Pierre-Michel Hillenbrand Experimental Studies of Nonperturbative Dynamics in Heavy-Ion-Atom Collisions

Day2: Aug 30th (Tue)

9:00	RL-2	Oscar Versolato Highly charged ions in laser-produced plasma for state-of-the-art EUV nanolithography
9:45	ST-8	Takeshi Higashiguchi Charge-separated ion spectra from a laser-produced plasma
10:05	ST-9	Emma Sokell High resolution imaging of laser plasmas revealing the effects of laser spot size on plasma emission.
10:25	ST-10	Chunhai Lyu Inferring the coherence time of EUV pulse trains via spectroscopy of highly charged ions
10:45	Coffee	
11:15	PR-6	Yu Zhang Hydrogen migration in the fragmentation of hydrocarbon dications
11:45	PR-7	P. Rousseau Charge migration in betaine by impact of fast atomic ions
12:15	ST-11	Jatin Yadav Hydrogen migration in three body fragmentation of acetylene trication
12:35	Lunch	
14:30	RL-3	Klaus Blaum Precision Measurements of Fundamental Atomic Properties using Highly Charged Ions in Penning Traps
15:15	ST-12	Jost Herkenhoff Sympathetic cooling of highly charged ions in a Penning trap using a self-cooled electron plasma
15:35	ST-13	Kathrin Kromer Direct high precision measurement of the Q-value of the electron capture in 163Ho and metastable states in highly charged ions
15:55	Break	
17:00 20:00	Poster session Virtual A	

Day3: Aug 31st (Wed)

9:00 12:00	Poster session Virtual B	
12:00	Lunch	
14:30	RL-4	Piet O. Schmidt An Optical Atomic Clock Based on a Highly Charged Ion
15:15	ST-14	Christian Warnecke A superconducting quadrupole resonator for laser-spectroscopy of highly charged ions at highest precision
15:35	ST-15	Elwin A. Dijck Dynamics of mixed species Coulomb crystals with highly charged ions in a superconducting Paul trap
	Coffee	
16:25	PR-8	M. Lestinsky First experiments with the CRYRING@ESR
16:55	ST-16	Leonard Isberner First Dielectronic Recombination Measurements at the Cryogenic Storage Ring
17:15	ST-17	Philip Pfafflein High-Resolution X-Ray Spectroscopy of He-like Uranium using Novel Microcalorimeter Detectors
17:35	ST-18	Robert Loetzsch High resolution measurement of the $2p_{3/2} \rightarrow 2s_{1/2}$ intra-shell transition in He-like uranium

Day4: Sep 1st (Thu)

9:00	RL-5	Marianna S. Safronova Search for new physics with highly charged ions
9:45	PR-9	Julian C. Berengut New physics searches with highly charged ion clocks
10:15	PR-10	Anastasia Borschevsky High accuracy theoretical investigations of highly charged ions
10:45	Coffee	
11:10	ST-19	Priti 5p-5s spectrum in highly charged W XII – W XIV Ions
11:30	ST-20	Xiaobin Ding Collisional-radiative model for the spectra of M1 transition of W^{53+} ion

11:50	ST-21	Hanbing Wang Laser cooling of relativistic O^{5+} ions at CSRe: experiment and simulation
12:10	ST-22	Ken Lukas Ueberholz First broadband laser cooling and XUV fluorescence detection of stored relativistic HCI
	Excursion + Banquet	

Day5: Sep 2nd (Fri)

9:00	PR-11	Wania Wolffa Aromatic molecules revisited under bare helium collision: experiment and theory
9:30	PR-12	Shuncheng Yan Fragmentation of the Heteronuclear Cluster by Electron Impact
10:00	Coffee	
10:30 12:30	Poster session Onsite	
12:30	Lunch	
14:30	RL-6	Jimmy Rangama Ion interaction with atomic and molecular dimers: a new way of looking at atoms and molecules
15:15	PR-13	Natalia S. Oreshkina Theoretical predictions of the structure of heavy muonic atoms
15:45	PR-14	S. Okada Muonic atom X-ray spectroscopy for QED test in strong Coulomb field
16:15	ST-23	Takuma Okumura High-resolution spectroscopy of electronic K x rays from muonic atoms
16:35	Coffee	
17:05	PR-15	Sonja Bernitt Resonant photoexcitation of trapped ions for x-ray astrophysics
17:35	ST-24	Adam Hosier Absolute nuclear radius of iridium from precision measurements and calculations of EUV and X-ray transitions in highly charged ions

17:55	ST-25	Phillip Imgram Laser Spectroscopy of $^{12}C^{4+}$: First results towards an all-optical charge radius determination
18:15	Summary	

Day6: Sep 3rd (Sat)

9:00 12:30	Networking
	adjourn

REVIEW LECTURES

RL-1

X-ray observations of cosmic plasmas

Kyoko Matsushita

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X-ray emitting celestial objects are the best laboratories to study cosmic plasmas. Their electron densities are orders of magnitude lower than those of laboratory plasmas on Earth. In the Universe, about 80% of baryons are thought to be in the form of plasmas. In clusters of galaxies, the largest gravitational bound objects in the Universe, plasmas with temperatures of $10^7 - 10^8$ K fill the gravitational potential of dark matter. Galaxies and clusters of galaxies grow by accretion of matter from their surroundings. The accreting gas is expected to be heated to the virial temperature by shock waves generated by mass accretion. In addition, in galaxies supernovae heat the interstellar medium and sometimes cause an outflow toward intergalactic space. X-ray observations enable us to study plasma physics from stars, and supernovae, to clusters of galaxies. In this talk, we will review the basic properties of cosmic plasmas, and new windows opened by high- resolution X-ray spectroscopy.

RL-2

Highly charged ions in laser-produced plasma for state-of-the-art EUV nanolithography

Oscar Versolato

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Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit Amsterdam,
De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

Highly charged tin ions play a key role in the continued miniaturization of semiconductor devices. Laser-produced plasmas containing such ions produce the extreme ultraviolet (EUV) light that is used in state-of-the-art nanolithography. The short wavelength EUV light, at 13.5nm, enables "printing" the smallest features. The EUV light originates from Δn=0, n=4–n=4 electronically excited states in Sn^{11+}–Sn^{14+} populated through electron impact in the hot and dense plasma [1]. In the tin system, the exponentially decreasing probability of excitation into multiply excited states is offset by the near-exponentially increasing density of states, resulting in a particularly prominent contribution of multiply excited states to the total opacity – and emission of EUV light [2,3]. This surprising finding underlines the importance of understanding the spectrum of tin highly charged ions in detail [4]. In this presentation I will introduce the field of EUV nanolithography and explain the role of tin plasmas in it, as produced through a series of carefully tailored laser pulses from tin microdroplets. As I will explain, the research performed at ARCNL on the physics of EUV-emitting laser-produced plasma ranges from advanced laser development, over studies of fluid dynamic response of droplets to impact, and radiation-hydrodynamics calculations of, e.g., ion "debris", to (EUV) spectroscopic studies of tin, in laser-produced plasma and, in collaboration with MPIK in EBIT plasma. Together, we will seek to answer the question: what really emits that EUV light?

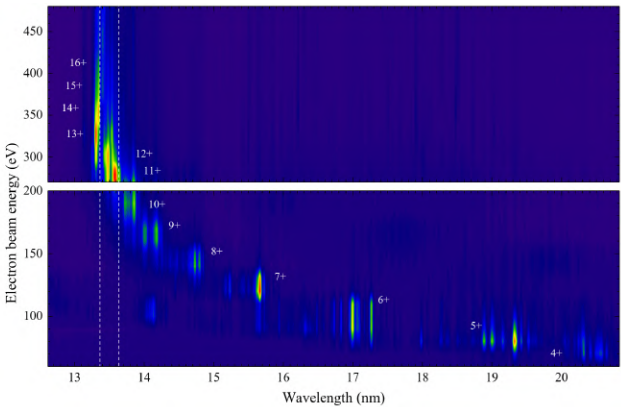

Figure 1: Spectral intensity map of Sn ions trapped in an EBIT [4].

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RL-3

Precision Measurements of Fundamental Atomic Properties using Highly Charged Ions in Penning Traps

Klaus Blaum

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An overview is given on recent mass and g-factor measurements with extreme precision on single highly charged ions stored in Penning traps. On the one hand, mass measurements provide crucial information for atomic, nuclear and neutrino physics as well as for testing fundamental interactions and their symmetries. On the other hand, g-factor measurements of the bound electron in highly charged hydrogen like ions allow for the determination of fundamental constants and for constraining Quantum Electrodynamics. The most recent results will be presented and their impact discussed.

RL-4

An Optical Atomic Clock Based on a Highly Charged Ion

Piet O. Schmidt

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
Institut für Quantenoptik, Leibniz Universität Hannover, Germany.

Optical atomic clocks are the most precise and accurate measurement devices ever constructed, reaching fractional systematic uncertainties below one part in 10^{18} [1]. Their exceptional performance opens up a wide range of applications in fundamental science and technology. The extreme properties of highly charged ions (HCI) make them highly sensitive probes for tests of fundamental physical theories [2, 3]. Furthermore, these properties make them significantly less sensitive to some of the leading systematic perturbations that affect state-of-the-art optical clocks, making them exciting candidates for next-generation clocks [4, 2]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [5], readout of their internal state via quantum logic spectroscopy [6], and finally the preparation of the HCI in the ground state of motion of the trap [7], which allows levels of measurement accuracy to be reached that were previously limited to singly-charged and neutral atoms. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts [8]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI. Measurements of some key atomic parameters confirm the theoretical predictions of the favorable properties of HCIs for use in clocks. The comparison to the $^{171}Yb^{+}$ E3 optical clock [9] places the frequency of this transition among the most accurately measured of all time. Furthermore, by comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ to improved atomic structure calculations, we were able for the first time to resolve the largely unexplored QED nuclear recoil effects. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^{+}/Ca^{14+} isotopes and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.

References

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RL-5

Search for new physics with highly charged ions

Marianna S. Safronova

Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA

The development of atomic clocks with systematic uncertainties in the 10^{-18} range enabled searches for "new physics" beyond the Standard Model (BSM) of elementary particles and interactions [1]. Highly charged ions (HCIs) in different charge states offer narrow optical transitions that are among the most sensitive to the BSM effects [2]. Recent experimental advances in trapping, sympathetic cooling, and quantum logic techniques with HCIs enabled a demonstration of an optical clock based on a transition in Ar^{13+} with comprehensively evaluated systematic frequency uncertainty of 2.2×10^{-17} [3], comparable to that of many optical clocks in operation.

I will give an overview of the application of highly charged ions to search for BSM physics, including searches for dark matter, variation of fundamental constants, violation of the local Lorentz invariance, and exotic forces. Proposals with clocks based on Cf^{15+} and Cf^{17+} [4,5] will be described in more detail.

I will also discuss recent theoretical developments in predicting properties of highly charged ions, with application to predicting properties of systems with many valence electrons. The new parallel version of the configuration interaction code was developed [6] and run on up to 2000 CPUs, allowing the treatment of more complicated systems. Applications to solving a long-standing puzzle in astrophysics in Fe^{16+} [7] and predicting rates of electronic bridge excitation of the nuclear transition in Th^{35+} [8] will be reported. Finally, I will discuss a release of the new version of an online portal for high-precision atomic data and computation [9] and future plans to add data for more systems and release computer codes.

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RL-6

Ion interaction with atomic and molecular dimers: a new way of looking at atoms and molecules

Jimmy Rangama

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Investigating reactions involving highly charged ions (HCI) and atomic/molecular dimers became a challenging subject in collision physics since the two last decades. However, intramolecular charge redistribution before dissociation usually limits the access to the primary process detailed information, as the identification of the active atomic/molecular site [1] in the dimer is lost. Rare-gas dimers are linked by van der Waals bonds which are much weaker than ionic or covalent bonds and are associated to larger internuclear/intermolecular distance. What should we expect for such weakly bound systems, made of two nearly independent atoms/molecules, when excited by impact of charged particles such as HCI [2]? How the low electron mobility between the two sites of the dimer target can allow to investigate primary process? To answer these questions, we performed experiments by using the so-called recoil-ion momentum spectroscopy technique to obtain kinematically complete measurements. Differences observed in the collision dynamics and the subsequent fragmentation for van der Waals bound targets when compared to covalent bound targets will be presented and discussed as well as recent results about relaxation processes in these collisional systems [3-5].

References

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PROGRESS REPORTS

PR-1

Addressing Molecular Dissociation using Ion Impact

Jyoti Rajput

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Initiating molecular dissociation by impact of energetic ions presents a case of impulsive excitation of a molecular system. Using such an excitation, a wide range of processes can be studied, post interaction, by measuring (i) the projectile parameters like charge state and momentum transfer (ii) momentum, energy and/or angular distribution of recoil fragments (iii) momentum, energy and/or angular distribution of emitted electrons, if any. In its interaction with a molecular target, an energetic ion removes electrons either by electron capture or by ionization or by both. The charge state and velocity of the energetic ions are tunable parameters and thus allows for exploring the effect of interaction strength and interaction time-scales.

In the present talk, few results from our recent experiments on ion-impact induced molecular dissociation will be discussed. In all these experiments a recoil ion momentum spectrometer was used to measure the momenta of all fragments (in coincidence) generated during the ion-molecule collision process. The study on ion impact dissociation of methane (CH_4) led us to realise that though the dication of this simple and important molecule have been studied in several ways, yet even the understanding of energetics of this system is far from complete. We reported on observation of three pathways in the kinetic energy release distribution of breakup of $[CH_4]^{2+}$ into $(H^+ + CH_3^+)$ [1]. Two of the pathways have been explained with the help of existing literature but one still remains unexplained.

Using the analysis method of "native frames" [2], we have proposed a new technique for measuring the subrotational lifetime of molecular ions [3] which are formed as intermediary species in sequential breakup of small multiply charged molecules. The proof of principle is given by measuring the lifetime of SO^{2+} which is formed as an intermediate in the sequential breakup of SO_2^{3+} leading to detection of (O^+, O^+, S^+) as the final set of fragments.

Hydrogen migration and/or bond rearrangement is a phenomenon which has been reported to occur in the singly and doubly charged species of several small molecules like CH_4, C_2H_2, CH_3OH. The acetylene (C_2H_2) molecule is a prototype for studying hydrogen migration on account of being the smallest molecule having two H atoms which are not attached to the same C atom. Hydrogen migration in this prototype has been studied in a wide range of experiments and the process is reported to occur on the electronic states of either the monocation or dication of acetylene molecule. From our experiment and by using the analysis method of "native frames" [2] we have provided the first experimental evidence of Hydrogen migration occurring in the tri-cation of this prototype molecule [4].

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PR-2

On the importance of dynamical screening in mean-field calculations involving many-electron systems

Alba Jorge

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Through the study of ion-atom and ion-molecules collisions, with multielectronic targets and in the range of impact energy of 0.1-100 MeV/u, the treatment under a time-dependent potential that considers the change of the electronic cloud of both the projectile and the target molecule during the dynamics, is studied. The dynamic screening [1] model allows us to study the importance of the changes of potentials during the collision in processes such as the electron detachment.

Targets such as Ne, H_2O and NH_3 and projectile's charges from 1 to 13 will be considred. A notable change in the absolute double differential cross sections (DDCS) and single differential cross sections (SDCS) is found when considering a dynamic screening, specially in the the forward-backward asymmetry, for multielectronic targets, medium charged projectiles and high impact energies. For low impact energies (250 keV) and a low charged projectile (proton), where the electron loss of the molecule is much lower, the dynamic screening and non-dynamic screening versions show little differences.

A detailed insight in the model and a deeper comparison with experiments will be presented at the conference.

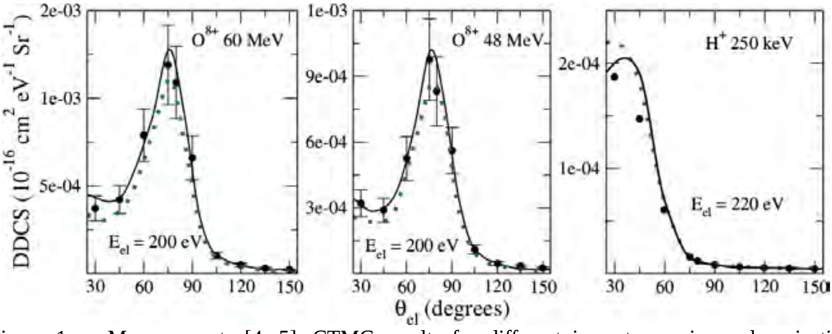

Figure 1: •: Measurements [4, 5]. CTMC results for different impact energies and projectiles colliding on the water molecule are shown as solid black and green dotted lines, with static and with time-dependent screening, respectively.

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PR-3

Relativistic effects on radiative properties and electronic collisions of highly charged heavy ions

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The relativistic and quantum electrodynamics (QED) effects in electron–electron interaction can be described by the Breit interaction, which was first introduced to precisely describe the energy levels of neutral He by G. Breit around 1930 [1]. In contrast to the minor contribution to atomic structrue, it has been found that the Breit interaction can have a significant contribution to collision processes of highly charged heavy ions with electrons, such as dielectronic recombination [2, 3], electron-impact ionization [4], electron-impact excitation [5], and resonant transfer and excitation [6]. The unexpectedly large or even dominant contribution in the electronic collisions is attributed to that the Breit term plays an important role in the electron-electron interaction operator [7].

On the other hand, the Breit interaction can hardly be expected to have a significant contribution to radiative transition probabilities. The transition rate is determined by the transition frequency ω and the transition matrix element $\langle b|\,\hat{o}\,|a\rangle$, where $\hat{o}$ represents the operator for the radiative transition. The Breit interaction has no contribution to the operator $\hat{o}$ and only a small contribution to ω and the wavefunctions of $|a\rangle$ and $|b\rangle$. Consequently, transition rates are expected to be less affected by the Breit interaction. In stark contrast to the previous studies, we predicted an unprecedentedly giant modification by the Breit interaction for electric dipole allowed transitions from the strongly correlated $1s2s^22p^2$ inner shell excited state of B-like heavy ions [8], and it has been experimentally demonstrated with the electron beam ion traps in Shanghai and Tokyo. We elucidate the underlying mechanism is due to the drastic change in the wavefunctions of the $1s2s^22p^2$ state resulting from the relativistic electron correlation effect appeared as a Breit-interaction-induced avoided crossing [9].

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PR-4

Charge exchange dynamics of highly charged ions with atomically thin materials

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Upon impact on a material surface, slow highly charged ions deposit up to several tens of keV of their potential energy within a material. This leads to an excitation of the material's electronic system and can result in material modification (nanostructuring) as well as emission of secondary particles, e.g. electrons. The emission of electrons due to impact of slow highly charged ions has been studied extensively in the past for several bulk materials [1]. There, however, the resulting electron yield comprises not only primary electrons emitted by the impinging ion, but also higher-generation electrons from sub-surface multiplication effects. Using free-standing two-dimensional materials as a target allows to exclude the latter and thus enables us to study the true ion-induced primary electron emission.

In our experiment, we irradiate monolayers of graphene with highly charged xenon ions and detect correlated pairs of emitted electrons (energy, yield) and transmitted ions (charge exchange, scattering angle, energy loss). Thereby, we are able to distinguish ions transmitted through the atomically thin layer from ions transmitted through the support structure in order to analyse solely the electron emission from the 2D material.

Figure 1 shows the electron energy distribution from single-layer graphene (red circles) induced by impact of 142 keV Xe^{15+} ions. A bimodal distribution can be observed with peaks at $\sim$ 2 eV and $\sim$ 10 eV. For comparison, we did similar (non-coincident) measurements with highly oriented pyrolitic graphite (HOPG, orange line) which agrees well with the data points achieved from graphene. To entangle the origin of these distributions we apply de-excitation cascade calculations of highly charged ions that take into account Auger de-excitation and radiative decay [2].

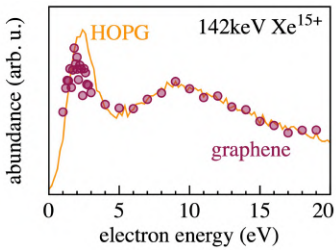

Figure 1: Electron energy distribution of electrons emitted due to impact of 142 keV Xe^{15+} ions on single-layer graphene (red circles) and HOPG (orange line).

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PR-5

Particle emission from 2d materials induced by highly charged ion impact

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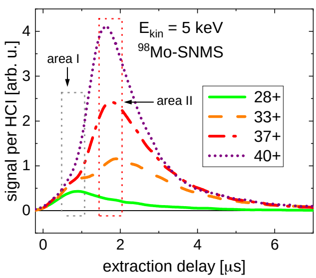
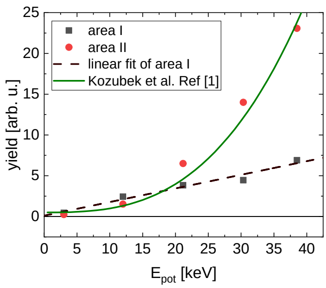
Two-dimensional (2d) materials such as graphene or transition metal dichalcogenides are expected to be key for novel applications and defect engineering by highly charged ion (HCI) beams could be a way to modify their unique properties even further.

An ion stores its energy in the form of the kinetic energy E_{kin} and the so-called potential energy E_{pot}, the latter corresponding to the energy required to create its respective charge state. Once the ion impinges on the surface its energy is deposited into the solid and can lead to sputtering. However, the fundamental mechanisms of defect formation due to HCIs are still under investigation.

Here we report on HCI induced damage of supported single layer MoS_2. We used Au substrates to minimize potential sputtering of the substrate and analyzed the emission of secondary ions and atoms under irradiation. Using laser-assisted time of flight (ToF) mass spectrometry the mass spectra



(a) Extraction delay measurements determined with a ToF mass spectrometer of emitted particles due to Xe^{q+} impact.



(b) Yield of particles emitted in area I and area II depending on the potential energy of the projectile.

Figure 1: Analysis of emitted neutral ^{98}Mo particles sputtered by HCI impact from an 2d MoS_2 sample supported on an Au substrate. Evaluation of area I and II from (a) in (b).

are detected with different extraction delays allowing the transformation into a velocity or energy distribution. [2] In Fig. 1a the signal dependence on the extraction delays is shown. The measured distributions have at least two contributions around 0.83 μs and 1.75 μs each. While the first one, assigned to kinetic sputtering, increases only slightly the later contribution in area II increases strongly with the potential energy and is therefore considered to be caused by potential sputtering (Fig. 1b). The potential sputtering of the substrate supported MoS_2 has a similar dependence on the potential energy as the pore formation found in freestanding MoS_2 after irradiation with HCIs.[1]

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PR-6

Hydrogen migration in the fragmentation of hydrocarbon dications

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Proton migration of hydrocarbon molecules plays a vital role in the chemical reactions concerning, e.g., combustion and interstellar media, which can significantly change the molecules' properties and thus result in bond rearrangement and/or isomerization processes. Different from the most of previous studies using the light to generate and steer the proton migration channels, the present study reports the dynamics of corresponding channels in typical hydrocarbon molecules, i.e. CH_4, C_2H_2, C_2H_4 and C_2H_6, observed on the 150 kV highly charged ion collision platform at Fudan University in Shanghai [1-5].

Formation mechanism of H_3^+ ions from doubly charged hydrocarbons is investigated by combining charged particle collision experiments and quantum chemistry calculations. The kinetic energy release (KER) distribution for each H_3^+ loss process was measured with the cold target recoil ion momentum spectroscopy. The good agreement between the mean KER and corresponding theoretical reverse activation energy, related to a transition state and the asymptote of the dissociation products, provides information on the H_3^+ formation dynamics. A H_2 roaming mechanism is proposed for the formation of H_3^+.The isomerization channel (C^+ +CH_2^+) in C_2H_2, (CH^+ +CH_3^+) in C_2H_4, and (CH_2^+ +CH_4^+) in C_2H_6 is also observed.

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PR-7

Charge migration in betaine by impact of fast atomic ions

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Here we exploit the zwitteronic nature of the betaine molecule to induce a double electron capture from the negatively charged carboxylate group of the molecule in the collision with a low-energy O^{6+} ion. This results in the formation of a molecular dication with two charges localised to both ends.

Beside the expected charge separation giving two charged fragments associated with both ends, we observe ion-pairs resulting from the dissociation of doubly charged ends and thus associated with a charge migration following the ionisation.

Nonadiabatic molecular dynamics calculations show that the electronic dynamics associated with charge migration occurs in the ground state of the betaine dication. It is efficiently populated in ion collisions by the resonant double electron capture.

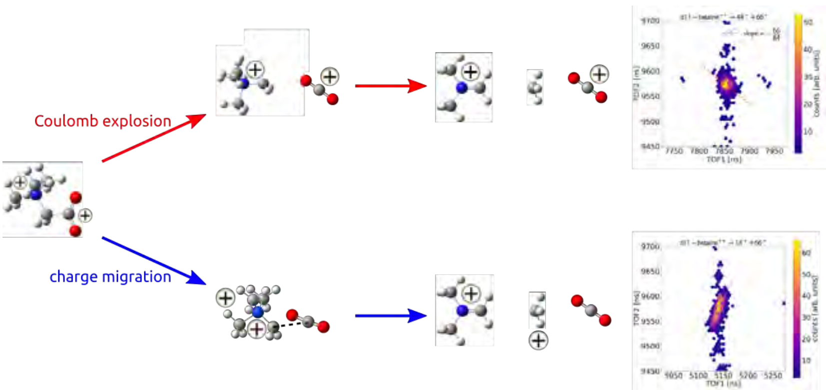

Figure 1: Competition between Coulomb explosion and charge migration in the dissociation of betaine dication produced in collision with 48 keV O^{6+} ions.

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PR-8

First experiments with the CRYRING@ESR

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The low-energy heavy ion storage ring CRYRING has been transported from Stockholm to Darmstadt, modernised and reconfigured, and has been integrated downstream from ESR into the accelerator complex at GSI/FAIR, where it now operates as CRYRING@ESR. Next to serving as a test platform for novel technologies of FAIR, it is a user facility for research in many domains.

Ions can be injected injected either in low charge states from a local ion source through a 300 keV/u RFQ linac, or in high charge states up to bare uranium through ESR. This allows for a very broad access to ions across the entire periodic system. CRYRING@ESR is able to de- or accelerate the ions and store beams of isotopically pure species in a desired charge state. With the powerful electron cooling method, the spatial and momentum spread are reduced to provide brilliant beams to the specification of the experimentalists. This gives an unprecedented access to precision spectroscopy in highly charged ions, for studying the dynamics of slow collisions in strong fields, for measuring nuclear reactions in the Gamow window, or in materials science for surface modifications by slow HCI beams, and more[1].

All major elements of the facility are now in service and routine operation as a user facility has been established. The SPARC collaboration of FAIR has prepared several experimental installations for merged beams electron-ion collisions, for atomic collisions in a dense gas-jet target, and on collinear laser spectroscopy. The first period of serving beamtimes to experiment proposals approved by the General Program Advisory Committee has now been completed. While the data analysis is still largely ongoing, these first results are already confirming that the high expectations on achievable resolution in spectroscopy experiments have been fulfilled.

We will review our present installations for experiments at the ring, discuss the data from first data runs and review the upcoming new installations for the coming years.

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PR-9

New physics searches with highly charged ion clocks

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The recent demonstration of spectroscopy in highly charged ions (HCIs) with atomic clock-level accuracy [1] portends a new era of precision atomic experiments. Narrow transitions in HCIs are available throughout the periodic table, with unique properties that can be exploited to improve searches for physics beyond the Standard Model such as possible variations in the fine-structure constant [2,3] and violations of Lorentz invariance [4] (see review [5]).

In some species it is possible to identify HCIs at "orbital crossings", where different orbitals have approximately the same binding energies. Choosing HCI near orbital crossings allows optical transitions with high sensitivity to new physics, and many opportunities to control systematics. A demonstration of narrow optical transitions between the $5p$ and $4f$ orbitals was presented in Pr^{9+} [6].

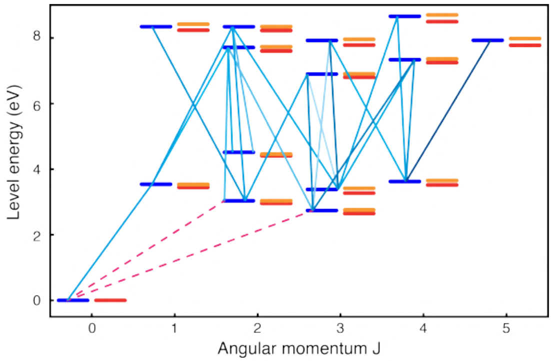

Figure 1: Grotrian diagram at the $5p-4f$ orbital crossing in Pr^{9+}. Blue: experiment; red: CI+MBPT calculations using AMBiT; orange: Fock-space coupled cluster calculations. Experiment and calculations presented in [6].

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PR-10

High accuracy theoretical investigations of highly charged ions

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Relativistic coupled cluster is considered one of the most powerful methods for accurate calculations of properties of heavy and highly charged atoms. Two variants of this method are usually used. The first variant, the single reference coupled cluster approach (SRCCSD(T)) is suitable for calculations of ground state properties in systems which can be well described by a single determinant. This approach can be used to obtain, for example, ionization potentials and other ground state properties. The second variant is the multireference Fock space coupled cluster method (FSCC), which is particularly useful for high accuracy calculations of excitation spectra and hyperfine structure parameters.

The talk will provide a brief introduction to the two variants of the relativistic coupled cluster approach. I will also introduce the recently developed scheme that we use to set uncertainties on the theoretical results [1]. Such uncertainties are particularly important when using theoretical predictions in experimental context. Examples of application of the relativistic coupled cluster to highly charge ions will be provided.

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PR-11

Aromatic molecules revisited under bare helium collision: experiment and theory

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Aromatic molecules are of multidisciplinary interest such as in bio-, atmospheric-, and astrochemistry, and are considered resistant to fragmentation to ion-impact in the intermediate energy range. Pyrimidine ($C_4H_4N_2$), pyridine (C_5H_5N), and benzonitrile (C_6H_5CN) were selected respectively as representative molecules in the related fields. The relevance of measuring the ionization and subsequent fragmentation of such molecules has been stressed in many works associated with hadron-therapy[1], cloud formation[2,] and aromatic hydrocarbon formation in the interstellar medium[3]. Here, we report the ionization and fragmentation of aromatic molecules under bare helium collision over a wide range of impact energies, 700 up to 6000 keV, using pulsed beams and extraction fields combined with a high-resolution time-of-flight spectrometer. There are few fragmentations studies on aromatic molecules following energetic ion interaction. Previously, fragmentation cross sections were measured for pyrimidine under proton impact for energies from 300 keV to 16000 keV[1]. Searching for charge effects on the ionization and break-up channels we compared the He^{2+} data with those measured of 50 to 150 keV protons and 20 to 2000 keV electrons colliding on these aromatic molecules. To understand the general behaviour of ion-aromatic cross sections we included theoretical results for the single ionization and electron capture of these species by combining the atomic cross section of its constituents with a stoichiometric approach[4]. These atomic values were obtained within CTMC and CDW-EIS methods and are examined to probe the importance of the electron capture phenomena at impact energies ranging from 25 keV to 250 keV. The derived data from this study can help to improve the estimates of astrophysical, biological and atmospheric models.

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PR-12

Fragmentation of the Heteronuclear Cluster by Electron Impact

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Via weak interactions such as van der Waals bond and hydrogen bond, the atoms can condense into a cluster. Then if one atom within the cluster is ionized, the following charge or energy transfer will induce new decay mechanisms absent in the isolated atom. One famous mechanism is termed interatomic Coulomb decay (ICD), where the excess energy transferred from an excited ion will trigger the ionization of a neighboring atom [1]. Recently, we carried out the fragmentation experiment of the heteronuclear cluster NeAr by electron impact at reaction microscope, we distinguished the ICD following Ne ionization from the ICD following Ar ionization [2]. The observed decay pathways will enhance the yield of low energy electrons on the nanoscale, and manifests the role of high energy secondary electrons in a new proposed radiation therapy scheme termed resonant Auger ICD [3].

On the other hand, the cluster fragmentation is also proposed to control chemical reactions [4, 5], e.g., by embedding a molecule into a cluster and ionizing its neighboring atom, the following energy and charge transfer will induce its dissociation along specific decay pathways, and achieve the goal of selective bond cleavage. In order to identify above prediction, we performed the fragmentation experiment of heteronuclear cluster ArCO, where two ions and one electron were measured in coincidence. As shown in figure.1, the yield ratio of $Ar^+/C^+/O$ ion pair to $Ar^+/O^+/C$ ion pair is about 6. Compared with the yield ratio of C^+/O ion pair to O^+/C ion pair in the isolated CO, this value increases five times. Our observation suggests that the polarization between Ar^{2+} ion and CO will lead to the formation of transient $(ArCO)^{2+}$ ion, which releases an O atom later, consequently, the produced ArC^{2+} metastable ion breaks into Ar^+/C^+ ion pair. This mechanism enhances the specific fragmentation pathway $CO \rightarrow C^+ + O$.

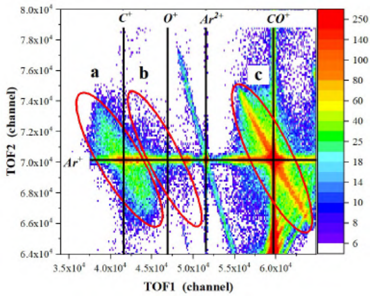

Figure 1: Two-dimensional TOF correlation map after ArCO ionization

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PR-13

Theoretical predictions of the structure of heavy muonic atoms

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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 muons 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. Finally, a long-standing problem of fine-structure anomalies in muonic atoms is revisited in the light of the last improvements on nuclear-polarization [4] and self-energy calculations [5].

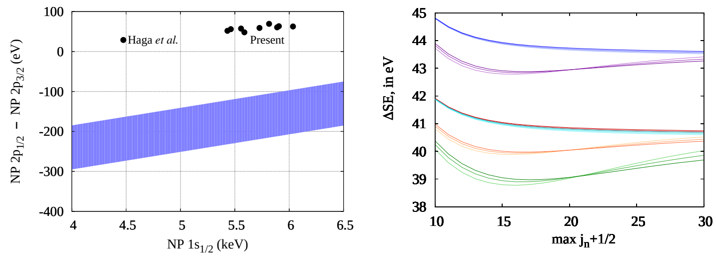

Figure 1: (left) Theoretical values of the nuclear polarization correction for muonic lead in relation to the experimentally allowed range for $\Delta 2p = |\Delta E^{\mathrm{NP}}_{2p_{1/2}} - \Delta E^{\mathrm{NP}}_{2p_{3/2}}|$ as a function of $|\Delta E^{\mathrm{NP}}_{1s_{1/2}}|$ [4]. (right) Self-energy contribution to the $2p_{1/2}$ state of muonic tin in units of eV as a function of maximal intermediate angular momentum j_n for different nuclear models and numerical grids [5].

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PR-14

Muonic atom X-ray spectroscopy for QED test in strong Coulomb field

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A negatively-charged muon can bind to an atomic nucleus via the Coulomb force. This is so-called a "muonic atom" which is essentially hydrogen-like in its electronic structure. Since a muon is 200 times more massive than an electron, a muonic atom has a Bohr radius 200 times smaller than that of atomic hydrogen. The electric field between the muon and the atomic nucleus is proportional to the square of the mass ratio of the electron to muon, which is 40,000 times stronger than that of a normal atom. This allows to test QED in strong field in a very different regime, since at such short distances the dominant QED contribution is the vacuum polarization, while it is the self-energy in highly-charged ions [1].

After a negatively-charged muon is captured by the nucleus in a highly excited state, the muon peels off electrons bound to the nucleus as Auger electrons, and thereby generating highly-charged muonic atoms in vacuum. While a low-density target is required to avoid rapid refilling of electrons into the highly charged muonic atom from the surrounding atoms, it has been experimentally difficult to efficiently stop muons in a low-density target. This is due to their large momentum distribution via traveling pion decay, resulting in insufficient x-ray yields with the conventional high-resolution x-ray spectroscopy technology based on diffraction from Bragg crystals, unless one uses a device like the PSI cyclotron trap.

We conducted high-resolution muonic atom X-ray spectroscopy experiments with low-density gas target with a combination of the world highest intensity pulsed negative muon beam at J-PARC MLF MUSE (Tokai, Japan) and an X-ray spectrometer based on a 240-pixel array of super-conducting transition-edge-sensor (TES) microcalorimeters which has both excellent energy resolution and collection efficiency [3,4]. In this presentation we will give an overview of this project and the recent progress.

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PR-15

Resonant photoexcitation of trapped ions for x-ray astrophysics

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Spectroscopic observations in the UV and X-ray bands with the newest generation of high-resolution instruments onboard current and future satellite observatories have the potential to reveal previously inaccessible details of processes in astrophysical plasmas, such as the ones in galaxy clusters and active galactic nuclei. This is essential for advancing our understanding of extreme environments and the evolution of the universe.

However, what can be reconstructed from spectra is currently limited by the availability and quality of atomic data, on which plasma models are built. That is especially the case for highly charged ions (HCI), ubiquitous in hot astrophysical plasmas [1]. For many years, electron beam ion traps (EBITs) have been valuable tools for laboratory measurements with HCI, providing a wide range of atomic data, like transtion energies and rates of ionization and recombination processes.

Here, work with the novel compact PolarX-EBIT [2], based on permanent magnets, is presented, in which radiation from ultrabrilliant UV and X-ray synchrotron light sources is used to resonantly excite electronic transitions in trapped HCI. Subsequent fluorescence and changes of ion charge state are detected, which allows to gather spectroscopic data under well-controlled conditions with unprecedented resolving powers and signal-to-noise ratios. This yields atomic data valuable not only for astrophysics but also for benchmarking general atomic structure theory [3].

One such case are the two 2p-3d transitions in Ne-like Fe^{16+}, commonly labelled 3C and 3D, for which measurements and calculations of oscillator strengths seemed to disagree significantly [4], until our recent experiments uncovered previously unaccounted-for contributions to the observed intensities [5].

Furthermore, the unique off-axis electron gun of PolarX-EBIT facilitates new experimental setups, in which electronic transitions in few-electron HCI are used as accurate and reproducible wave-length references [6].

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SELECTED TALKS

ST-1

First Laboratory Verification of Magnetic-field-induced Transition Effect in Fe X

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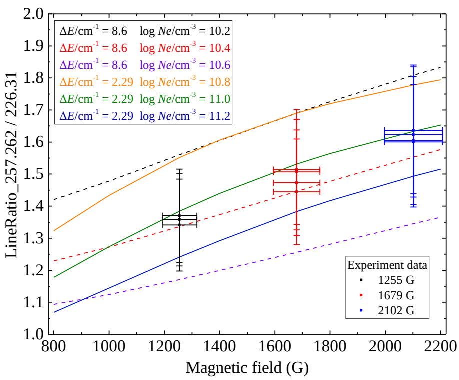
The magnetic field is extremely important for understanding the properties of the solar corona. However, there are still difficulties in the direct measurement of coronal magnetic fields. The discovery of the magnetic-field-induced transition (MIT) in Fe X, which was also observed in the coronal spectra, opened up a new method for measuring the coronal magnetic field. In this work, we obtained the Fe X extreme ultraviolet (EUV) spectra in the wavelength range of 174–267 Å in Shanghai high-temperature superconducting electron beam ion trap, and for the first time, verified the effect of MIT in Fe X by measuring the line ratios between 257.262 Å and reference line of 226.31 Å (257/226) at different magnetic field strengths. The plasma electron density that may affect the 257/226 value was also obtained experimentally and then verified by comparing the density-sensitive line ratios with the theoretical prediction, and there was good agreement between them. By comparing the simulated line ratios of 257/226 with the experimental values at given electron densities and magnetic fields, the critical energy splitting of the fine-structure levels, one of the most critical parameters to determine the MIT transition rate, was obtained. Possible reasons which may lead to the difference between the obtained energy splitting and the recommended value in previous work are discussed. Magnetic field response curves for the 257/226 value were calculated and compared to the experimental results, which is necessary for future MIT diagnostics.



Theoretical and experimental values of line ratios of 257.262 Å and 226.31 Å versus the magnetic field

ST-2

First observation of giant quadrupole plasmon resonance in C_{60} in high perturbation HCI collisions

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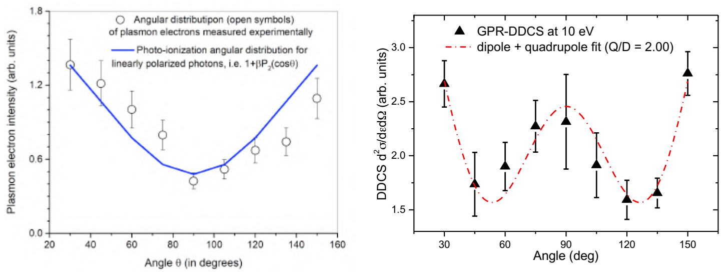
We give a classic example of using high perturbation caused by HCIs to explore new mechanisms in ion collisions with a nano-particle namely C_{60}-fullerene. The collective plasmon excitation mode known as the GPR (giant plasmon resonance), where the entire delocalised valence-electron cloud of C_{60} oscillates collectively about the ionic shell, has been well-studied using photo-excitation, electron-impact and ion-impact excitation [1-3]. A direct observation of the dipole mode of the GPR has been reported earlier [3] by using F^{9+} ions (q=9, v~12.7 a.u) for which angular distribution reveals a parabolic shape, characteric of dipole-nature [Fig 1(a)] We have now measured the double differential cross section (DDCS) at even higher perturbation (q/v) i.e. in collisions with 91 MeV Si^{12+} ions (q=12, v~11.4 a.u). The DDCS spectrum at low energy indicates a quadrupole plasmon resonances (GQPR) in addition to the dipole plasmon (GDPR). The measured DDCS angular distribution at low energies (around 7-8 eV) reveal a double valley structure [Fig 1(b)] which is characteristic of quadrupole resonance. The elegant technique of using high perturbation collision allows us to identify the characteristic GQPR mechanism. We have unambiguously identified the dipole and quadrupole modes by using state-of-the-art TDDFT calculations[6]. This is the first such unambiguous experimental demonstration of the quadrupole excitation in atomic system[6].



(a) (b)

Figure 1: Angular distribution of plasmon-electrons from C_{60} under fast-ion collisions: (a) Projectile: F^{9+} (4MeV/u, v=12.7)[3], (b) Si^{12+} (3.2MeV/u, v=11.4)

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ST-3

Lifetime measurement of the microsecond-order electric-quadrupole transition: Application of plasma-assisted laser spectroscopy

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Lifetime measurements of forbidden transitions in highly charged ions (HCIs) have provided remarkable examples for evaluating atomic physics theories [1-3]. Previous measurements employed isolated HCIs in a magnetic ion storage device and observed de-excitation processes from metastable states prepared in a plasma ion source. This is a useful method for lifetimes on the order of milliseconds, and has been widely applied for various transitions. However, the conventional method cannot eliminate re-population effects due to cascade processes from upper energy levels. This intrinsic problem has prevented the broad extension of the technique to microsecond (μs)-order lifetime measurements.

Recently, we demonstrated plasma-assisted laser spectroscopy of HCIs trapped in an electron beam ion trap (EBIT) [4]. In this demonstration, we succeeded in laser excitation between the metastable fine-structure levels of Pd-like HCIs with the aid of plasma excitation processes in the EBIT. This laser spectroscopy has the potential to be applied to state-selective lifetime measurements which avoid the abovementioned problem. In this presentation, we discuss this application and its prospects by demonstrating the lifetime measurement of the μs-order electric-quadrupole (E2) transition $(4d_{3/2}^{-1}\,5s_{1/2})_{J=2}$ - $4d^{10}$ in Pd-like I^{7+}.

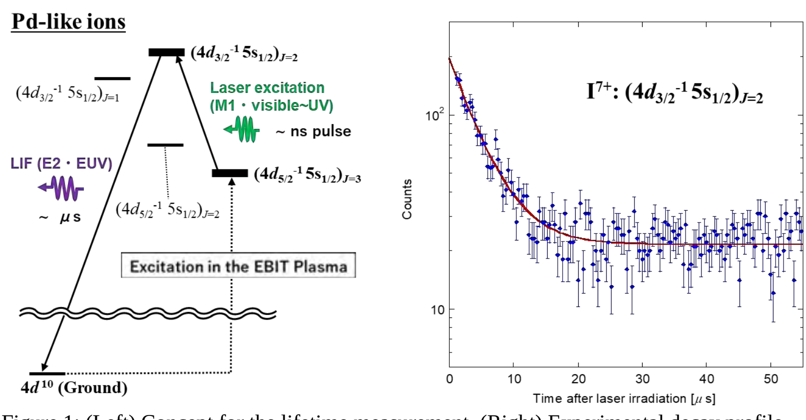

Figure 1: (Left) Concept for the lifetime measurement. (Right) Experimental decay profile.

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ST-4

Analysis of E3 transitions in Ag-like high-Z ions observed with the NIST EBIT

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Measurements and analyses of forbidden lines in highly charged ions provide invaluable information on diverse effects including quantum-electrodynamic and relativistic effects in atomic structure as well as offer new diagnostic techniques for very hot plasmas. Recently, Sakaue et al [1] reported on observation of electric-octupole (E3) spectral lines in Ag-like W^{27+} using the compact electron beam ion trap (EBIT). The well-resolved $4f_{7/2,5/2}$-5s transitions were recorded in the extreme ultraviolet (EUV) spectrum. Using the HULLAC atomic code, the authors of Ref. [1] showed that the E3 lines are strongly enhanced for W and developed an advanced collisional-radiative model which predicts E3 line intensities for the other members of the isoelectronic sequence.

In this work we report on measurements and identifications of the E3 $4f_{7/2,5/2}$-5s transitions in W and other high-Z elements including Re (Z=75), Os (Z=76), and Ir (Z=77). The EUV spectra were recorded with the NIST EBIT using a grazing-incidence EUV spectrometer. The present higher resolution results for W and GRASP2K calculations strongly confirm the Ref. [1] findings. Our collisional-radiative model developed with the NOMAD and FAC codes offers a deep insight into the population kinetics for Ag-like ions of heavy elements. The simulation allowed the identification of new spectral lines in the spectra. We will present a detailed discussion of the observed spectra and comparisons of the measured and simulated line intensities.

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ST-5

Elastic x-ray scattering by highly charged ions

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The elastic scattering of x-rays by atoms and highly charged ions is one of the fundamental processes in the interaction of radiation with matter. Over the past few years, increasing attention has been paid to the study of the properties of scattered photons. In particular, the linear polarization of the outgoing radiation was measured in a recent experiment at the PETRA III synchrotron facility at DESY in Hamburg [1]. This experiment demonstrated that by analyzing the polarization of the scattered light, one can obtain information not only about the atomic structure of the target atoms, but also about the polarization of the incident synchrotron radiation. In our poster, we study the polarization properties of elastically scattered x-rays by highly charged ions and neutral atoms. We illustrate how the polarization of incident x-rays can be determined only with the polarization of scattered photons, without any need for the theoretical scattering amplitudes [2]. Moreover, we explore how the interference between Rayleigh and Delbrück scattering may affect the polarization properties of the outgoing radiation.

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ST-6

Radiative Double-Electron Capture by Highly-stripped Ions on Graphene

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Radiative double-electron capture (RDEC) occurs when the capture of two electrons by an ion is accompanied by the simultaneous emission of a single photon. This process, fundamental in atomic collisions, is considered the inverse of double photoionization by a single photon. RDEC has been successfully studied with $F^{9,8+}$ ions on gas [1] and thin-foil [2] targets. Only recently has it been investigated for single-layer graphene [3]. This work was done at WMU with the 6-MV tandem van de Graaff accelerator. For the graphene, a target (~0.35 nm thick) was mounted on a silicon nitride grid (200 nm thick) consisting of ~6400 holes of 2 μm diameter on a 200 μm thick substrate. A Si(Li) spectrometer placed at 90° to the beam detected emitted x rays in coincidence with magnetically separated outgoing charged particles counted with silicon surface-barrier detectors.

In preliminary work for RDEC with graphene [3], results for 2.11 MeV/u $F^{9,8+}$ ions suggested very large cross sections, approaching values found for thin-foil targets when the thickness of the graphene was about a hundred times smaller. In the present work, the RDEC measurements have been repeated with single-layer graphene as well as identical targets that had no graphene on them.

Figure 1 shows new results for RDEC for 2.11 MeV/u $F^{9,8+}$ incident on graphene where the number of counts is plotted against the time difference between the x rays and particles detected. The upper panel shows the results for F^{9+} on graphene, the middle panel for F^{9+} with no graphene, and the bottom panel for F^{8+} incident on the graphene. The top panel for F^{9+} shows about 7-8 counts in the peak (near a time difference of 1950 ns) after background subtraction, the middle panel exhibits no counts for the target without graphene as expected, and the bottom panel for F^{8+} displays counts but none in the peak, a reasonable expectation for this one-electron ion when compared with earlier results for F^{8+} on gas targets [1].

A tentative cross section can be calculated for the F^{9+} projectile, and the differential value at 90° is 1.3 b, corresponding to a total cross section (assuming isotropy) of 11 b. These values are more in line with the earlier values found for F^{9+} incident on gas targets, but larger by about a factor of 4, and are reasonable in view of the target thickness for the graphene compared to gas.

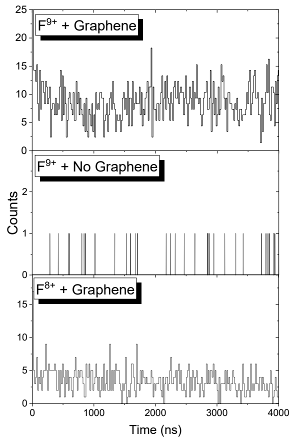

Figure 1: RDEC results for $F^{9,8+}$ on single-layer graphene

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ST-7

Experimental Studies of Nonperturbative Dynamics in Heavy-Ion-Atom Collisions

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Experimental data for atomic collisions of highly-charged ions are essential for benchmarking the theoretical description of dynamical processes in atomic physics. Of particular challenge is the accurate description of those processes that exceed the applicability of relativistic first-order perturbation theories. Recently, we have investigated two characteristic cases of such collision systems at the Experimental Storage Ring ESR of the GSI heavy-ion accelerator facility in Darmstadt, Germany:

(1) For fast collisions of U^{89+} projectiles with N_2 and Xe targets at 76 MeV/u, we studied the electron-loss-to-continuum cusp both experimentally and theoretically. We compared the continuum electron spectra of the two collision systems, which originate from the ionization of the projectile, and we were able to identify a clear signature for the nonperturbative character of the collision systems [1].

(2) For slow collisions of Xe^{54+} and Xe^{53+} with a Xe target at 30 and 15 MeV/u, we performed an x-ray spectroscopy experiment focusing on the target $K\alpha$ radiation. Experimental data for such slow symmetric collision systems are important for testing relativistic two-center calculations and provide an intermediate step towards understanding heavy-ion collisions in super-critical fields. We used the target $K\alpha$ satellite and hypersatellite lines to derive cross-section ratios for double-to-single target K-shell vacancy production and compared our experimental results to theory applying a fully relativistic time-dependent two-center approach [2].

At GSI, new prospects of investigating slow Xe^{54+}-Xe collisions under improved conditions will now be facilitates by the low-energy heavy-ion storage-ring CRYRING@ESR. Corresponding experiments are currently being devised.

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ST-8

Charge-separated ion spectra from a laser-produced plasma

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Extreme-ultraviolet (EUV) lithography at 13.5 nm is expected to be introduced in high-volume manufacturing of integrated circuits (ICs) having node sizes less than 10 nm. Lithography at this wavelength is capable of reaching feature sizes below 5 nm. Beyond that, switching to a shorter wavelength of around 6.*x* nm, while maintaining or increasing throughput in the lithography system, would improve resolution by a further factor of two and extend the technology to feature sizes less tha 2 nm. Plasmas of the rare-earth elements gadolinium (Gd) and terbium (Tb) produce strong resonant emission due to the presence of an intense unresolved transition array (UTA) around 6.*x* nm in the spectra of their ions. Because the emitting ions in Gd and Tb, plasmas have an electronic structure largely similar to Sn, they are expected to exhibit a similar spectral behavior, and emit an intense UTA due to $4p - 4d$ and $4d - 4f$ transitions at shorter wavelengths [1]. Recently, the suitability of CO_2 laser-produced plasma (LPP) EUV sources based on Gd and Tb has been demonstrated for efficient, high power operation [2].

We observed the ion debris using an electrostatic analyser (ESA) to separate the charge states. Figure 1 shows the charge-separated ion energy spectra. The maximum charge state was Gd^{17+} (not shown) with a most probable energy higher than 20 keV. We show some dependence of the laser intensity and its pulse duration.

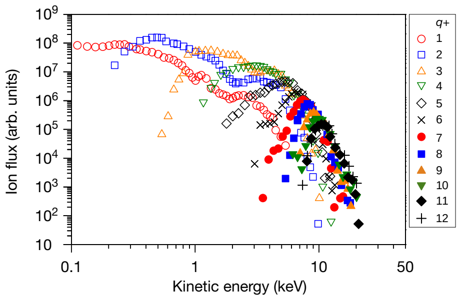

Figure 1: Charge-separated ion spectra from a laser-produced Gd plasma.

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ST-9

High resolution imaging of laser plasmas revealing the effects of laser spot size on plasma emission

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Laser plasmas can produce a high flux of soft x-ray radiation from a small volume, making them ideal for illumination for applications such as in EUV nano-lithography [1] and in cell imaging via soft x-ray microscopy [2].

In order to investigate the effects of the focal spot size on the plasma shape and intensity, a molybdenum target was irradiated with a Nd:YaG 1064nm driving laser. Images of the subsequently formed plasmas were generated using a 5µm pinhole which images soft x-rays through a 1µm Al filter onto a soft x-ray camera with a pixel size of 2.4µm and the imaging axis parallel to the target and perpendicular to the laser. The filter transmission combined with the camera quantum efficiency produces images in the 0.5nm to 3nm region. Such images were produced with laser energies ranging from 20mJ to 271mJ with several laser focus spot sizes.

The plasma images were simulated using a skewed pseudo-Voigt profile combined with regression techniques to generate noise reduced plasma images. The resulting areas and shapes (the ratio of the plasma widths parallel and perpendicular to the target measured through the centre of a plasma iamge) of the simulated plasma images were measured as demonstrated in Fig 1.

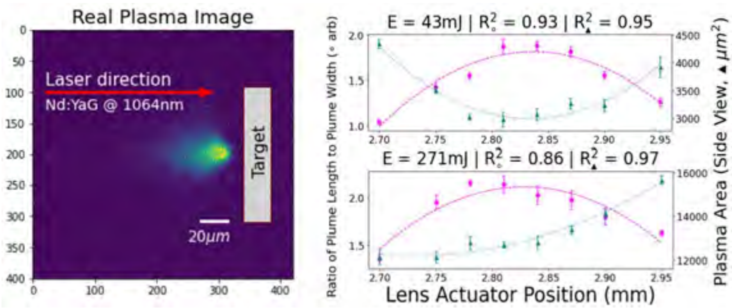

Fig 1: Left: Real plasma image with schematic target drawn. Right: Demonstration of the change in plasma area and plume shape (the ratio of the plume width perpendicular to the target and width parallel to the target) as a function of lens position fro two labelled energies.

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ST-10

Inferring the coherence time of EUV pulse trains via spectroscopy of highly charged ions

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Coherent extreme-ultraviolet (EUV) pulse trains are produced via intra-cavity high-harmonic generations of high-intensity infrared pulse trains. They represent well-defined EUV frequency combs that can enable high-precision spectroscopy of specific EUV transitions in highly charged ions (HCIs) with a relative accuracy to the level of $\delta\omega/\omega = 10^{-17}$. In return, such ionic spectroscopy can also provide information of the temporal coherence of the EUV frequency combs at timescales ranging from nanosecond to several seconds.

In this contribution, we present a scheme to interrogate the EUV-comb coherence time via interactions with highly charged Mg-like ions [1]. The excitation dynamics are simulated [2] for ions interacting with EUV pulse trains of various temporal coherences. We show that while all EUV pulse trains induce stepwise excitation of HCIs at the beginning of the interactions, the ionic excitations undergo chaotic fluctuations when the coupling time becomes longer than the comb coherence time. These investigations indicate that one can achieve coherent control of HCIs via current available EUV pulse trains and enable quantum optics studies in the EUV range.

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ST-11

Hydrogen migration in three body fragmentation of acetylene trication

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We report on the three body fragmentation of $[C_2H_2]^{3+}$ into (H^+, C^+, CH^+) fragments in interaction of neutral acetylene with a slow highly charged ion (Xe^{9+} having velocity ≈ 0.5 a.u.). The momenta of all these three fragments were measured in coincidence using the technique of Recoil Ion Momentum Spectroscopy (RIMS). For this particular fragmentation channel, three different dissociation pathways are observed, namely concerted breakup in acetylene configuration, concerted breakup in vinylidene configuration and sequential breakup via $[C_2H]^{2+}$ intermediate molecular ion.

To extract information about the different dissociation pathways, we have used Newton diagram [1] and the method of native frames [2] for analysing the momentum correlations. Figure 1(i) shows the γ - KER_2 distribution generated by using the method of native frames and by assuming $[C_2H]^{2+}$ as an intermediate ion in sequential mode of breakup. KER_2 represents the kinetic energy release associated with the second step of the sequential breakup. The angle between the direction of the first two-body breakup and second two-body breakup in their respective centre-of-mass frames is represented by angle (γ). The uniform distribution observed parallel to the γ - axis is an evidence of a long-lived electronic state of the $[C_2H]^{2+}$ molecular ion. The distribution is divided into two regions A and B based on the value of KER_2 and two separate Newton diagrams are plotted as shown in figure 1(ii) and 1(iii). The semi-circular arc like feature observed in figure 1(ii) is a signature of sequential breakup via $[C_2H]^{2+}$ and the high intensity areas belong to concerted breakup. In figure 1(iii), the angle between the momentum vectors of H^+ and C^+ take two distinct values around 25° and 165°. A low value of this angle corresponds to acetylene configuration and a high value corresponds to vinylidene configuration.

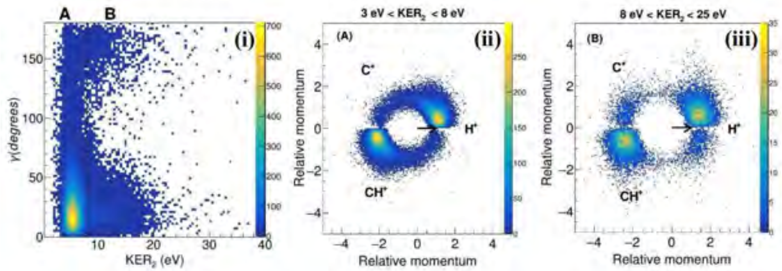

Figure 1: (i) A distribution of KER_2 with γ for all events. (ii) and (iii) shows Newton diagrams for selected values of KER_2 as indicated on the figure (see text for more information).

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ST-12

Sympathetic cooling of highly charged ions in a Penning trap using a self-cooled electron plasma

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The amazing evolution of precision in recent Penning-trap experiments is driving the need for ever-improving cooling techniques. In this talk, the prospect of a new sympathetic cooling technique using an electron-plasma coupled to a single highly charged ion is presented. Utilizing the synchrotron-radiation of electrons in a strong magnetic field enables cooling to very low motional quantum numbers, almost to their ground state. Using a common-resonator, the motion of this self-cooled electron plasma can be coupled to an ion stored in a spatially separated Penning trap, allowing sympathetic cooling of all modes of the ion. The extremely low expected temperatures in the milllikelvin range open up an exciting new frontier of measurements in Penning traps.

ST-13

Direct high precision measurement of the Q-value of the electron capture in ^{163}Ho and metastable states in highly charged ions

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The high-precision Penning-trap mass spectrometer Pentatrap [1] features a stack of five Penning traps and determines mass-ratios with a relative uncertainty below 10 ppt. Mass-ratio determinations of stable and long-lived highly charged ions have numerous applications, among others, in neutrino physics [2] and the search of possible clock transitions in highly charged ions (HCI) [3]. The unique features of Pentatrap include access to HCI, a stable 7 T magnet, and a cryogenic detection system with single ion phase sensitivity. The latest measurements include the Q value of the beta-decay of ^{163}Ho with a relative uncertainty of below 7 ppt. In ^{208}Pb a long-lived metastable electronic state was discovered.

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ST-14

A superconducting quadrupole resonator for laser-spectroscopy of highly charged ions at highest precision

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Highly charged ions are excellent candidates for novel optical frequency standards [1] and quantum algorithms [2], since they are very unsusceptible to electromagnetic noise due to the suppression of e.g. the quadratic Zemann shift scaling with Z^{-4}[1]. However, gaining quantum control over the motional modes of cold HCI had been a challenge for the last decades since they lack of fast cycling transitions for laser cooling. Quantum logic spectroscopy of the M1 transition in Ar^{13+} which was sympathetically cooled by a single Be^{+} logic ion lowered the uncertainty by eight orders of magnitude to about 10^{-15} opening a branch for new frequency standards in near future [3]. Complementing these new types of optical clocks, a cryogenic Paul trap experiment with a quasi-monolithic superconducting quadrupole resonator with a high operating quality factor of about 30000 [4] was developed at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany to challenge some of the resulting issues: Due to the high fidelity of the radio-frequency resonance at about 35 MHz, radial mode heating of the HCI is strongly suppressed. Furthermore, the trapped ions are shielded inside the cavity due to the Meissner-Ochsenfeld effect from electromagnetic noise, reducing decoherence effects and therefore increasing interrogation times of the HCI. We will present the features of this resonator and provide first characterizations with re-trapped HCI.

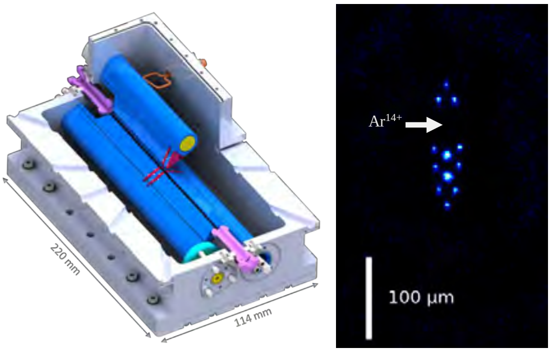

Figure 1: Left: Sliced view of the superconducting quadrupole resonator. Right: Single, crystallized Ar^{14+} trapped and sympathetically cooled beryllium ions inside it.

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ST-15

Dynamics of mixed species Coulomb crystals with highly charged ions in a superconducting Paul trap

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The CryPTEx-SC project at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, is designed to perform precise spectroscopy of highly charged ions (HCIs), which are excellent candidates for the development of next-generation atomic clocks and sensitive probes in the search for new physics [1]. The spectroscopy trap is formed by merging a linear Paul trap with a superconducting radio-frequency resonator, providing ultralow-noise radial confining potentials [2]. Control and read-out of HCIs will be implemented using quantum logic spectroscopy with co-trapped Be^+ ions.
We present results from the first cold highly charged ions stored in our ion trap. After production of the HCIs in an electron beam ion trap (EBIT), they are extracted in pulses into an electrostatic beamline where they are decelerated and bunched. The HCIs are then captured in and sympathetically cooled by a Coulomb crystal of several dozen laser-cooled Be^+ ions trapped in the Paul trap beforehand. Subsequent controlled removal of Be^+ ions by exciting secular motion is used to prepare mixed species ion crystals comprising various numbers of Be^+ ions and HCIs, down to a single HCI with a single Be^+ ion, the prerequisite for quantum logic spectroscopy.
The flexible retrapping technique will be discussed, which opens up the extensive range of highly charged ion species to precision studies and additionally allows to explore the dynamics of mixed species Coulomb crystals consisting of ions with disparate charge-to-mass ratios.

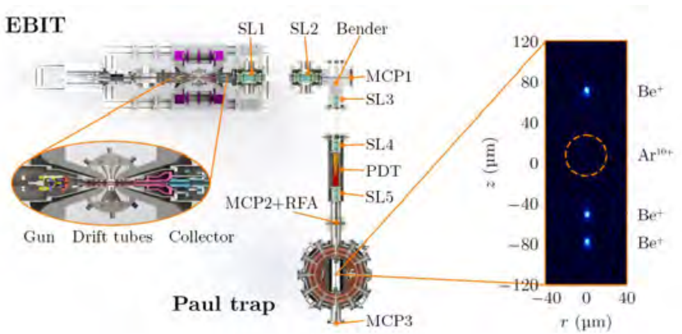

Figure 1: Overview of producing HCIs in an electron beam ion trap, transferring through a beamline and retrapping in a superconducting resonator Paul trap with example EMCCD image of a mixed species Coulomb crystal comprising three $^{9}Be^+$ ions and one $^{40}Ar^{10+}$ ion.

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ST-16

First Dielectronic Recombination Measurements at the Cryogenic Storage Ring

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The charge balance in plasmas is governed by competing processes for ionization and recombination. For the understanding and modeling of plasmas in astrophysical environments as well as terrestrial applications, data on the recombination of atomic ions with free electrons are of high importance [1]. Over the past three decades, such recombination processes have been studied extensively in magnetic heavy-ion storage rings by applying the electron-ion merged-beams technique [2]. A challenge of these experiments is the background produced by electron capture from residual gas. Because of the relatively high vacuum pressure of conventional room temperature magnetic storage rings, measurements were restricted to ions with a high charge-to-mass ratio, which could be stored at sufficiently high energies where the rate coefficient for residual-gas-related electron capture drops. Data on low-charged heavy ions are still widely missing.

The electrostatic Cryogenic Storage Ring CSR [3], located at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany, combines the mass-independent storage of electrostatic storage rings with the excellent vacuum conditions provided by its fully-cryogenic beam environment. It is equipped with an electron cooler and a suitable single particle detector. The unique environment of CSR, thus, is promising for the investigation of electron-ion recombination in low-charged heavy ions.

Here, we report on the first recombination studies with atomic ions at CSR. We have investigated dielectronic recombination of Ne^{2+} and Xe^{3+}, where we observed resonant recombination features in agreement with quantum-theoretical predictions. Our results clearly demonstrate the feasibility of atomic recombination studies with heavy low-charged ion species at CSR.

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ST-17

High-Resolution X-Ray Spectroscopy of He-like Uranium using Novel Microcalorimeter Detectors

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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. 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 $K_{\alpha1}$ and $K_{\alpha2}$ lines. Furthermore, the various unique aspects resulting from the selected detection geometry in combination with the broad spectral acceptance of the detectors will be presented.

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ST-18

High resolution measurement of the 2p3/2→2s1/2 intra-shell transition in He-like uranium

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He-like ions, the simplest multi-body atomic systems, offer the possibility to probe QED correlation and electron interaction effects. The theoretical description of these effects in extrem high electric fields, as for high-Z ions, is still challenging and different approaches leaves to different results. Thus tests by experiments are needed. By measuring the difference in transition energies between He- and Li-like ions, it is additionally possible to effectively isolate the electron correlations effects. Precision spectroscopy of He-like heaviest ions is also experimentally very challenging and the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in uranium was only measured in an pilot experiment [1] at the ESR with limited accuracy.

We measured the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in He-like uranium at the ESR of GSI, employing a bent crystal Bragg spectrometer. This allows for an energy resolution of ~2.7 eV and an statistical accuracy of ~0.06 eV. By comparing the line to the corresponding transition in Li-like uranium, we reach for an accuracy of ~0.15 eV on the absolute energy of the He-like and ~0.06 eV for the relative measurement of the two lines. This allows for an unmatched test of electron correlation effects and two-loop corrections of Quantum Electrodynamics in few electron systems in strong electric fields with the errors of the measurement comparable to the best theoretical values.

This research has been conducted in the frame-work of the SPARC collaboration, experiment E125 of FAIR Phase-0 supported by GSI. It is further supported by the Extreme Matter Institute EMMI and by the European Research Council (ERC) under the European Union's Horizon 2020 research as well as by the innovation pro-gramme (Grant No 682841 "ASTRUm") and the grant agreement n° 6544002, ENSAR2. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA) too.

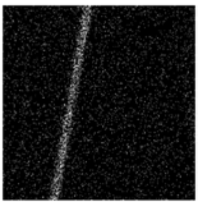

Figure 1: Detector image of the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in He-like uranium. Dispersion is in the horizontal direction. The slant of the line is due to the Doppler shift.

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ST-19

5p-*5s* spectrum in highly charged WXII - WXIV Ions

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Spectral lines from highly charged tungsten ions, specially, from WIV-WXVI have been predicted to be useful in diagnostic of the ITER divertor plasma [1]. Tungsten ions having charge state WXII - WXVI are anticipated to show the transitions lines from the 5*p* to the 5*s* subshell in EUV region. These ions are highly correlated system with an open 4*f* subshell for which accurate calculations are challenging. Due to the complexity of observed spectra there was an ambiguity in charge state identification in previous study [2]. Also, there is no data available for W XII in extreme ultraviolet (EUV) range [3-4]. We present detailed theoretical analysis of 5*p*-5*s* transition of W XII–W XIV ions for the spectroscopic measurements performed at compact electron beam ion trap (CoBIT) [5-6]. The analysis of the observed spectra is based on the detailed collisional-radiative modeling with fine structure sub-levels atomic kinetics. The wavelength and rate of the transitions of W XII–W XIV ions calculated by the relativistic configuration interaction using flexible atomic code. Theoretical results are in reasonable agreement with the experimental observations (∼18-28nm), which provides the clear assignment of the ionization stage and corresponding lines.

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ST-20

Collisional-radiative model for the spectra of M1 transition of W^{53+} ion

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The emission spectrum of tungsten ions can be used to diagnose the status of the fusion plasma[1,2]. Based on the experimental study of M1 transition spectrum of W^{53+} ion by Ralchenko et al. [3], the collisional-radiative model (CRM) were used to investigate the spectrum.

The configurations included in the present CRM are $3s^23p^63d^3, 3s^13p^63d^4$, and $3s^23p^53d^4$. In order to consider the electron correlation effects, the SD excited configurations, such as, $3s^13p^63d^34l(l = 0-2)$, $3p^63d^5$, $3p^63d^34s^2$ and $3s^23p^63d^26l(l = 0-4)$ are included as the correlation configurations.

The simulated spectrum is in good agreement with the observed spectrum on the EBIT. Five observed transitions were identified and assigned to the transitions within the multiplets of the ground configuration. The transition *m* in Fig1.(c) is predicted to be the M1 transition of W^{53+} ions which is not assigned in the previous work. This work provided the knowledge of the highly charged W ions which will be helpful for the future investigation on these ions and the fusion plasma.

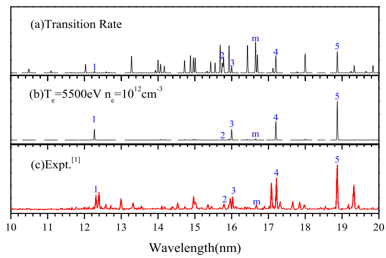

Figure 1: (a) Radiative transition rate, (b) Intensity from CRM. (c) Experimental spectra from the EBIT [3]. Each individual transition was assumed to have Gaussian profile with FWHM = 0.02nm.

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ST-21

Laser cooling of relativistic O^{5+} ions at CSRe: experiment and simulation

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Laser cooling of O^{5+} ion beams with an energy of 275.7 MeV/u was successfully achieved at the storage ring CSRe in Lanzhou, China [1, 2]. To the best of our knowledge, the Li-like O^{5+} ions are the highest charge state and highest transition energy ions that have ever been laser-cooled. To explain the experimental results, we simulate the Schottky spectrum of bunched O^{5+} ions with and without laser cooling by employing the multi-particle tracking method. In the simulation, both the transverse oscillation and the photon-ion resonant interaction process are considered. For bunched ion beams, the power of the central peak is about several orders of magnitude higher than that of the sidebands, which was attributed to the 'coherent effect'. The simulation systematically studied the dependence of the Schottky power on the ions number at different bunching and observation harmonics, and the 'coherent effect' has been interpreted for the first time [3]. For laser-cooled bunched ion beams, both the experimental and simulation Schottky spectra are shown in Fig. 1. The simulation result shows good agreement with the experimental result, providing a precise method to extract the momentum spread of the laser-cooled O^{5+} ion beams. In the experiment, the dynamics of laser cooling processes have been investigated systematically by detuning frequency between the bucket and the laser. With most of the ions laser-cooled to the center of the bucket, the relative longitudinal momentum spread of the O^{5+} ion beams reached $\Delta p/p \approx 1.5 \times 10^{-6}$, which is limited by the diagnostic resolution of the Schottky diagnostics for bunched ion beams. The experiment and simulation will benefit the further laser cooling and precision laser spectroscopy experiments at the storage rings and also Gamma Factory at CERN [4].

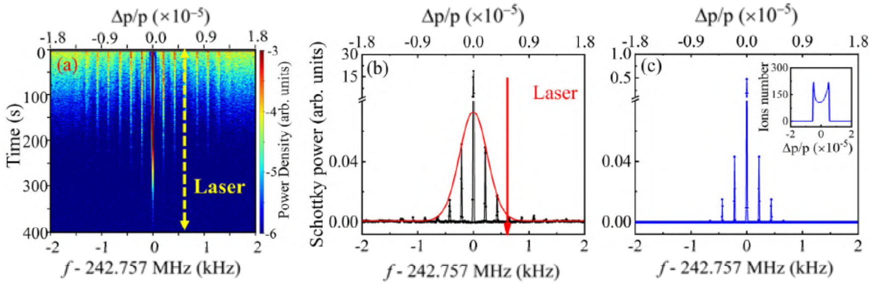

Figure 1 (a) The Schottky spectrum of laser-cooled bunched O^{5+} ions at the CSRe. (b) The Schottky spectrum extracted from figure (a) at 150 s. (c) The corresponding simulated Schottky spectrum of figure (b), in which the inset shows the momentum distribution used in the simulation.

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ST-22

First broadband laser cooling and XUV fluorescence detection of stored relativistic HCI

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At the highly relativistic energies and high intensities of the ion beams in the new SIS100 accelerator at FAIR, conventional beam cooling techniques (*e.g.* electron and stochastic cooling) have some limitations and laser cooling is a more elaborate and efficient method for cooling. Despite one specific requirement, *i.e.* the need for a fast electronic transition in the ions, at the SIS100 many different ions (element & charge state) can be laser-cooled, owing to the large magnetic rigidity of the SIS100 (max. 100 Tm). Importantly, the use of new pulsed (rep. rate ~MHz) and tunable CW laser systems (UV and VIS wavelengths) will greatly enlarge and enhance the potential of this cooling method. However, the much higher beam energies at the SIS100 also require new approaches for *in vacuo* detection of the fluorescence emitted by the ions, as it is required for laser spectroscopy and laser cooling.

In May 2021, an improved XUV fluorescence detection system and a new tunable pulsed UV laser system were employed for laser cooling of bunched relativistic (47% of c) carbon ions at the Experimental Storage Ring of GSI Helmholtzzentrum Darmstadt, Germany. Successful broadband laser cooling was demonstrated using this powerful (~200 mW), high repetition rate (~10 MHz) and tunable (wavelength and pulse duration) UV laser system. The experiment and its results will be discussed.

In addition, we will present our new fluorescence detection and spectroscopy system for the laser cooling project at the upcoming SIS100 accelerator. The new dispersed flourescence detection system uses an aberration corrected laminar grating in grazing incidence geometry and an open face micro-channel plates detector in Chevron stack configuration (sensitive in the soft X-Ray regime) with postion and time sensitive delay-line readout. If no energy resolution is required, the system can also be used for direct detection of the fluorescence photons with a significantly larger acceptance.

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ST-23

High-resolution spectroscopy of electronic *K* x rays from muonic atoms

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A muonic atom consists of a negatively-charged muon and a nucleus, sometimes accompanied by bound electrons. When a negative muon encounters an atom, the muon is captured in a highly excited state of the atom and then deexcites to lower energy levels step-by-step with the emission of Auger electrons and muonic x rays. Electron holes formed during this cascade process are immediately filled by the upper-level electrons, e.g., via characteristic x-ray emission.

We carried out high-resolution measurements of electronic *K* x rays from muonic atoms at J-PARC using a state-of-the-art x-ray detector, Transition-Edge Sensor (TES) microcalorimeters.

For muonic Fe (μFe) in a Fe metal [1], we observed an asymmetric and broad peak of electronic *K*α x rays, as shown in Figure 1. This feature reflects the dynamics of the cascade process because the energies of the *K* x rays are sensitive to the nuclear-charge screening by the muon and electron holes at the moment of the x-ray emission. In dense targets like metals, electron refilling from the surrounding follows, which is similar to de-excitation dynamics of highly-charged ions in metals [2].

On the other hand, for muonic Ar (μAr) in a gas phase [3], we found distinctively-resolved several peaks corresponding to highly-charged muonic atoms with a few bound electrons, where electron refilling is absent.

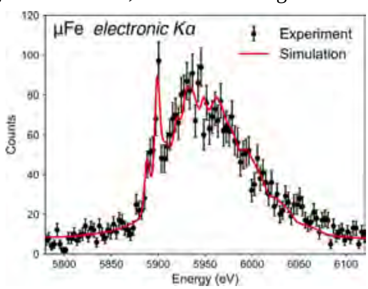

Figure 1: electronic *K* x-ray spectrum.

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ST-24

Absolute nuclear radius of iridium from precision measurements and calculations of EUV and X-ray transitions in highly charged ions

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The absolute nuclear radius of ^{193}Ir [1] has been determined by precisely measuring the relative difference in charge radii between osmium and iridium isotopes by novel spectroscopic observations of highly charged ions in the extreme ultraviolet (EUV) and x-ray regime. The electron beam ion trap (EBIT) at the National Institute of Standards and Technology (NIST) was used at a beam energy of about 18 keV to produce highly charged ions of Os and Ir.

The light-emission spectra generated by electron impact excitation were observed using a flat-field grazing-incidence spectrometer [2] over a range of 4 nm to 20 nm and recorded using an EUV CCD detector with a pixel resolution of about 0.008 nm. Simultaneously, x-ray photons were collected with the NIST Transition-Edge Sensor (TES) microcalorimeter [3] over a broadband energy range of roughly 500 eV to 8000 eV with an energy resolution of around 4 eV.

The dominant spectral lines of both Os and Ir observed in the EUV and x-ray range were Na-like $3s$–$3p_{1/2}, 3s - 3p_{3/2}$ and Mg-like $3s^2$–$3p_{1/2}, 3s^2 - 3p_{3/2}$ transitions respectively. The difference in the wavelength between the corresponding Ir and Os transitions was measured over the course of several days by cycling the injection of Os, Ir into the EBIT. Calibration of the instrument was regularly performed during the run by injecting Ne and observing lines from trace elements of Xe and Ba.

The observed wavelength differences are directly related to the difference in the mean square radii through the expansion of the nuclear Seltzer moment. Precision atomic structure calculations were performed using GRASP2K [4] and RMBPT [5] packages. A comparison with prior nuclear physics experimental methods will be reported.

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ST-25

Laser Spectroscopy of $^{12}C^{4+}$: First results towards an all-optical charge radius determination

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The size of an object is one of the most obvious observables. This also holds true for very small objects such as atomic nuclei. Therefore the nuclear size is of scientific interest since the discovery of its existence by Rutherford. Different measurement techniques have been developed over time such as elastic electron scattering or muonic spectroscopy to extract nuclear charge radii whereas atomic spectroscopy has so far been limited to H and He or to the differential nuclear charge radii of short-lived isotopes accessed by collinear laser spectroscopy (CLS). In a new approach we want to exploit the fast measurement scheme of CLS to optically measure the absolute charge radius of further He-like ions (Be^{2+}, B^{3+}, C^{4+}, ...) by exciting the ions from the metastable 2 $^3S_1$ state, which has a lifetime of a few 10-100 ms, to the 2 ^3P_J states. A transition frequency accuracy of approx. 1 MHz is targeted using simultaneous collinear and anticollinear laser spectroscopy. This experimental value is to be compared with nonrelativistic QED calculations [1] that are currently being performed. The results will compliment and improve existing measurements of nuclear charge radii.
The first high-precision collinear laser spectroscopy measurements of $^{12}C^{4+}$ have been carried out at the Collinear Apparatus for Laser Spectroscopy and Applied Physics (COALA) at the Institute of Nuclear Physics of TU Darmstadt which has recently been upgraded with an electron beam ion source to produce the highly charged ions. This contribution will summarize the current status of the project and present first results which will serve to benchmark the QED calculations. This project is supported by the German Research Foundation (Project-ID 279384907 – SFB1245).

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POSTERS A

A01

Probing surface magnetism with highly charged ions

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The interaction between highly charged ions and surfaces started in the '90s and it has been deeply investigated since then. Few studies have been accomplished with surfaces that present some defined magnetic order, as magnetic domains of a ferromagnetic phase. Here, we investigate slow HCI, during a grazing collision that capture electrons in highly excited states from the very first atomic layers, which could be in a particular magnetic phase. The working hypothesis is that the subsequent electron and photon emission bears the fingerprint of the local spin-ordering of the sample allowing magnetic properties' characterization of the sample. The ability to detect the presence of a ferromagnetic ordered phase in ion–surface interaction, even with no external magnetic field applied, was demonstrated in the past using Auger spectroscopy [1]. In these first attempts, only a qualitative evidence was obtained and a dispute arose in the scientific community on the general applicability of this method. Theoretical studies could not clarify this controversy. The goal of our project is to provide answers to these questions with a new approach where emitted X-ray photon and ion charge state (coupled eventually with energy loss) after the collision are simultaneously detected. This experimental method should allow us to characterize the collisional dynamics and provide quantitative information on the surface magnetization. The coincidence between X-rays and ions with a limited modification of their charge by the collision will enable us to efficiently identify grazing collisions for which the interatomic Coulomb decay [2] is not dominant. Indeed, this process does not conserve the spin orientation and consequently the information about a possible spin orientation of the sample surface. The energy of the X-rays selected by ion detection coincidence will allow identifying the spin of the populated levels and, accordingly, the magnetic phase of the sample surface. Preliminary results will be presented.

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A02

Shape and satellite studies of HCI high-accuracy X-ray spectra by Bayesian methods

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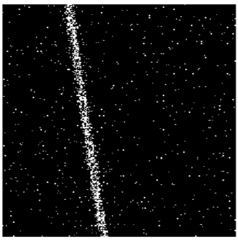
High-accuracy spectroscopy commonly requires dedicated investigations on spectral line modeling to avoid to add possible systematic errors. For such a kind of problem, analysis of χ^2, likelihood values or other criteria, are normally implemented to choose between the different spectrum modeling. These standard practices are however affected by several problems and, in the first place, their uselessness if there is no a clear propensity to a specific model. Such issues are fixed by Bayesian statistics in the context of which a probability can be assigned to different models/hypotheses from the analysis of a same set of data. These probabilities are calculated from the integration of the likelihood function over the model parameter space with the evaluation of the so-called Bayesian evidence. Here I will apply the Bayesian model selection method in the context of heavy HCI X-ray spectroscopy. In particular, I will present the result of the analysis of spectral lines corresponding of helium-, lithium- and beryllium-like uranium ions obtained in a recent experiment [1] (fig. left). I will show how to assign probabilities to different line profiles (Gaussian, Supergaussian, . . . , straight line, curved line, . . .) from the evaluation of the Bayesian evidence. Moreover, when the presence of a satellite line cannot be excluded (fig. right), I will present how to correctly estimate the position of the main spectral component. These analyses have been obtained by the freely available code `nested_fit` [2] based on the nested sampling algorithm for the evaluation of the Bayesian evidence [3].



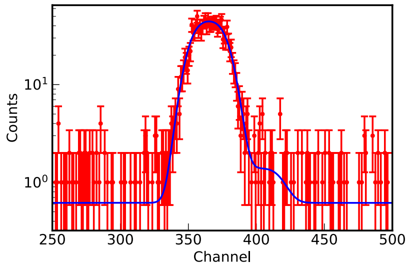


Figure 1: Left: $1s^22p_{3/2} \rightarrow 2s^22s_{1/2}$ lithium-like uranium transition detected by a X-ray CCD mounted on a high-resolution Bragg spectrometer. Right: Projection on the dispersion axis modeled with two spectral contributions.

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A03

Testing QED in heliumlike high-Z ions, a Bayesian approach

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Quantum Electrodynamics (QED) is, at present, the most tested foundalental theory, with an accuracy of one part in a trillion for the gyromagnetic factor of free electron. In atomic systems, the situation is more complex due to the presence of a nucleus structure and even more demanding for heavy highly charged ions (with $Z\alpha \lesssim 1$), due to the non-converging perturbation expansion in $Z\alpha \lesssim 1$. In light of new high-accuracy measurements on He-like ions, in 2012 Chantler and coworkers claimed a deviation of QED predictions, with a dependency on Z^3, for the energies of $n = 2 \to 1$ transitions in medium/high-Z two-electrons ions [1]. Such a claim has been fought back from more recent studies via alternative statistical analyses and new measurements [2–5], all confirming QED predictions. These investigations are however exclusively based on standard (frequentist) statistical methods. Here we present a new study based on Bayesian probability to test the relevance of a possible deviation of QED predictions in He-like ion transitions. Differently to frequentist methods, where only criteria are available to choose among models, Bayesian methods allow to assign probabilities to different hypotheses (QED is right, a deviation with a dependency on Z, on Z^2, etc.). The evaluation of each model probability is based on the computation of the Bayesian evidence (marginalized likelihood), which consist on the integration of the likelihood function over the model parameter values. We present here the results of new different statistical studies (Bayesian and frequentist), including the very recent measurements on He-like sulfur and uranium [6], which will be compared with the past results. In particular, when the same data than Ref. [1], the Bayesian analysis indicates a dependency on Z^2 as the most probable, and not on Z^3 like Chantler et al [1].

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A04

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 hydrogenlike 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 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]. 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 [2].
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 [3]. 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.

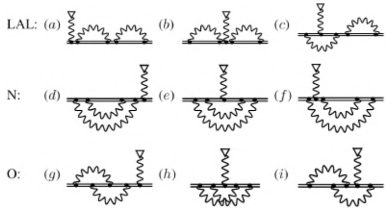

Figure 1: Furry-picture Feynman diagrams of the two-loop self-energy correction to the bound-electron g-factor.

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A05

Theory of the magnetic moments and hyperfine splitting of $^3He^+$

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In an external magnetic field, the ground state of the $^3He^+$ ion is split into into four sublevels due to the combined hyperfine splitting and Zeeman effect. By measuring transition frequencies between these sublevels, it is possible to determine the g-factor of the bound electron, the ground-state hyperfine splitting as well as the shielded magnetic moment of the nucleus [1].
In this work, we present the theoretical calculations of the nuclear shielding constant, the ground-state hyperfine splitting and the bound-electron g-factor [2]. The theoretical uncertainty of the bound-electron g-factor is dominated by the uncertainty of the fine-structure constant α. This would allow an independent determination of α in future, provided that the experimental precision can be improved accordingly [3]. Combining the experimental value for the shielded nuclear magnetic moment and the theoretical value for the nuclear shielding constant, we extracted the magnetic moment of the bare nucleus with unprecedented precision, enabling new applications in magnetometry. Furthermore, we extracted the nuclear Zemach radius from the experimental hyperfine splitting value, in tension with the established literature value [4].

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A06

Calculations of Delbrück scattering to all orders in αZ

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Delbrück scattering is the process in which a photon is elastically scattered by the Coulomb field of a nucleus or ion via the production of virtual electron-positron pairs, see figure 1.

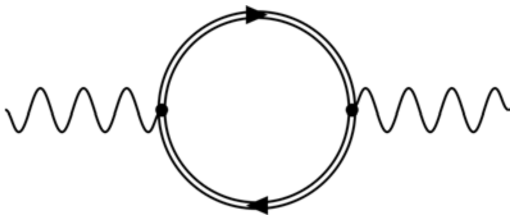

Figure 1: Leading-order Feynman diagram for Delbrück scattering.

It is one of the few non-linear quantum electrodynamical processes that can be observed experimentally [1] and, hence, testing the respective theoretical predictions serves as an important test of the QED theory in strong electromagnetic fields. However, despite the strong motivation for the theoretical analysis of Delbrück scattering, most of the previous studies have been limited to approximations regarding the coupling between the virtual electron positron pairs and the nucleus. For example, many authors have used the first order Born approximation in which all interactions with the Coulomb field beyond the lowest order are neglected [2]. The accuracy of this approximation wanes for higher nuclear charges which are of particular experimental interest. Other methods, like the high-energy large- and small-angle approximation, also have strong limitations on the parameter regimes in which they are applicable [3].

In this contribution, therefore, we present an efficient approach to calculate amplitudes for Delbrück scattering [4]. Our formalism is based on the exact analytical Dirac-Coulomb Greens function and, hence, accounts for the interaction with nucleus to all orders including the Coulomb corrections.

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A07

Direct high precision measurement of the Q-value of the electron capture in ^{163}Ho and metastable states in highly charged ions

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The high-precision Penning-trap mass spectrometer Pentatrap [1] features a stack of five Penning traps and determines mass-ratios with a relative uncertainty below 10 ppt. Mass-ratio determinations of stable and long-lived highly charged ions have numerous applications, among others, in neutrino physics [2] and the search of possible clock transitions in highly charged ions (HCI) [3]. The unique features of Pentatrap include access to HCI, a stable 7 T magnet, and a cryogenic detection system with single ion phase sensitivity. The latest measurements include the Q value of the beta-decay of ^{163}Ho with a relative uncertainty of below 7 ppt. In ^{208}Pb a long-lived metastable electronic state was discovered.

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A08

High-Resolution X-Ray Spectroscopy of He-like Uranium using Novel Microcalorimeter Detectors

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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. 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 $K_{\alpha 2}$ lines. Furthermore, the various unique aspects resulting from the selected detection geometry in combination with the broad spectral acceptance of the detectors will be presented.

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A09

Laser Spectroscopy of $^{12}C^{4+}$: First results towards an all-optical charge radius determination

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The size of an object is one of the most obvious observables. This also holds true for very small objects such as atomic nuclei. Therefore the nuclear size is of scientific interest since the discovery of its existence by Rutherford. Different measurement techniques have been developed over time such as elastic electron scattering or muonic spectroscopy to extract nuclear charge radii whereas atomic spectroscopy has so far been limited to H and He or to the differential nuclear charge radii of short-lived isotopes accessed by collinear laser spectroscopy (CLS). In a new approach we want to exploit the fast measurement scheme of CLS to optically measure the absolute charge radius of further He-like ions (Be^{2+}, B^{3+}, C^{4+}, ...) by exciting the ions from the metastable 2 $^3S_1$ state, which has a lifetime of a few 10-100 ms, to the 2 ^3P_J states. A transition frequency accuracy of approx. 1 MHz is targeted using simultaneous collinear and anticollinear laser spectroscopy. This experimental value is to be compared with nonrelativistic QED calculations [1] that are currently being performed. The results will compliment and improve existing measurements of nuclear charge radii.
The first high-precision collinear laser spectroscopy measurements of $^{12}C^{4+}$ have been carried out at the Collinear Apparatus for Laser Spectroscopy and Applied Physics (COALA) at the Institute of Nuclear Physics of TU Darmstadt which has recently been upgraded with an electron beam ion source to produce the highly charged ions. This contribution will summarize the current status of the project and present first results which will serve to benchmark the QED calculations. This project is supported by the German Research Foundation (Project-ID 279384907 – SFB1245).

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A10

High resolution measurement of the 2p3/2→2s1/2 intra-shell transition in He-like uranium

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He-like ions, the simplest multi-body atomic systems, offer the possibility to probe QED correlation and electron interaction effects. The theoretical description of these effects in extrem high electric fields, as for high-Z ions, is still challenging and different approaches leaves to different results. Thus tests by experiments are needed. By measuring the difference in transition energies between He- and Li-like ions, it is additionally possible to effectively isolate the electron correlations effects. Precision spectroscopy of He-like heaviest ions is also experimentally very challenging and the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in uranium was only measured in an pilot experiment [1] at the ESR with limited accuracy.

We measured the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in He-like uranium at the ESR of GSI, employing a bent crystal Bragg spectrometer. This allows for an energy resolution of ~2.7 eV and an statistical accuracy of ~0.06 eV. By comparing the line to the corresponding transition in Li-like uranium, we reach for an accuracy of ~0.15 eV on the absolute energy of the He-like and ~0.06 eV for the relative measurement of the two lines. This allows for an unmatched test of electron correlation effects and two-loop corrections of Quantum Electrodynamics in few electron systems in strong electric fields with the errors of the measurement comparable to the best theoretical values.

This research has been conducted in the frame-work of the SPARC collaboration, experiment E125 of FAIR Phase-0 supported by GSI. It is further supported by the Extreme Matter Institute EMMI and by the European Research Council (ERC) under the European Union's Horizon 2020 research as well as by the innovation pro-gramme (Grant No 682841 "ASTRUm") and the grant agreement n° 6544002, ENSAR2. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA) too.

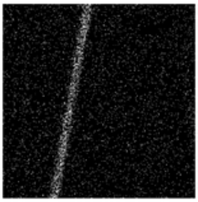

Figure 1: Detector image of the $2p_{3/2}\rightarrow 2s_{1/2}$ transition in He-like uranium. Dispersion is in the horizontal direction. The slant of the line is due to the Doppler shift.

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A11

Path integral formalism for Dirac propagators in atomic physics

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Current improvements in the experimental study of highly charged ions allow to determine the various properties of these ions with unprecedented accuracy. The recently constructed PENTATRAP Penning-trap setup enables a direct access to electron binding energies in a given quantum ground state, to scrutinize atomic structure theory and quantum electrodynamics with electronvolt precision [1-3]. This suggests a novel formulation of QED, enabling to take into account the strong, non-perturbative effect of the binding nuclear field. The very basic building blocks of perturbative calculations in atomic structure and collision theory are Green's functions. We extend this study of Green's functions, in the nonperturbative regime, using Feynman's path integral approach.

As a first step towards a full path-integral based formalism, we derive the free propagator describing the electrons moving in the absence of a potential [4], followed by the propagator in the presence of a strong attractive Coulomb field or the Dirac Coulomb Green's function (DCGF). This work is then followed by the calculation of the energy shift due to vacuum polarization using perturbation theory based on the path integral.

For the free relativistic Dirac particle, the effective Hamiltonian for the iterated Dirac equation is constructed. The corresponding Green's function is expanded into partial waves in spherical coordinates. The radial part of this Green's function is then converted into a path integral, through reparametrisation of the paths by local time rescaling, followed by a one-to-one mapping of the radial variable with the local time parameter [5]. This yields a closed form of the Green's function. Following the same procedure, the DCGF is diagonalised in Biedenharn's basis [6] into a radial path integral, the effective action of which is similar to that of the non-relativistic hydrogen atom. We convert the radial path integral from Coulomb type to that of an isotropic harmonic oscillator through coordinate transformation along with local time rescaling. As such, an explicit path integral representation of the DCGF is obtained, along with the energy spectrum of the bound states. Once an explicit form of the DCGF is obtained, we use it to study the energy shift produced by the Uehling potential where we constuct the modified action with the insertion of a perturbing potential. The perturbed Green's function is then obtained at order n with n insertions of this perturbing potential. The energy perturbation is obtained from the poles of this Green's function.

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A12

Multi-configuration Dirac-Hatree-Fock calculations for W^{67+} and Pb^{75+}

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Energy levels and radiative data are presented for 15 fine-structure levels belonging to the configurations $1s^2 2s^2 2p^3$, $1s^2 2s^1 2p^4$ and $1s^2 2p^5$ of W^{67+} and Pb^{75+} ions using general-purpose relativistic atomic structure package (GRASP2k)[1]. Radiative data have been calculated for electric dipole (E1) and magnetic quadrupole (M2) among these levels. Our calculated data of W^{67+} and Pb^{75+} agree very well with the results presented by C. Naze et al. [2] and J. Li. et al. and H. L. Zhang and D. H. Sampson [3,4]. We believe that our results may be useful in the areas of astrophysical investigations and application and fusion plasma research.

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A13

Radiative properties of Rb-isoelectronic Technetium (Tc VII), Ruthenium (Ru VIII) and Rhodium (Rh IX) ions for astrophysical applications

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In this work, we present high-accuracy spectroscopic properties such as line strengths, transition probabilities and oscillator strengths for allowed transitions among $nD_{3/2,5/2}, n'S_{1/2}$ and $n'P_{1/2,3/2}(n = 4, n' = 5, 6)$ states of Rb-isoelectronic Tc (Tc VII), Ru (Ru VIII) and Rh (Rh IX) ions due to their necessity for the analysis of astrophysical phenomena undergoing inside the heavenly bodies containing Tc, Ru and Rh ions. Due to scarcity of computational data of atomic properties as well as considerable discrepancies lying within the literature of these ions, the precise determination of these properties is prerequisite. Therefore, for this purpose, we have implemented relativistic many body perturbation theory (RMBPT) for the evaluation of wave functions of the considered states. For better accuracy, we have accounted for electron interactions through random phase approximation, Brückner orbitals and structural radiations of wave functions in our RMBPT method for further evaluation of electric dipole amplitudes precisely. Combining these values of the observed wavelengths, the above transition properties and radiative lifetimes of a number of excited states of Tc VII, Ru VIII and Rh IX ions have been calculated. For further validation of our work, we have compared our results with the data already available in literature.

A14

Delhi Penning Trap for measurements of radiative lifetimes of atomic metastable states

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The study of forbidden optical transitions of highly ionized atoms is the subject of fundamental research and plays an essential role in the generation of atomic frequency standards [1], determining fundamental constants [2], tests of the Standard Model [3], astrophysics [4], and testing quantum electrodynamics (QED) for simple multi-body systems [2].

A cryogenic Penning trap at Inter-University Accelerator Centre (IUAC), New Delhi, has been designed and developed to capture highly charged ions of specific m/q from an external Electron Cyclotron Resonance (ECR) ion source. The highly energetic ions from the ECR ion source are decelerated before being captured at the center of the Penning trap. The overall schematic of the Delhi Penning Trap (DPT) is shown in figure 1.

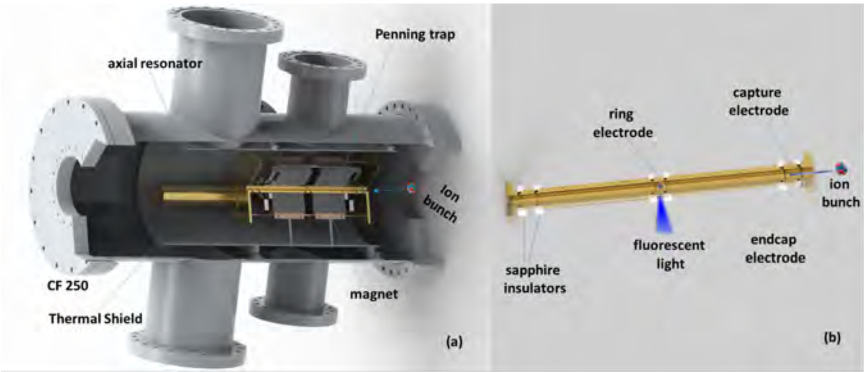

Figure 1: (a) Schematic overview of the Delhi Penning Trap, (b) Cross-section view of electrodes

In this paper, recent developments of the DPT at IUAC are described, including the design, fabrication, testing of the trap, its detection system, and the use of this Penning trap to precisely measure the radiative lifetimes of metastable states of atomic systems. The first results on the metastable lifetime of the $^2P_{1/2} \rightarrow {}^2P_{3/2}$ transitions in the boron-like ions are expected in the near future.

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A15

InF^+ molecule for future nuclear–spin–dependent P–violating experiments

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Precision experiments to measure the nuclear–spin–dependent parity violation (NSD-PV) using diatomic molecular ions are promising. The use of molecules gives the possibility to amplify the observable signals using close-lying opposite parity eigenstates. Specifically, in systems containing heavy nuclei, the NSD-PV effects are dominated by the P-odd anapole moment contribution. The measurement of the anapole moment has a relevant impact on nuclear physics as its value is related to a set of parameters describing low-energy hadronic PV interactions. In this work, we study the InF^+ molecule as a promising candidate for measuring the anapole moment. We use high–accurate electronic structure methods to calculate the enhancement parameter W_a, which describes the sensitivity of this molecule to the anapole moment, and we estimate the uncertainty in our predictions. Additionally, we study the suitability of InF^+ for laser cooling for the initial experiment steps of the proposed measurements.

A16

Two-photon processes and its relevance to astrophysics and precision atomic physics

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Two-photon processes (TP) have been studied extensively since the birth of quantum mechanics by Göppert-Mayer (1931). The forbidden transition of $2s \to 1s$ is a prime example of the substantial experimental and theoretical work dedicated to the first excited state of the simplest atom of hydrogen and this effort was originally triggered from astrophysics. While TP of hydrogen and helium have been extensively investigated, both experimentally and theoretically, other elements and ionic states cannot be overlooked for astrophysical models. For example, the first excited state of Be-like ions cannot undergo via a one-photon decay due to the $0 \to 0$ selection rule. Therefore, without external electromagnetic fields and for zero-spin nuclear isotopes, the most dominant decay mode of this state is a rare TP transition that is very sensitive to relativistic and electronic correlation effects and can have lifetimes from a few decades to a few minutes, depending on the ion specimen. Only four theoretical calculations are available with notorious disagreements between each other and without any experimental measurement (Amaro 2016 [1]).

An overview of the theoretical framework for two-photon related processes that was employed at the group LIBPhys-UNL will be provided, together with most recent developments.

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A17

QED calculations of Be-like ions

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Quantum electrodynamic (QED) description of energy levels in highly charged Be-like ions poses serious challenges for high-precision theoretical physics. The reason is that a number of states of the same symmetry (including the ground one) are quasi-degenerate and the use of the standard approach based on a QED perturbation theory for single levels can lead to unsatisfactory results. The situation is complicated by a strong interference between the QED and electron–electron correlation effects. We overcome these and other difficulties by applying the QED perturbation theory for quasi-degenerate levels. In the developed approach [1,2], the contributions of all the relevant Feynman diagrams up to the second order are taken into account. The many-electron QED effects are treated in the Furry picture. The correlation effects of the third and higher orders are accounted for within the Breit approximation. In addition, the nuclear recoil and nuclear polarization effects are considered.

The developed methods are applied to the QED calculations of the binding and transition energies in Be-like argon, krypton, molybdenum, xenon, lead, and uranium. The obtained theoretical predictions are generally in agreement with the available experimental values [3-5]. For the $2s2p\,^3P_1$–$2s^2\,^1S_0$ transition in xenon, however, some discrepancy with the most precise measurement [6] is found. New experiments to explore the electronic structure of highly charged Be-like ions are in demand.

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A18

Nuclear magnetic shielding in Li- and B-like ions

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The nuclear magnetic moments are presently in the focus of interest, since the uncertainty of their determination from the widely accepted nuclear magnetic resonance method may be significantly underestimated [1]. An independent method, free from the environment effects which are difficult to estimate, was proposed in [2] and developed further in [3]. It is based on the g-factor measurement in highly charged ions. To implement this method, theoretical calculations are necessary for both the electron g-factor and the hyperfine-interaction correction, which is also termed as the nuclear magnetic shielding constant.

This constant was previously calculated for H-like [4,5,6], Li-like [7], and B-like ions [8,9]. In Li- and B-like ions the first-order interelectronic-interaction correction was calculated [7,9] with the Coulomb potential as the zeroth approximation.

Use of the screening potential provides an opportunity to take into account some part of the higher-order contributions. Spread of the results obtained in different potentials allows one to estimate the remaining uncertainty. In this work, we present the corresponding results for the nuclear magnetic shielding constant in Li- and B-like ions. The calculations are performed within two independent approaches – the perturbation theory and the finite-field method. In both methods, we use the finite basis set constructed in the framework of the dual-kinetic-balance (DKB) approach [10,11]. Within the finite-field method the axially symmetric magnetic field is included in the Dirac Hamiltonian. The results obtained within both methods are found in good agreement, confirming the correctness of the numerical procedure.

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A19

One-Electron Energy Spectra of Heavy Highly Charged Quasimolecules: Finite-Basis-Set Approach

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Quasimolecular systems emerging in heavy ion-ion or ion-atom collisions provide a possibility to investigate the critical phenomena of the bound-state quantum electrodynamics, e.g., spontaneous electron-positron pair production. Collisions of highly charged ions with neutral atoms are presently available for experimental investigations at the GSI Helmholtz Centre for Heavy Ion Research while the upcoming experiments at the GSI/FAIR [1], NICA [2], and HIAF [3] facilities might even allow the observation of the heavy ion-ion collision up to U^{92+}–U^{92+}. In that case, the total nuclear charge ($Z = 184$) is larger than the critical one ($Z_c = 173$), the ground one-electron state can "dive" into the Dirac negative-energy continuum at small enough internuclear distances [4, 5]. So, this is a strongly non-perturbative regime of QED and the theoretical calculations for such systems must be performed to all orders in αZ (α is the fine-structure constant).

We present the fully relativistic calculations of the ground and a few lowest excited σ-states of the few-electron heavy diatomic quasimolecules. Some results for the homonuclear quasimolecules were already presented in Refs. [6, 7] and compared with the previously published values [8–10]. In this work we extend these investigations to the heteronuclear systems, in particular, U–Cf. The dual-kinetic-balance approach is employed to solve the Dirac problem [11, 12]. Two different choices of the coordinate system origin, (1) in the center-of-mass of a quasimolecule and (2) in the center of a nucleus, are compared for both two-center and monopole-approximation results. This analysis can be used to quantify the deviation from the yet unknown two-center results, e.g., for the QED contributions available only within the monopole approximation so far.

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A20

Many-electron effects in the theory of the g factor of lithiumlike ions

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Over the past decades, significant progress has been made in the study of the g factor in highly charged ions. The measurement accuracy for H-like, Li-like, and B-like ions reached the level of $10^{-9} - 10^{-11}$ [1-5]. Such high-precision measurements for H-like ions combined with the theoretical studies have led to the most accurate up-to-date value of electron mass [6]. Future studies are expected to provide an independent determination of the fine structure constant α [7]. Calculations performed to date for Li-like ions achieved an accuracy of $10^{-6} - 10^{-9}$. The theoretical results of Refs. [4,8] agree with high-precision g-factor measurements for Li-like silicon [2,4] and calcium [3], demonstrating the most rigorous test of many-electron QED effects in the presence of magnetic field. However, the corresponding theoretical values obtained in [9,10] disagree with the experiment. To clarify this situation, we recalculated the most problematic contributions [11], and the results confirmed our previous value [4].

At present, the interelectronic-interaction contributions of the first and second order to the g factor of Li-like ions are calculated within the framework of the bound-state QED. Higher-order contributions are accounted for within the Breit approximation by nonperturbative methods, for example, the CI-DFS method [8]. The computations in this work were performed using a novel approach built on the recursive formulation of perturbation theory with a finite basis set of many-electron wave functions constructed in the form of Slater determinants [12]. As shown in [4,11], for the third and higher orders, the perturbation theory provide significantly better accuracy than the CI-DFS method. In our recent paper [11], the application of this method to the g factor of Li-like silicon and calcium has been demonstrated. In this work, these calculations are extended to a wide range of Li-like ions.

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A21

Recursive perturbation theory for highly charged ions

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Modern high-precision calculations for highly charged ions usually include leading contributions on electromagnetic interactions within quantum electrodynamics (QED) for bound states. For approximate consideration of higher orders within the relativistic theory of atom, various methods based on the Dirac-Coulomb-Breit Hamiltonian have been developed. Despite the widespread use of non-perturbative methods, perturbation theory often turns out to be more effective, especially when it is formulated in recursive form to access arbitrary high orders. In [1] the recursive formulation of perturbation theory was combined with a finite basis set in the form of Slater determinants of one-electron functions constructed by the dual kinetic balance method [2]. The proposed method has been applied to the calculation of the interelectronic-interaction contribution to the energies of lithium-like and boron-like ions [1,3]. The extension of this method to the case of quasi-degenerate states allowed us to carry out similar calculations for helium-like ions [4,5]. In addition, in [3,6] the contribution of the interelectronic interaction to the nuclear recoil effect was calculated for the energies of lithium- and boron-like ions.

The evaluation of quantities such as the g-factor and hyperfine splitting requires that the contribution of the negative-energy solutions of the Dirac equation be properly accounted for. A corresponding approach was developed in [7] and the interelectronic-interaction corrections of the 3rd and higher orders to the g-factor and the hyperfine splitting of lithium-like ions were calculated [7–9]. Generalisation of the recursive scheme to the case of several perturbations allows for evaluation of more subtle effects, such as many-electron QED [7,9] and nuclear recoil contributions [10–12]. The leading contributions of the 1st and 2nd orders have been calculated rigorously within the framework of the bound-state QED, which together gave the best theoretical accuracy to date for the g-factor of lithium- and boron-like ions.

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A22

g factor of the ground-state of highly charged ^{229}Th ions as a tool to determine the M1 transition probability between the isomeric and ground nuclear states

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The exceptionally low-energy (about 8 eV) isomeric state in ^{229}Th attracts a great interest of atomic and nuclear physics communities [1-3]. The smaller sensitivity of the nuclear transitions to external perturbations, compared to electronic transitions in atoms, makes this nucleus an ideal candidate for the nuclear optical clock which could serve as a new metrological frequency standard [4]. The practical realization of this application requires the precise knowledge of the excitation energy as well as other fundamental nuclear properties of the ground and isomeric states. Among these properties, one should consider the $M1$ transition probability between the nuclear states.

In this work, we propose to determine the $M1$ nuclear transition amplitude and hence the lifetime of the "nuclear clock transition" between the low-lying (~ 8 eV) isomeric state and the ground state of ^{229}Th from a measurement of the *ground-state* g factor of few-electron ^{229}Th ions. The approach is based on a nuclear hyperfine mixing (NHM) of the states, which is due to the small excitation energy of the isomeric state and the strong hyperfine interaction. In ^{229}Th^{89+} or ^{229}Th^{87+} ions, the mixing coefficient enters the g factor of the ion and contains the information about the M1-transition probability. Hence, the decay property of the isomeric state can be experimentally deduced from an ion that is in the nuclear ground state. We show that the experimental determination of the ground-state g factor of H-like ^{229}Th ion to the precision of about 10^{-7} allows one to get the $M1$ transition probability with a few-percent accuracy. Furthermore, a comparison of the measurements of the ground-state g factors of H-, Li-like, and B-like ^{229}Th ions has a potential to improve the result for a single charge state and to determine the nuclear magnetic moment to a higher accuracy than that of the currently accepted value. The details of the method and the related calculations can be found in Ref. [5].

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A23

Evaluation of the $1s^22s2p^6$ - $1s^22s^22p^5$ transition energy in fluorine-like nickel

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The structure and dynamic properties of highly charged ions up to an extremely high precision are a*b initio* described by quantum electrodynamics (QED). QED is currently considered to be one of the most accurate theories of fundamental interactions. As its extraordinary precision offers unique scientific opportunities, e.g., search for new physics, stringent experimental tests of QED continue to be of high importance. In comparison with neutral atoms or low-charged ions, many physical phenomena are greatly enhanced in highly charged ions (HCIs). Moreover HCI are important for diagnostics of hot laboratory plasma, notably in magnetic nuclear fusion and tokamaks, study of nearly all classes of cosmic x-ray sources and etc.

In the present work we focused on study of fluorinelike nickel ions. The QED calculations of the transition $1s^22s2p^6\ {}^2S_{1/2} - 1s^22s^22p^5\ {}^2P_{3/2}$ energy in fluorinelike nickel is based on the QED perturbation theory in the extended Furry picture. The zero-order Hamiltonian is the Dirac one, where in addition to the nuclear Coulomb potential a screening potential, which partially accounts for the inter-electronic interaction, is added. For constructing the perturbative expansion, we use the two-time Green function method [1]. In the present calculations, we account entirely for the first-order correction, which are given by the one-photon exchange and the one-electron self-energy and vacuum polarization diagrams. The second-order diagrams include the many-electron radiative (so-called screened QED), one-electron two-loop, and two-photon exchange corrections. Here, we evaluate only the screened QED correction employing the techniques and methods thoroughly presented in Refs. [2]. For the one-electron two-loop contribution, we use the hydrogenic values from Ref. [3]. The terms which were not accounted for by the rigorous QED theory have been evaluated within the Breit approximation employing the configuration-interaction Dirac-Fock-Strum (CI-DFS) method [4]. Thus, the CI-DFS method is used to calculate the second and higher orders interelectronic-interaction corrections. Moreover, we have evaluated the recoil correction employing the many-body relativistic mass shift Hamiltonian [5].

For comparison with the most accurate recent experimental data, which have been obtain using high precision dieelectronic recombination spectroscopy [6], the energy of autoionization $(1s^22s2p^6[2S_{1/2}]6s)_{J=1}$ state has been evaluated based on the stabilization method (see, e. g. Ref. [7] and references therein). The obtained results are the most accurate in the literature and in reasonable agreement with recent experimental data.

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A24

Radiative rates for E1, E2, M1, and M2 transitions in He-like Cd

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Atomic data have received a great deal of attention, due to their need for the upcoming ITER project (International Thermonuclear Experimental Reactor). So, extensive spectroscopic studies both experimental and theoretical have been performed in the last years in order to estimate the power loss from the impurities in the forthcoming fusion reactors [1]. Accurate values of wavelengths and their errors are required for interpretation of a wealth of high-resolution data obtained in the last two decades by the Chandra X-ray Observatory and the European Space Agency's X-ray Multi-Mirror Mission [2].

As previously published [3,4,5,6,7], we continue to focus on He-like ions. Energy levels, wavelengths, weighted oscillator strengths, transition probabilities and lifetimes are calculated for all levels of $1s^2$ and $1snl$ ($n = 2 - 6$) configurations of He-like cadmium ion.

The calculations were carried out using the GRASP2018 code based on the multiconfiguration Dirac-Hartree-Fock (MCDHF) [8]. Transition probabilities are reported for all types of transitions ($E1$, $E2$, $M1$ and $M2$ transitions). Breit interactions and quantum electrodynamics effects are included in the RCI calculations. Comparisons were made with other data found in the literature and a good agreement was found which confirms the reliability of our results. We identified some new data that are calculated for the first time. This computational approach enables us to present a consistent and improved data set of all important transitions of the Cd XLVII spectrum, which are useful for identifying transition lines in further investigations.

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A25

Study of radiative properties of helium isoelectronic sequence

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The radiative properties of ions (Z=2-53) belonging to the helium isoelectronic sequence are reported. Energy levels for the ground state and the lowest 1s2l singly excited states are considered. The effects of correlation effects are studied for the selected ions by increasing the active set (AS). Relativistic effects such as the Breit interaction and the QED corrections are also computed. The heavy elements with high Z are of potential interest in controlled thermonuclear fusion and astrophysics. Indeed, they could be used in plasma-facing materials such as the divertors in tokamaks or/and could be generated by neutron-induced transmutations of divertor’s materials. So, extensive spectroscopic studies both experimental and theoretical have been performed in the last years in order to estimate the power loss from the impurities in the forthcoming fusion reactors [1].
In this work, two independent theoretical atomic structure computational approaches have been considered, i.e. the ab initio multiconfiguration Dirac-Hartree-Fock with subsequent relativistic configuration interaction method (MCDHF-RCI) implemented in the code GRASP2018 [2] and the Dirac-Fock-Slater (DFS) implemented in the code FAC (Flexible Atomic Code) [3]. The relativistic configuration interaction method was applied to estimate the electron correlation effects. The transition probabilities and the oscillator strengths calculated for E1, E2, M1 and M2 transitions spanning the spectral range from Uv to IR. Our results are compared with available experimental and other theoretical values. Good agreement was found for the majority of cases. Lifetimes are also considered in this work, first to check the accuracy of calculated results of transitions rates and second, to complete the databases by a complete and accurate values of lifetimes. This can help future works by experimentalists to compare their results with those results calculated theoretically. Finally, this study underlines the importance of relativistic corrections especially for the heavy atomic ions. This computational approach enables us to present a consistent and improved data set of all-important atomic data of the helium isoelectronic sequence, which are useful for identifying transition lines in further investigations.

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A26

Accurate calculations of atomic data structure for Helium-Like Ions using the Configuration Interaction approach for singly and doubly excited states

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Accurate atomic data is considered to be the principal way to effectively solve the future energy problem as a clean and infinite energy resource and it is being developed internationally via the International Thermonuclear Experimental Reactor ($ITER$) Project [1]. Then, extensive spectroscopic studies both experimental and theoretical have been performed in the last few years in order to estimate the power loss from the impurities in the forthcoming fusion reactors. Furthermore, accurate values of wavelengths and their errors are required for the interpretation of a wealth of high-resolution data obtained in the last two decades by the Chandra X-ray Observatory and the European Space Agency's X-ray Multi-Mirror Mission. As previously published [2, 3], we continue to focus on Helium-like ions [4]. In this work, energy levels, wavelengths and transitions rates have been calculated for the lowest singly excited 70 levels among $1snl(n \leq 6, l \leq (n-1))$ configurations and the lowest doubly excited 250 levels arising from the K-vacancy $2ln'l'(n' \leq 6,\ l' \leq (n'-1))$ configurations of helium-like ions with $Z = 5 - 9$. The calculations were performed using the Configuration Interaction (CI) method implemented in the Flexible Atomic Code (FAC) [5]. Some comparisons were made with other available results reported in the literature [6, 7, 8, 9] and some discrepancies have been noted and explained. Finally, the accuracy of the present calculations is enough to facilitate the identification of many observed spectral lines, plasma modelling as well as diagnostics of astrophysical plasma and controlled thermonuclear fusion.

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A27

Fully-stripped beryllium-ion collisions with atomic hydrogen initially in an excited state

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The ITER and JET projects use beryllium-containing materials in plasma facing wall components. Due to the high temperature environments, the erosion of the wall followed by ionisation of Be is inevitable. Therefore, collisions between resulting Be ions with atomic hydrogen can take place when a neutral beam of hydrogen atoms is injected into the plasma for heating and diagnostic purposes. However, due to the toxicity of Be, there are no experimental measurements of cross sections for such collisions. This makes theoretical calculations of beryllium ion collisions with hydrogen [1, 2] the only source of data for plasma modelling. We studied collisions between bare beryllium ions and ground state atomic hydrogen in our previous work [3]. This was done using the wave-packet convergent close-coupling (WP-CCC) approach which solves the three-body Schrödinger equation by employing a two-centre expansion for the total scattering wave function. This work is now extended to Be^{4+} ion scattering on hydrogen in its lowest excited states within the projectile-energy domain between 1 keV/u and 500 keV/u. Specifically, this includes collisions with the hydrogen target initially in the 2s, $2p_0$ and $2p_1$ states. Integrated total and state-selective electron-capture cross sections are calculated. The results suggest that at low energies, collisions with hydrogen in each considered excited state produce a total electron-capture cross section approximately an order of magnitude larger than for scattering on the ground state. However, as projectile energy increases, the cross section for capture from the excited states falls well below the H(1s) electron capture cross section. A possible reason for this observation could be related with the way the target electron radial densities are distributed in different initial states. The results obtained in this work are compared to previous calculations where available. In terms of the n-resolved charge-exchange cross sections, where n is the principal quantum number of the formed Be^{3+} ion in the final state, significant disagreement is found between our results and some previous calculations available in the literature.

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A28

Coulomb explosion imaging of carbon monoxide dimers

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Experimental results concerning collisions of 135 keV highly charged Ar^{9+} ions with a carbon monoxide dimer $(CO)_2$ target will be presented. Cold target recoil ion momentum spectroscopy and Coulomb explosion imaging are used to reconstruct the geometrical structure of the CO dimers. The three-dimensional structure is deduced from the two-body and three-body dissociation channels from which both the intermolecular bond length and the relative orientation of the two molecules axis are determined. For the three-body channels, the experimental data are interpreted with the help of a Coulomb explosion classical model in which the trajectories of the three emitted fragments are numerically integrated.

From the (CO^+ + CO^+) two-body dissociation channel kinetic energy release, we experimentally determine the equilibrium intermolecular distance to be R_e = 4.2 Å. The orientation of both CO molecules with respect to the dimer axis is obtained from the three-body fragmentation of $(CO)_2^{q+}$ (q = 3 to 5) and found to be quasi-isotropic which might be due to the residual vibrational temperature of the supersonic gas jet [1].

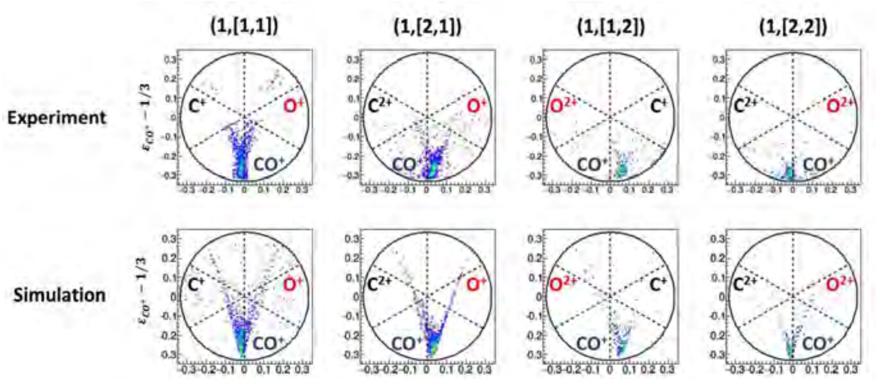

Figure 1: Experimental and simulated Dalitz plots for the (CO^+, [C^+,O^+]), (CO^+, [C^{2+},O^+]), (CO^+, [C^+,O^{2+}]) and (CO^+, [C^{2+},O^{2+}]) fragmentation channels of $(CO)_2^{3+}$ induced by 135 keV Ar^{9+} ion impact.

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A29

Investigation of the carbon monoxide dication lifetime using $(CO)_2$ dimer fragmentation

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Doubly charged diatomic molecular ions have unusual properties leading to a wide range of lifetimes against dissociation. Their stability depends on both the accessible decay mechanisms and the position of the populated rovibronic levels with respect to the potential barrier height. The fragmentation of carbon monoxide dimers induced by collisions with 135 keV Ar^{9+} ions is investigated using the cold target recoil ion momentum spectroscopy technique [1]. The presence of a neighbor molecule in the dimer serves as a diagnostic tool to probe the lifetimes of the CO^{2+} molecular dications excited states resulting from the collision. The existence of metastable states with lifetimes ranging from 2 ps to 200 ns is clearly evidenced experimentally through a sequential three-body fragmentation of the dimer, whereas fast dissociation channels are observed in a so-called concerted three-body fragmentation process. The fast fragmentation process leads to a kinetic energy release distribution also observed in collisions with monomer CO targets. This is found in contradiction with the conclusions of a previous study [2] attributing this fast process to the perturbation induced by the neighbor molecular ion.

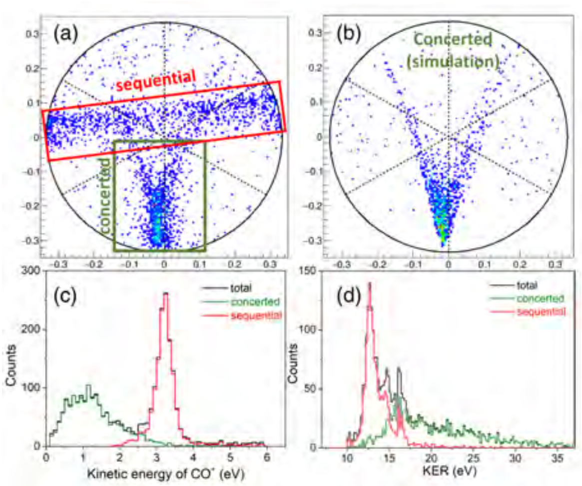

Figure 1: Identification of the concerted and sequential fragmentation processes in $(CO)_2^{3+} \rightarrow CO^+ + C^+ + O^+$ dissociation channel. (a) Dalitz plot of experimental data showing the selection window for concerted and sequential dissociation. (b) Dalitz plot for simulated concerted fragmentation. (c) CO^+ molecular ion kinetic energy for concerted and sequential fragmentation. (d) Total KER of the three-body sequential and concerted fragmentation.

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A30

Alpha Particle Transport Modeling in a Realistic Biological Environment with TILDA-V

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Radiotherapy is nowadays one of the main methods for treating cancers, along with chemotherapy and surgery. In the current work, we focus on internal vectorized radiotherapy that consists in coupling a radionuclide to a biological molecule (vector) able to target tumor cells. Describing the properties of such a radio-element thus becomes challenging in medical physics research. Through Monte Carlo numerical simulations, it may be possible to describe the radiation-induced energy deposits in biological samples. However, in order to correctly simulate particle transport in a given medium, Monte Carlo track structure (MCTS) codes require access to large databases of differential and total cross sections to describe the various interactions induced by the particles in the biological medium irradiated. In this context, we here detail all the models we developed and implemented into our *TILDA-V* code [1] to describe the transport of helium particles in water and DNA components. For modelling the elastic scattering, we used a quantum-mechanical approach to describe the interaction potential between the biological samples and the charged particles, that is implemented into a classical description of the elastic process. For describing the He^{q+}-induced ionization, we developed a CDW-EIS prior model with an effective projectile screening. Finally, semi-empirical models were used to model the other inelastic interactions (capture, excitation and electron loss, see Fig. 1). To check the reliability of the *TILDA-V* code, we provided comparisons with literature in terms of range, stopping power and dose profiles for α-particles. Comparisons with existing data [2,3] exhibited a good agreement.

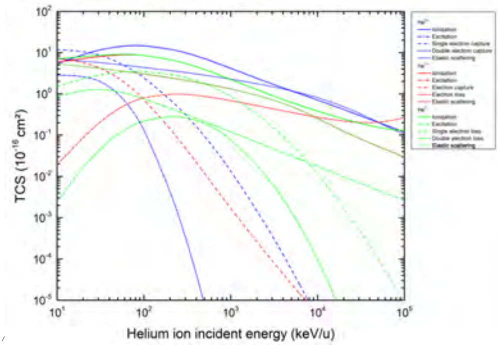

Figure 1: Total cross sections for the different charge states of helium particles in water (He^{2+}: blue; He^{+}: red; He^{0}: green).

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A31

Performance of a keV/u ion spectrometer for the FISIC platform

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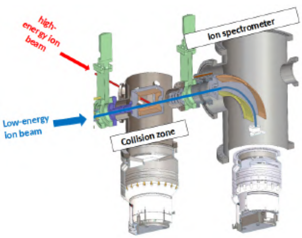
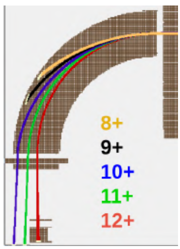
Electronic processes in ion-ion collisions play an important role in astrophysical and fusion plasmas as well as in ion-matter interaction. In the so-called intermediate velocity regime where the ion stopping power is maximum, there is a lack of both experimental and theoretical data on the electronic cross sections. The FISIC set-up is a mobile experiment designed to perform collisions between a slow (keV/u) ion beam coming from the FISIC platform and fast (MeV/u) ion beams, at different facilities. For the first experiments, the FISIC platform will be connected to the CRYRING storage ring at GSI [1]. The FISIC platform is equipped upstream the collision zone with an ECR ion source, a low-energy beam line and an omega-shaped purification system [2], and downstream the collision chamber with a home-made ion spectrometer (Fig 1a). This set-up is inspired by the ion-ion collisions carried in the low velocity regime by the Giessen group [3]. The purpose of the ion spectrometer is to separate the collision products from the main low-energy beam, in view of their detection. It is made of two 90° curved plates to separate the charge states and two Matsuda plates for the focusing of the ion beams. The detection system currently used consists of a Faraday cup to measure the beam intensity, and a position sensitive detector (two MCPs with a delay-line resistive anode) to image the position of the other charge states. Test measurements have been performed at the ARIBE facility (GANIL, Caen). Results compared to numerical simulations carried out by using the SIMION software (Fig 1b) will be presented. Conclusions and possibilities for improvement of the device will be also discussed.



(a) Ion spectrometer located after the collision chamber



(b) Ion trajectory simulations of Ar^{q+} (q from 12 to 8) with an energy of 120 keV.

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A32

X-ray Emission Study Performed for Hydrogen-like Lead Ions at the Electron Cooler of CRYRING@ESR

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The study of x-ray emission associated with radiative recombination (RR) at ultra-cold cooling conditions, as it prevails at electron cooler devices at ion storage rings, allows for a stringent test of atomic structure and the investigation of subsequent x-ray emission characteristics. In particular, for highly charged ions at high Z it enables us to probe in detail the prevalent cascade decay dynamics and gain more insight into the final state population of the recombination process itself.

We report on an experiment where bare lead ions were decelerated down to 10 MeV/u in the ESR storage ring at GSI, Darmstadt and injected into CRYRING@ESR [1] and, subsequently, the x-ray emission of hydrogen-like lead ions were studied at the electron cooler. For this purpose, at the extension part of cooler section dedicated vacuum chambers were used, equipped with beryllium view ports allowing for x-ray detection under 0° and 180° with respect to the ion beam axis. The x-ray detection was accomplished by two high-purity, planar germanium x-ray detectors. In order to suppress the dominant background, stemming from bremsstrahlung caused by cooler electrons and the natural background, an ion detector was operated downstream to the cooler, enabling all x-ray events to be registered in coincidence with down-charged Pb^{81+} ions from electron cooler section.

In this experiment, we observed for the very first time for stored ions the full x-ray emission pattern. Most remarkably, at 0° no line distortion effects due to delayed emission are present in the well-defined spectrum, spanning a wide range of x-ray energies (from about 5 to 100 keV), which enables us to identify fine-structure resolved Lyman, Balmer, and Paschen x-ray lines along with the RR transitions into the K-, L- and M-shell of the ions. To compare with theory, an elaborate theoretical model is established taking into account the initial population distribution via RR for all atomic levels up to Rydberg states with principal quantum number n = 165 in combination with cascade calculations based on time-dependent rate equations. Most notably, this comparison sheds light on the contribution of prompt and delayed x-ray emission to the observed x-ray spectra, originating in particular from Yrast transitions into inner shells.

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A33

First Dielectronic Recombination Measurements at the Cryogenic Storage Ring

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The charge balance in plasmas is governed by competing processes for ionization and recombination. For the understanding and modeling of plasmas in astrophysical environments as well as terrestrial applications, data on the recombination of atomic ions with free electrons are of high importance [1]. Over the past three decades, such recombination processes have been studied extensively in magnetic heavy-ion storage rings by applying the electron-ion merged-beams technique [2]. A challenge of these experiments is the background produced by electron capture from residual gas. Because of the relatively high vacuum pressure of conventional room temperature magnetic storage rings, measurements were restricted to ions with a high charge-to-mass ratio, which could be stored at sufficiently high energies where the rate coefficient for residual-gas-related electron capture drops. Data on low-charged heavy ions are still widely missing.
The electrostatic Cryogenic Storage Ring CSR [3], located at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany, combines the mass-independent storage of electrostatic storage rings with the excellent vacuum conditions provided by its fully-cryogenic beam environment. It is equipped with an electron cooler and a suitable single particle detector. The unique environment of CSR, thus, is promising for the investigation of electron-ion recombination in low-charged heavy ions.
Here, we report on the first recombination studies with atomic ions at CSR. We have investigated dielectronic recombination of Ne^{2+} and Xe^{3+}, where we observed resonant recombination features in agreement with quantum-theoretical predictions. Our results clearly demonstrate the feasibility of atomic recombination studies with heavy low-charged ion species at CSR.

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A34

Micro-Calorimeters as a Universal Tools for High Resolution Energy Dispersive Photon Detection

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Cryogenic micro-calorimeters like the maXs-detectors have proven to be a particularly promising tool for x-ray spectroscopy experiments as they are proposed within the frame of the SPARC collaboration [1]. Due to their measurement principle requiring very low operation temperatures ($< 50\,mK$), they provide an intrinsically high energy resolution ($E/\Delta E_{FWHM} \approx 6000$) comparable to crystal spectrometers [2]. At the same time, their energy resolution is mostly independent of the measured photon energy, therefore making them operable in a broad spectral range of energies ($\approx 0.1 - 100\,keV$). Thus, they combine the advantages of several conventional energy dispersive photon detection methods.

However, to achieve this high level of performance, besides a technically challenging operating setup, the signal readout relies on an almost complete digital signal processing with very few analog stages. Therefore, calorimeters require a complex signal analysis software based upon a detailed understanding of the detector. During the last years, several experiments were conducted at the ion storage rings of GSI/FAIR in Darmstadt where calorimeter detectors have been deployed for high resolution x-ray spectroscopy. The insights gained during these campaigns were used to develop and improve an analysis software API within the frame of this work. Results of the analysis will be presented with the particular focus on experiments performed at the ESR, namely, the study of x-rays produced in collisions of Xe^{54+} projectiles with Xe gas atoms at 50 MeV/u as well as for U^{89+} on N_2 collisions at 76 MeV/u (see fig. 1).

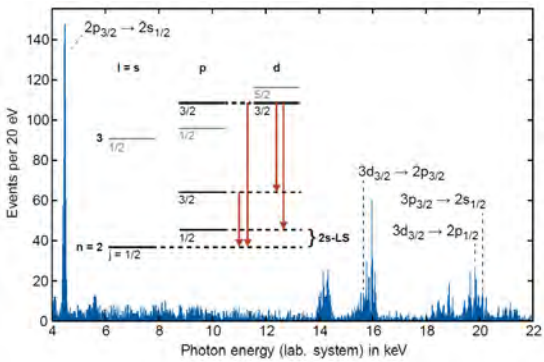

Figure 1: X-ray spectrum recorded by a maXs-30 detector resulting from the collision of U^{89+} ions (76 MeV/u) with a N_2 gas-target in the internal target of the ESR of GSI.

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A35

Experimental Studies of Nonperturbative Dynamics in Heavy-Ion-Atom Collisions

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Experimental data for atomic collisions of highly-charged ions are essential for benchmarking the theoretical description of dynamical processes in atomic physics. Of particular challenge is the accurate description of those processes that exceed the applicability of relativistic first-order perturbation theories. Recently, we have investigated two characteristic cases of such collision systems at the Experimental Storage Ring ESR of the GSI heavy-ion accelerator facility in Darmstadt, Germany:

(1) For fast collisions of U^{89+} projectiles with N_2 and Xe targets at 76 MeV/u, we studied the electron-loss-to-continuum cusp both experimentally and theoretically. We compared the continuum electron spectra of the two collision systems, which originate from the ionization of the projectile, and we were able to identify a clear signature for the nonperturbative character of the collision systems [1].

(2) For slow collisions of Xe^{54+} and Xe^{53+} with a Xe target at 30 and 15 MeV/u, we performed an x-ray spectroscopy experiment focusing on the target $K\alpha$ radiation. Experimental data for such slow symmetric collision systems are important for testing relativistic two-center calculations and provide an intermediate step towards understanding heavy-ion collisions in super-critical fields. We used the target $K\alpha$ satellite and hypersatellite lines to derive cross-section ratios for double-to-single target K-shell vacancy production and compared our experimental results to theory applying a fully relativistic time-dependent two-center approach [2].

At GSI, new prospects of investigating slow Xe^{54+}-Xe collisions under improved conditions will now be facilitates by the low-energy heavy-ion storage-ring CRYRING@ESR. Corresponding experiments are currently being devised.

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A36

High-resolution dielectronic recombination spectroscopy with slow cooled Pb^{78+} ions in the CRYRING@ESR storage ring

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Dielectronic recombination (DR) spectroscopy is a widely used and very successful technique to study the properties of highly charged ions [1–3]. Its high precision and versatility make it an important spectroscopic tool in the physics program of the SPARC collaboration, e.g. outlined in Ref. [4]. The heavy-ion storage ring CRYRING@ESR of the international FAIR facility in Darmstadt is a very attractive machine for performing DR spectroscopy because of its electron cooler that is equipped with an ultra-cold electron beam promising highest experimental resolving power. Here, we report on results from the first DR experiment with highly charged ions at this new facility.

The measured DR spectra of Pb^{78+} in the electron-ion collision energy range of 0–40 eV cover the $2s2p\ (^3P_1)\ 19\ell$ and $2s2p\ (^3P_1)\ 20\ell$ resonances resulting from electron capture of the Be-like core. While the data analysis is still ongoing, the preliminary results show good agreement of relative peak positions and peak strengths with theoretical calculations using the methodology described in Ref. [5]. For kinematic reasons the resolving power is highest at the lowest collision energies. We will exploit this in the future using few-electron heavy ions which exhibit DR resonances at energies below 1 eV.

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A37

Coherent treatment of transfer excitation processes in swift ion-atom collisions

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For more than 40 years since the first ion-atom collision investigations of the two-electron process of electron transfer with excitation (TE) and its resonant (RTE) and non-resonant (NTE) features, a satisfactory quantum mechanical treatment has been lacking. Here, we present the first such comprehensive TE treatment using a three-electron close-coupling approach, exemplified by $C^{4+}(1s^2)$ + He collisions at 0.5-18 MeV impact energies.

We focus on the production of the $C^{3+}(1s2p^2\ ^2D)$ state, which shows the strongest TE resonance amongst the KLL states. Single differential cross sections (SDCS) are experimentally determined using zero-degree Auger projectile spectroscopy (ZAPS), by detecting the emitted Auger electron at $\theta=0^o$ with respect to the beam direction. Our recently proposed "two-spectra measurement" *in situ* technique [1] was applied to separate the $C^{4+}(1s^2)$ ground state contributions from the delivered $C^{4+}(1s^2,\ 1s2s\ ^3S)$ mixed-state beam. Our theoretical treatment considers, for the first time, the dynamics of three active electrons using semiclassical close-coupling calculations within a full configuration interaction approach [2]. This implementation allows for a coupled and coherent treatment of all processes such as target and projectile excitation, ionization, single electron capture [3], as well as TE and therefore goes well beyond past methods.

The calculated single differential cross sections are found to be in excellent agreement with the ZAPS measurements at the high impact energies between 6-18 MeV where RTE is prominent. At the lower energies, 0.5-6 MeV, a second maximum is observed in the theoretical results but could not be recorded experimentally due to low beam currents provided by our facilities in this regime. The low energy structure is interpreted through a new nonresonant correlated mechanism, never considered to date. In the conference, detailed information, such as transition probabilities as a function of impact parameter and energy, will be presented to illustrate the different features of the two mechanisms exposed in our results.

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A38

Classical calculation of ionization, total and state selective electron capture cross sections in collisions between fully stripped ions with ground state hydrogen atoms

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Recently, ionic impurities with nuclear charges $Z \leq 8$ are found in the core of thermonuclear fusion plasmas. These elements are fully ionized because of the high temperature and density in the core. These impurities play a role in the loss of radiant energy that causes the plasma to cool when colliding with the primary plasma components such as neutral hydrogen atoms. Therefore, it is essential to know the interaction between bare ions and hydrogen atoms.
The standard three-body classical trajectory Monte Carlo (CTMC) model is a well-known classical treatment for modelling atomic collisions [1]. But due to the lack of quantum features in the standard model, the CTMC model is not able to describe accurately the cross sections mostly at lower impact energies when the quantum mechanics characteristic is dominant. Therefore we developed a three-body quasi classical trajectory Monte Carlo (QCTMC) model taking into account quantum feature of the collision system, where the Heisenberg correction term is added to the standard classical Hamiltonian of the collision system to mimic the Heisenberg uncertainty principle [2-4]. In this work, we present ionization, total and state selective cross sections in the collisions between bare ions with H(1s). Figure 1 shows the projectile energy dependent ionization and total electron capture cross sections in C^{6+} + H(1s) collisions. We found that our QCTMC results are in good agreement with the previously obtained quantum-mechanical results. Our model with simplicity can time efficiently provide accurate results where maybe the quantum mechanical ones become complicated [5].

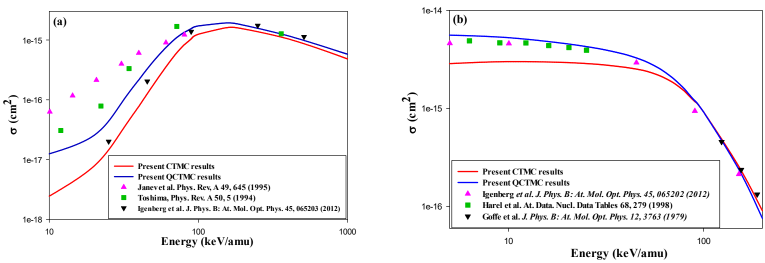

Figure 1: Projectile energy dependent (a) ionization (b) total electron capture cross sections in C^{6+} + H(1s) collisions.

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A39

Interaction of C^{5+} ions with hydrogen atoms

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Collisions between multiply charged ions and atomic hydrogen are important in determining the radiation losses and neutral beam heating efficiencies in tokamak plasmas [1]. In this work a 4-body classical trajectory Monte Carlo (CTMC) and a 4-body quasi-classical Monte Carlo (QCTMC) model of the Kirschbaum and Wilets were used to calculate the cross sections in C^{5+} and H(1s) collisions. We present target ionization and charge exchange cross sections in the projectile energy range between 0.833 keV/amu and 5.833 MeV/amu and compared them with previously obtained results [2]. According to our knowledge, this is the first time to present cross section data using the QCTMC method for this collision system. Figure 1. shows the target ionization cross sections in a collision between C^{5+} ions with H atoms as a function of impact energy. We found that the cross sections obtained by the QCTMC model are higher than that of the cross sections calculated by the standard CTMC model and these cross sections are closer to the previous experimental and theoretical data. Moreover, we also show that the interaction between the projectile and the target electrons plays a dominant role in the enhancement of the cross sections at lower energies.

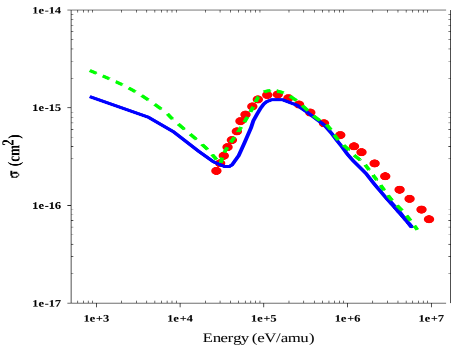

Figure 1: Target ionization cross sections in a collision between C^{5+} ion and H(1s) atom as a function of impact energy. Blue solid line: The present four-body CTMC results [2]. Green dashed line: The present 4-body QCTMC results [2]. Red circles: The 3-body CTMC calculation by R.K. Janev et al. Ref [3].

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A40

Ion-impact induced two-body dissociation of methane dication

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The dissociation of CH_4^{2+} into H^+ and CH_3^+ has been studied using the technique of cold target recoil ion momentum spectroscopy. The methane dication is formed in the interaction of Ar^{9+} and N^{3+} and neutral CH_4 molecules, while keeping ion-molecule interaction time as constant. The recoil ions are detected in coincidence with charge changed projectiles (Ar^{8+} or Ar^{7+} and N^{2+} or N^+) and results on four different data sets are presented. We observe three distinct dissociation pathways for each data set with mean kinetic energy releases of around 4.7 eV, 5.8 eV and 7.9 eV. The electronic states that are populated correspond to electronic configurations $(1t_2)^{-2}$ and $(2a_1)^{-1}(1t_2)^{-1}$ of CH_4^{2+}. We have also been able to estimate the relative branching ratios for the three pathways, and a strong correlation with the specific nature of the ion-molecule interaction is noted.

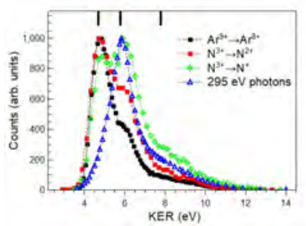

Figure 1: Typical KER spectra measured for two body breakup of methane dication, $CH_4^{2+} \rightarrow H^+ + CH_3^+$. For reference, KER data from a core ionization experiment is also plotted [3]

Existing *ab-initio* calculations [1-3] provide an explanation for the 5.8 eV pathway, and we propose a possible pathway for the 7.9 eV pathway. However, the pathway leading to 4.7 eV remains to be explained [4].

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A41

Electron emission from methane molecule in fast ion impact ionization

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Investigation on ionization of molecules in collisions with fast ions is important in molecular physics and related sciences. Methane (CH_4) is a simpler hydrocarbon molecule which is abundant in earth's atmosphere as well as in the interstellar medium. Also methane works as a reference molecule for larger and complicated hydrocarbons, such as, PAH molecules and bio-molecules etc.

We present electron double differential cross section (DDCS) for ionization of methane in 70 MeV He like Si ion impact. The fast Si ions are obtained from the 14 MV Pelletron accelerator. Measurement is done for the electron energy region of 1-400 eV and at different scattering angles between 20°-160°. Energy distributions and angular distributions of the absolute DDCS are compared with continuum distorted wave-eikonal initial state (CDW-EIS) model using three different target descriptions [Figure 1]. These are the complete neglect of differential orbital (CNDO) approximation and molecular orbital (MO) approximation with bond length, d=0.7 and 1.0. It is shown that the calculation with d=1 matches better with experimental data. The C-KLL Auger peak is observed along with hypersatellite component which appears due to the double K shell vacancy in carbon atom. Double to single ionization ratio is found to be very large i.e. about 37%. Forward-backward ratio of the e-DDCS shows an oscillatory behaviour which is yet to be understood. However, it could possibly arise due to the Young type interference effect from the C-H bond in the molecule. Single differential cross section and total cross section are derived by integrating the DDCS over the energy and scattering angles. Overall we found a very good agreement with the theoretical model.

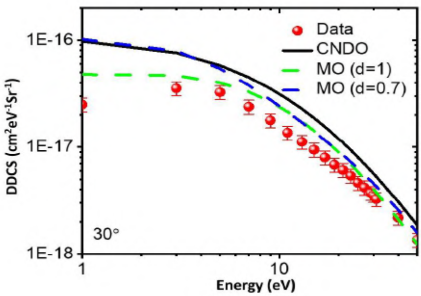

Figure 1: Energy distribution of e-DDCS at scattering angle 30° along with CDW-EIS calculations

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A42

Hydrogen migration in three body fragmentation of acetylene trication

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We report on the three body fragmentation of $[C_2H_2]^{3+}$ into (H^+, C^+, CH^+) fragments in interaction of neutral acetylene with a slow highly charged ion (Xe^{9+} having velocity ≈ 0.5 a.u.). The momenta of all these three fragments were measured in coincidence using the technique of Recoil Ion Momentum Spectroscopy (RIMS). For this particular fragmentation channel, three different dissociation pathways are observed, namely concerted breakup in acetylene configuration, concerted breakup in vinylidene configuration and sequential breakup via $[C_2H]^{2+}$ intermediate molecular ion.

To extract information about the different dissociation pathways, we have used Newton diagram [1] and the method of native frames [2] for analysing the momentum correlations. Figure 1(i) shows the γ - KER_2 distribution generated by using the method of native frames and by assuming $[C_2H]^{2+}$ as an intermediate ion in sequential mode of breakup. KER_2 represents the kinetic energy release associated with the second step of the sequential breakup. The angle between the direction of the first two-body breakup and second two-body breakup in their respective centre-of-mass frames is represented by angle (γ). The uniform distribution observed parallel to the γ - axis is an evidence of a long-lived electronic state of the $[C_2H]^{2+}$ molecular ion. The distribution is divided into two regions A and B based on the value of KER_2 and two separate Newton diagrams are plotted as shown in figure 1(ii) and 1(iii). The semi-circular arc like feature observed in figure 1(ii) is a signature of sequential breakup via $[C_2H]^{2+}$ and the high intensity areas belong to concerted breakup. In figure 1(iii), the angle between the momentum vectors of H^+ and C^+ take two distinct values around 25° and 165°. A low value of this angle corresponds to acetylene configuration and a high value corresponds to vinylidene configuration.

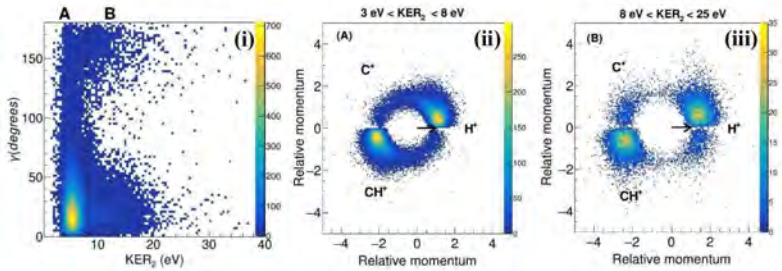

Figure 1: (i) A distribution of KER_2 with γ for all events. (ii) and (iii) shows Newton diagrams for selected values of KER_2 as indicated on the figure (see text for more information).

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A43

Direct observation of molecular oxygen formation due to ion impact-induced molecular fragmentation of carbon dioxide

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The study of molecular fragmentation upon ion impact is important from the viewpoint of underlying fundamental physics, has interests in radiation biology [1], fusion and astrophysical plasmas [2], to name a few. The mentioned experiment was performed with 0.49 au Xe^{10+} ions produced in ECR (Electron Cyclotron Resonance) ion source, this beam was interacted with Supersonically cooled jet of neutral CO_2 molecules inside COLd Target Recoil Ion Momentum Spectrometer (COLTRIMS). These Xe^{10+} ions captured two electrons from the molecule and formed CO_2^{2+} ions in the reaction,

$$Xe^{10+} + CO_2 \rightarrow Xe^{8+} + CO_2^{2+} \rightarrow Xe^{8+} + C^+ + O_2^+$$

C^+ and O_2^+ recoil ions were detected in coincidence with charge state changed projectile ion, with Chevron configured MCP-DLD detector setup.

We also detected other fragmentation channels of CO_2^{2+} ions, but this particular channel is of great importance. After interaction, the newly formed CO_2^{2+} ion starts to bend, and after sufficient bending, a new bond formation between two O species takes place, which results in production of O_2^+. While the dication was formed, it may have formed in an electronic level which supports this bending of the molecule.

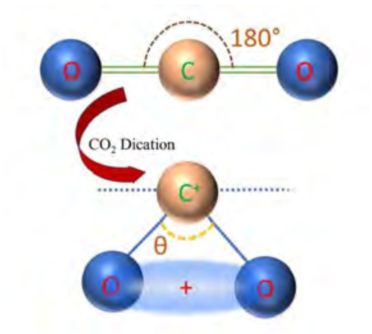

Figure 1: Dynamics of bending of the CO_2^{2+} molecular ion.

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Development of a COLTRIMS setup to study electron transfer processes in highly charged ion-atom/molecule collisions

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We report on the development of a COLd Target Recoil Ion Momentum Spectrometer (COLTRIMS)[1, 2] setup at TIFR, which is built to study various atomic and molecular processes involving the interaction of slow, highly charged ions from an Electron Cyclotron Resonance based Ion Accelerator[3]. We give a detailed description of the experimental setup along with the development of a beam cleaner and a final charge state deflector. We have also present some initial results on the single electron-capture process in collisions of Ar^{8+} ions with He targets. We present the longitudinal momentum transfer and state-selective Q-value spectrum in case of 2, 4, 6 and 25 keV/u Ar^{8+} beam in collisions with He. We also report the state-selective scattering angle distributions for 2, 4, and 6 keV/u collision systems under investigation and explore the effects of dynamical coupling. In the below figure we have shown the two-dimensional momentum density plot for $Ar^{8+}-$He collision system.

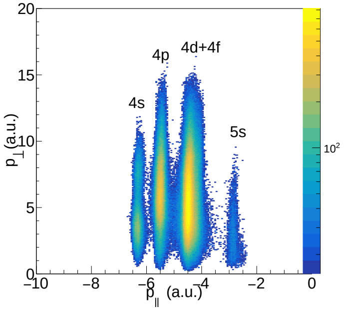

Figure 1: Two dimensional momentum density plot for 2 keV/amu $Ar^{8+}-$He SEC process.

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A45

Electron capture by highly charged ions in collision with water

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In case of low energy ion-molecule collisions, such as keV energy range, the electron capture process dominates over ionization and excitation [1-3]. The strong capture channel has a huge contribution towards the energy-loss of the projectile inside a medium. This is important particularly in estimating the Bragg peak (in keV-MeV energy range) of energy-loss for high energy (GeV) ions which are typically used for hadron therapy. A new experimental setup is developed to study the electron capture processes using highly charged low energy ion beams. Experiments are carried with highly charged ions (C^{4+}) colliding with water molecule in the energy range 100-1300 keV. The incoming C^{4+} beam is collimated by a set of collimators of ID ~1.5 mm and 2.5 mm. Further, the beam is passed through a gas cell (pressure ~0.08 mtorr) where electron capture process occurs. Thereafter, the beam is deflected by an electrostatic deflection plate and finally the original beam is collected in a Faraday cup and beam current is measured by a newly installed femtometer. The beam current is minimized to ~200 fA. A movable beam stopper is also employed before the micro channel plate (MCP) to stop the beam. Capture events are detected using a position sensitive detection system comprising of MCPs and a delay line detector (DLD). In case of C^{4+} beam, one to four e-capture events are observed, which is shown in Figure 1. These e-capture events can be a result of pure capture reactions as well as transfer ionization. Capture cross-section is calculated for one, two, three, and four e-capture events. Total capture cross-section is also calculated and it is found to decrease sharply with the beam energy. Capture ratios such as four e-capture to single capture, three to one capture, and two to one capture are also calculated for different beam energies.

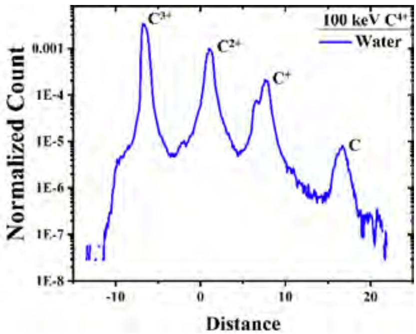

Figure 1: Electron capture spectrum of 100 keV C^{4+} beam in collision with water, which shows one, two, three, and four electron capture.

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A46

Production of high charge state of projectile ions inside the target and its role in electron capture leading to the subshell resolved L shell ionization

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Here in an ultra-thin $_{76}$Os target bombarded by 4-6 Mev/u fluorine ions, the inner shell ionisation mechanism for the L-subshell was investigated. The L X-ray production cross sections of Os were measured using five distinct beam energies of ^{19}F ions with varied charge states q = 6+, 7+, and 8+ in the energy range of 4–6 MeV/u in this study. We have incorporated multiple ionisation effects by adjusting fluorescence and Coster-Kronig yields while evaluating L-subshell ionisation cross sections deduced from production one. However, this isn't enough to get a satisfactory match between theory and experiment. We compared our results to theoretical predictions such as I the relativistic semi-classical approximation (RSCA), (ii) the shell wise local plasma approximation (SLPA), and (ii) the ECUSAR theory. Aside from that, the coupled-states model (CSM) and a standard formalism take care of vacancy sharing among subshells and electron capture (EC). Knowledge of the projectile's charge state "q" inside the target is required to determine the capture cross sections. The Lorentzian charge state distribution was used to calculate projectile charge state fractions inside the target [1]. The Fermi gas model [2] is used to calculate mean charge state inside the target, and the Novicov and Teplova approaches are used to calculate the width [3]. The interplay between electron capture and loss determines the charge state of the projectile ions inside the target. We utilised the Lapicki-Losonsky prescription [4], which is based on the Oppenheimer-Brinkman-Kramers (OBK) approximation [5], to quantify the electron-capture cross sections. Even when recent fluorescence and Coster-Kronig yields are taken into account, it appears that the theory ECUSAR-CSM-EC represents the best excitation function curve among all theories, the theoretical calculations are still roughly a factor of two less than the actual values. Due to a single vacancy, these contradicting observations may raised doubts on the theoretically derived initial atomic properties. When the L1 fluorescence yield is roughly doubled, parameter optimization indicates that experimental findings match theoretical predictions. We support this theory with findings from other studies of proton-induced L-shell ionisation of uranium atoms [6], as presumably, the proton beam does not produce SMI in the target. So that the complication of multiple ionisation is ruled out as a source of complexity. It is apparent that reliable measurements and theoretical computations of atomic characteristics need to be re-evaluated immediately.

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A47

Studying Sn ion collisions with H_2 molecules to advance EUV nanolithography

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Nanolithography machines of the latest generation work with light in the extreme ultraviolet (EUV) regime. This light is generated by a laser-produced plasma (LPP) of Sn. Apart from the EUV photons, the LPP also emits highly-charged Sn ions with up to several tens of keV of energy that may damage plasma-facing surfaces. Therefore, industry uses a buffer gas to slow these ions. The only gas that barely absorbs the EUV light is H_2. Further optimization of this technique by simulations requires accurate atomic data on the energy loss and charge exchange processes in collisions of Sn ions of a specific energy and charge state with H_2 molecules. We are working on obtaining this missing data at the ZERNIKELEIF facility at the University of Groningen where we can generate a beam of Sn ions of a pre-selected energy (keV range), charge state (up to q = 12), and mass (isotope).

We have obtained the single electron capture cross sections for Sn^{3+} on H_2 and on D_2 in the energy range 1-51 keV [1]. We compare our measurements to semi-classical calculations and find good agreement at the higher energies. However the experimental values increase more strongly towards the lower energies. Moreover, we find a substantial isotope effect which is not present in the theoretical models.

We will also present the first energy-loss distributions obtained from our RFA measurements. These measurements will be compared to predictions from the simulation software SRIM and also from a code we have developed ourselves, GIonS. With this code we are able to take the ionic nature of the projectile as well as charge exchange into account.

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A48

Dielectronic recombination in He-like oxygen ions investigated at CRYRING@ESR

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Electron-ion recombination is a fundamental atomic process occurring in plasmas. Accurate experimental recombination cross-sections are particularly important for astrophysical models. Among the recombination processes the dielectronic recombination (DR) process especially affects the dynamics of astrophysical objects [1, 2].

DR is a two-step process. The first step, called dielectronic capture, is essentially the time reversal of the Auger process. This way, an excited state is produced. To complete the DR process a radiative deexcitation takes place in a second step. One should note that autoionization is also a possible deexcitation channel but, in this case, no electron-ion recombination can be observed.

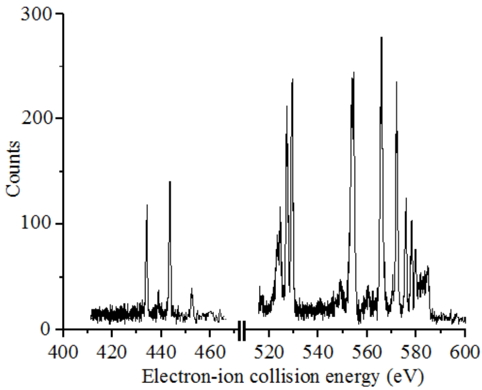

Figure 1: Preliminary results of measured DR resonances of O^{6+} ions at CRYRING@ESR electron

In order to provide the experimental data for both high and low temperature plasmas, DR has been investigated in the *Δn=1* and *Δn=0* regimes, respectively. The data presented in Figure 1 was collected for K-Ln (n=L, M, N, …) DR of He-like oxygen ions. Oxygen is one of the most abundant elements in the Universe and, therefore, is of particular importance [1,2]. The experiment took place at the low-energy storage ring CRYRING@ESR. DR spectra were measured by applying collision spectroscopy of ions merged in a cold electron beam [3]. He-like oxygen ions were passing hundreds of thousands times per second a cold electron beam. This beam was essentially a target, and as a signature for recombination, O^{5+} ions were detected. The resonant condition was achieved by changing the relative electron-ion energy. This high-precision spectroscopy method has been successfully used before [3]. It is of special importance within the research program of the SPARC Collaboration [4].

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A49

Higher-order recombination processes in Argon ions observed via x-ray emission in an EBIT

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The electron-electron interaction is a crucial aspect of atomic reactions involving electron-ion recombination. A good understanding of these processes in the laboratory provides diagnostics tools to determine the physical conditions of plasmas present in astrophysical objects [1]. The most basic recombination process, which involves the electron-electron interaction, is dielectronic recombination (DR) [2, 3]. In this resonant process, a free electron is captured while another bound electron is excited due to the direct interaction between the two electrons. The recombination is completed through radiative stabilization of the excited ion. The research presented here was conducted using an EBIT [4] at Jagiellonian University. The resolution of the x-ray detector enabled the K-LL DR resonances to be distinguished for He- up to O-like Ar ions. In Figure 1, the projection of DR spectra on the electron-energy axis is presented. These results encouraged more detailed studies of trielectronic recombination (TR), specifically KK TR. There, the resonant capture of a free electron to an ion-bound state transfers two K-shell electrons to a higher atomic shell. This way, a doubly-excited K-shell state is produced and, in most cases, decays via emission of two cascade photons. The first electron deexcites to the empty K shell, and thus the hypersatellite transition (K_α^h) occurs by photon emission with energy slightly higher than the second photon. The following photon refers to the satellite transition (K_α^s) when there is only a single vacancy in K-shell. This KK TR process has not been reported yet to the best of our knowledge. This work presents significant arguments for a successful observation of the KK-LMM TR process in Ar ions. Figure 2 presents an observed maximum-like behavior of the K_α^h/K_α^s intensity ratio. Simulation shows the absolute value of background production of the K_α^h/K_α^s intensity ratio.

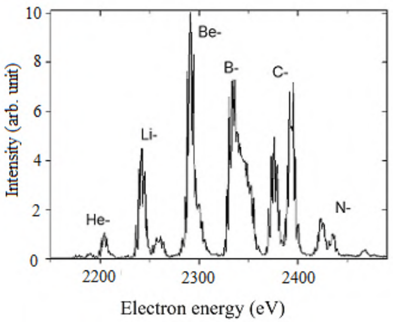

Figure 1. DR spectra with electron-beam energy observed in Ar. K-LL resonances for He- to O-like Ar ions are shown.

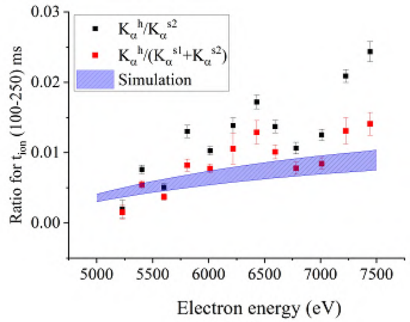

Figure 2. Ratio of Ar hypersatellite to satellite peaks (K_α^h/K_α^s) scanned in the expected KK-LMM TR electron energy range.

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A50

Dynamical benchmark of the metastable line formation in O VII near the collisional excitation threshold

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X-ray measurements of O VII carried out at the FLASH- Electron Beam Ion Trap (EBIT). The decay of the metastable state $1s2s\ ^3\mathrm{S}_1$ population was directly observed (mean lifetime of around $956\ \mu$s in the literature [1]) with an electron beam energy scheme defined by a triangular wave. We observed the He-like dielectronic recombination (DR) KLn structure, as well as resonant excitations (RE) superimposed to collisional excitations (CE) of H-like and He-like ions. A good agreement was found between the experimental results and a preliminary spectrum calculated with Flexible Atomic Code (FAC). A time dependent Collisional Radiative Model (CRM), based on a previous work [2], was implemented to study the physical parameters, in particular to model the spectrum baseline caused by the z-line emissions from the slow decay of the metastable population. This model calculates the population dynamics of each individual energy level, as well as the resulting emissions, based on the the ion-electron collisional processes and decay rates between atomic states. The now benchmarked collisional-excitation cross-sections, which are highly important in astrophysical plasma modeling, are being compared with calculations obtained from Multiconfiguration Dirac-Fock (MCDF) [3], as all as the main atomic databases relevant in astrophysics.

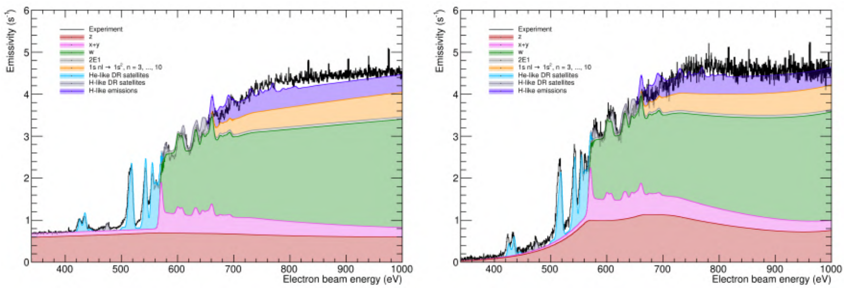

Figure 1: X-ray emission measurements of O VII compared with the time dependent CRM results for a energy scheme period of 1 ms (left) and 20 ms (right).

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A51

Comprehensive laboratory measurements resolving the LMM dieletronic recombination satellite lines in Ne-like Fe XVII ions

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L-shell transitions of highly charged iron dominate the $15 - 18$Å range of the spectra emitted by astrophysical hot plasmas (MK) [1]. Due to its high ionization potential, Fe XVII is a very stable species and its emissions due to dielectronic recombination (DR) can be used as diagnostic tools to evaluate the temperature and electron density of the plasma [2].

We investigate both experimentally and theoretically the DR populating doubly excited configurations 3l3l' (LMM) in Fe XVII, one of the strongest channel for soft x-ray line formation in this ubiquitous species [3]. We used two different electron beam ion traps and two complementary measurement schemes for preparing the Fe XVII samples and evaluating their purity, observing negligible contamination effects [4]. This allowed us to diagnose the electron density in both EBITs. The measurements in one of the traps enabled the direct observation of spectral dynamics due to population time evolution, from which we achieved a good agreement with a charge-state dynamics simulation, performed for the experimental conditions. We compare experimental results from both EBITs with an independent storage ring measurement [5], as well as with configuration-interaction, multiconfiguration Dirac-Fock, and many-body perturbation theories. The latter showed outstanding predictive power in comparison with the combined independent experimental results. From these, we also inferred DR rate coefficients, which unveiled discrepancies with widely atomic databases.

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A52

State-selective cross sections for electron capture and excitation in Be^{4+} + H(*2s*) collisions at intermediate energies.

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Collisions between multiply charged ions and hydrogen atoms are relevant in tokamak plasmas. In particular, collisions with Be ions are of special interest because Be is a plasma facing material of tokamaks. On the other hand, excited hydrogen is produced in the plasma and state-selective cross sections between Be^{q+} ions and H needed in charge-exchange recombination spectroscopy (CXRS) diagnostics [1,2].

We have employed two computational models to study Be^{4+} + H(*2s*) collisions: the classical trajectory Monte Carlo (CTMC) method, with two different initial distributions to describe the H(*2s*) target, and the numerical solution of the time-dependent Schrödinger equation (GTDSE) [3]. We have computed integral *n* and *nl* partial cross sections for H excitation and electron capture and, compared the results at two energies: 20 and 100 keV/u. We find a good agreement in the *n* partial cross sections in both processes, illustrated in Figure 1. The *nl* partial electron capture cross sections exhibit a similar behavior while the agreement is less satisfactory in the *nl* partial excitation cross sections. We suggest a mechanism of the excitation process in ion collisions with H(2s) that will be discussed at the Conference.

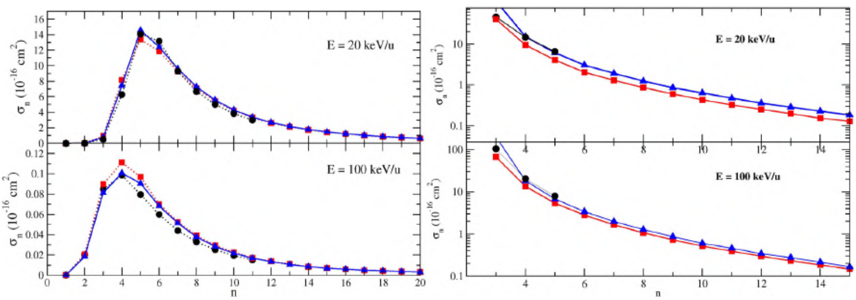

Figure 1: Integral *n* partial cross sections for electron capture (left panel) and for excitation (right panel) in Be^{4+} + H(*2s*) collisions at E= 20 and 100 keV/u. (- ● -) GTDSE; (- ■ -) microcanonical-CTMC and (- ▲ -) hydrogenic-CTMC calculations.

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A53

First observation of giant quadrupole plasmon resonance in C_{60} in high perturbation HCI collisions

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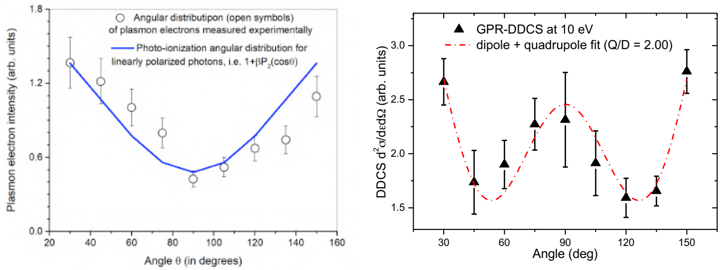
We give a classic example of using high perturbation caused by HCIs to explore new mechanisms in ion collisions with a nano-particle namely C_{60}-fullerene. The collective plasmon excitation mode known as the GPR (giant plasmon resonance), where the entire delocalised valence-electron cloud of C_{60} oscillates collectively about the ionic shell, has been well-studied using photo-excitation, electron-impact and ion-impact excitation [1-3]. A direct observation of the dipole mode of the GPR has been reported earlier [3] by using F^{9+} ions (q=9, v~12.7 a.u) for which angular distribution reveals a parabolic shape, characteric of dipole-nature [Fig 1(a)] We have now measured the double differential cross section (DDCS) at even higher perturbation (q/v) i.e. in collisions with 91 MeV Si^{12+} ions (q=12, v~11.4 a.u). The DDCS spectrum at low energy indicates a quadrupole plasmon resonances (GQPR) in addition to the dipole plasmon (GDPR). The measured DDCS angular distribution at low energies (around 7-8 eV) reveal a double valley structure [Fig 1(b)] which is characteristic of quadrupole resonance. The elegant technique of using high perturbation collision allows us to identify the characteristic GQPR mechanism. We have unambiguously identified the dipole and quadrupole modes by using state-of-the-art TDDFT calculations[6]. This is the first such unambiguous experimental demonstration of the quadrupole excitation in atomic system[6].



(a) (b)

Figure 1: Angular distribution of plasmon-electrons from C_{60} under fast-ion collisions: (a) Projectile: F^{9+} (4MeV/u, v=12.7)[3], (b) Si^{12+} (3.2MeV/u, v=11.4)

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A54

Transformation of amorphous alloy surface under impact of slow heavy ions

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Amorphous alloys, far from thermodynamic equilibrium, undergo stress relaxation and partial crystallization if some amount of energy is supplied [1–2]. This transformations under a single ion impact is related to thresholds, either in the potential energy, 10 keV deposited by slow highly charged ion (HCI) or in electronic energy loss, 5 keV/nm transferred by swift heavy ion (SHI) [1]. The transfer of energy results in local increase of internal energy followed by structural and/or magnetic phase transformations.

In this work thin foils of amorphous alloys of $Fe_{73}Si_{16}B_7Cu_1Nb_3$ were irradiated with 200 keV Ar ions at doses varying from 1010 to 1013Ar/cm2. The process of selective surface modification during implantation were in-situ monitored with PIXE and it was shown that elements like Cu, and probably Fe, are preferentially sputtered from the surface, thus enriching it with remaining elements, like Nb, Si or B [2]. This change of surface composition influences on parallel running local structural modification of the surface due to delivery of crystallization energy to electron-ion system. With the use of *ex-situ* conversion electrons Mossbauer spectroscopy (CEMS) and transmission electron microscopy (TEM), Fe and Fe(Si) clusters accompanied by Fe_3Si and even $Fe_{23}B_6$ nano-crystals were spotted in the samples irradiated at lower Ar fluence, whereas rather amorphous structures can be found in samples more heavily implanted with Ar.

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A55

Theoretical model of the nanohillock formation by an impact of slow highly charged ions on the metal surface

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Highly charged ions impinging upon a solid surface modify its structure inducing the formation of the nanostructures such as hillocks, craters, pits, etc. Theoretical studies of surface nanostructure creation are of fundamental importance for the understanding of the mechanism responsible for surface modification. For this purpose we propose a theoretical model of the nanohillock formation on the metal nanolayers (gold and titanium) by an impact of the slow highly charged Xe^{Z+} (charge $Z \gg 1$) ions. We employ the quantum two-state vector model and the micro staircase model for the neutralization energy calculation and the charge dependent ion-atom interaction model for the nuclear stopping power calculation. The corresponding energies deposit into the surface during the ionic motion above and below the surface, respectively [1]. The contribution of these two energies in the surface nanostructure creation is described by the critical ionic velocity [1]: for velocities lower than the critical one, the neutralization energy has the main influence and an appearance of the hillocks is expected, while for the larger velocities the deposited kinetic energy has a dominant effect and surface structures are craters.

Within the proposed theoretical model we analyze the size of the surface nanohillocks as velocity dependent quantity. According to the model, the total deposited energy(consisted of the neutralization energy and the deposited kinetic energy), induces the decreasing of the initial cohesive energy in the active volume area of the target in the intermediate stages of the surface modification [2]. That is, during the nanohillock formation the decreasing of the atomic density and the binding energy (per atom) of the target compared to these values of the unmodified metal surface occur. The diameters of the nanohillocks are obtained for a given degree of the target modification. We estimate the target perturbation in accord with the diameters of the hillocks observed experimentally [3] by the impact of Xe^{Z+} ions upon the titanium and the gold targets.

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A56

Electron binding energy calculations for high-precision determination of absolute atomic masses

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The Heidelberg PENTATRAP experiment can measure the mass of highly charged ions with extraordinary accuracy [1]. This allows us to determine the absolute mass of the corresponding neutral atoms by adding up the total mass of the ionized electrons as well as their binding energies. While the mass of the electron has been measured with an accuracy to the level of μeV, the binding energies are only known with an accuracy of several hundred eV. In this contribution, we combine the multi-configuration Dirac–Hartree–Fock method and relativistic configuration interactions [2] to calculate the binding energies with sub-10 eV accuracy. This would 1) improve the relative accuracy of the absolute mass of various heavy elements around ^{208}Pb to the level of 10^{-11} [3], 2) have applications in direct measurement of neutrino mass [1] as well as constraining the conjectured fifth force [4].

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A57

Inferring the coherence time of EUV pulse trains via spectroscopy of highly charged ions

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Coherent extreme-ultraviolet (EUV) pulse trains are produced via intra-cavity high-harmonic generations of high-intensity infrared pulse trains. They represent well-defined EUV frequency combs that can enable high-precision spectroscopy of specific EUV transitions in highly charged ions (HCIs) with a relative accuracy to the level of $\delta\omega/\omega = 10^{-17}$. In return, such ionic spectroscopy can also provide information of the temporal coherence of the EUV frequency combs at timescales ranging from nanosecond to several seconds.

In this contribution, we present a scheme to interrogate the EUV-comb coherence time via interactions with highly charged Mg-like ions [1]. The excitation dynamics are simulated [2] for ions interacting with EUV pulse trains of various temporal coherences. We show that while all EUV pulse trains induce stepwise excitation of HCIs at the beginning of the interactions, the ionic excitations undergo chaotic fluctuations when the coupling time becomes longer than the comb coherence time. These investigations indicate that one can achieve coherent control of HCIs via current available EUV pulse trains and enable quantum optics studies in the EUV range.

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A58

Elastic x-ray scattering by highly charged ions

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The elastic scattering of x-rays by atoms and highly charged ions is one of the fundamental processes in the interaction of radiation with matter. Over the past few years, increasing attention has been paid to the study of the properties of scattered photons. In particular, the linear polarization of the outgoing radiation was measured in a recent experiment at the PETRA III synchrotron facility at DESY in Hamburg [1]. This experiment demonstrated that by analyzing the polarization of the scattered light, one can obtain information not only about the atomic structure of the target atoms, but also about the polarization of the incident synchrotron radiation. In our poster, we study the polarization properties of elastically scattered x-rays by highly charged ions and neutral atoms. We illustrate how the polarization of incident x-rays can be determined only with the polarization of scattered photons, without any need for the theoretical scattering amplitudes [2]. Moreover, we explore how the interference between Rayleigh and Delbrück scattering may affect the polarization properties of the outgoing radiation.

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A59

Long-gap laboratory atmospheric discharge

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Despite in the nature a lightning is a relatively frequent and common phenomenon, in its physics there are still “white places”. At present it seems to be established that the high-energy effects are caused by runaway electrons. Formerly, all X-ray effects were attributed to thunderclouds with large scale electric fields. But Moore et al. in 2001 and Dwyer et al. in 2005 detected emission of energetic radiation from rocket-triggered, as well as from natural lightning. Due to these measurements it seems to be proved that vast majority of negative leaders emit hard X-rays and hence produce runaway electrons. For air at standard conditions, relativistic electrons with energies below several tens of MeV lose energy predominantly via ionization and excitation processes; for higher energies, the energy losses from bremsstrahlung become important as well.
Our motivation is the study of long-gap laboratory high-voltage discharges in air at atmospheric pressure which it helps to elucidate some processes appearing in lightning and in this way to contribute to safety of air traffic, sensitive electronics, and to protection of human health. The basic features of lightning are already known: the runaway electrons are generated and due to that even X-rays are emitted. It turns out that moment of their birth is reasonably well known, however, the spatial localization as well as the instantaneous local environment are a little bit vague and should be improved. Sufficiently energetic X-rays initiate photonuclear reactions: from atmospheric nuclei fast neutrons are released, unstable isotopes are created that transform further to stable ones at simultaneous birth and later annihilation of positrons.
In this work we present results from experiment with long-gap laboratory discharge at atmospheric pressure. After designing and assembling apparatus, the device was electrically tested for a short circuit to detect weak regions. Basic measurements of voltage (based on capacitor-resistor divider) and current (by Pearson current monitor) were re-calibrated. After that experiments with longer discharges (with length from 30 to 50 cm) were performed. All discharges were observed optically by photocamera with/without neutral density filter. For most of the experiment, measurements of both neutrons (in the first phase using a BDT bubble detector) and X-rays were performed using two detectors: a BICRON BC408 plastic scintillator (sensitive to X-rays with energy <100 keV) and a Saint-Gobain LaBr3:Ce photomultiplier (X-rays with energy <10 MeV). For spatial resolution, an X-ray pinhole camera was designed and constructed: consisting of a filter, a pinhole chamber and a registration plate. Then an attempt was made to stabilize the primary-leader´s head position by inducing there a disturbance, the source of which will be well separated from the spark. The development of a long spark discharge at atmospheric pressure in an inhomogeneous environment with an injected "plasmoid" (i.e. an aerosol cloud, which is formed during a short discharge on the surface of a conductive liquid (e.g. salt water). However, notwithstanding the fact that the inter-electrode distance has been extended to 60 cm, it appears that no hard X-ray emission is detected in the region of the discharge current maximum, which would be indicative of runaway electron generation.

Acknowledgement
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A60

Measurement of ion-induced desorption yields for accelerator vacuum

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The outgassing due to ion induced desorption is a severe intensity limitation in modern accelerators. It is produced when an ion beam impacts on a solid target leading to the release of gas molecules trapped over and inside the material. In accelerators, the targets are mainly the wall of vacuum vessels, the beam dumps and slits, mostly made in stainless steel, copper or tungsten. The number of particles removed by incident ion (named the desorption yield, η) can vary from one to several thousand depending on the beam energy and the nature of the irradiated material. Consequently, the pressure may drastically increase by one or two orders of magnitude with respect to the base pressure affecting strongly the transmission of the ion beam [1, 2, 3].
The surface quality of the material that may be irradiated is a key parameter to reduce significantly the desorption yield. In the context of the development of accelerators (GSI/FAIR, CERN, GANIL/SPIRAL2), we have studied the impact on the desorption yield of different surface treatments on samples of stainless steel, copper and tungsten. Samples with various treatments such as chemical attacks, annealing or beam conditioning have been bombarded with 4.8 MeV/u Ca^{19+} or Ca^{10+} ions delivered by the UNILAC accelerator at GSI. Absolute values of the desorption yield have been measured to evaluate the best treatment. Thanks to a calibrated Residual Gas Analyser, the evolution of the partial pressures of released gas (CO_2, CO, H_2 or others) under irradiation have been obtained. Additionally, the scrubbing effect that corresponds to the cleaning of the surface by the beam itself (Figure 1) has been investigated.

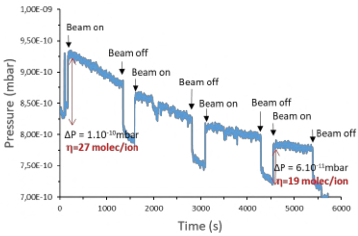

Figure 1: Scrubbing effect on Cu sample with a 4.8 MeV/uma Ca^{19+} ion beam.

Description of the experimental setup, the different methods of measurements and the results will be presented at the conference.

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A61

Tank-Circuit Assisted Coupling Method for Sympathetic Laser Cooling of Highly charged ions in Penning Traps

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Penning traps have been proven as a versatile tool for fundamental physics. A multitude of high-precision measurements have been performed at Penning trap facilities, such as measurements of atomic masses and magnetic moments or *g*-factors of elementary particles [1]. Recently, by confining highly charged ions (HCIs) in Penning traps it provides a unique system to probe atomic properties and to test Quantum electrodynamics (QED) in strong electric field [2]. In a cryogenic penning trap, the motional temperature of ions is thermalized with a cryogenic superconducting tank circuit at 4.2 K. Owing to the particle oscillation amplitude, the accuracy of frequency determinations is limited by systematic uncertainties caused by anharmonicities arising from field imperfections and eventually special relativity. In *g*-factor measurements, a lower particle temperature furthermore decreases axial frequency fluctuations and thus helps to achieve higher fidelity of the spin state determination, which is specifically crucial for heavy ions with a comparably small magnetic moment. To reduce the ion temperature into the millikelvin regime, sympathetic cooling is a common method in rf traps. However, the co-trapping of different ions leads to drastic modifications of the motion of the ion of interest via the Coulomb interaction in penning traps. To solve the Coulomb disturbance, a cooling technique proposed by Heinzen and Wineland in 1990 is based on the coupling of two species in separate traps that share a common endcap electrode [3]. This way, the ions can interact via their image charges induced into the shared endcap electrode. However, with realistic trap parameters the coupling strength is too small to achieve highly efficient sympathetic cooling.

Here, we present a new coupling technique for two ion species in separate traps via a common superconducting tank circuit which can significantly enhance the coupling strength [4]. At ALPHATRAP this tank-circuit assisted coupling of two HCIs are investigated by observing the resulting avoided crossing of the coupled frequencies. The determined coupling strength is a factor of 760 larger than the method of common endcap coupling. Furthermore, we propose an intermittent laser cooling method for highly efficient sympathetic cooling. The numerical simulations show the possibilities of sympathetic cooling of arbitrary types of ions to the millikelvin regime within reasonable cooling times.

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A superconducting quadrupole resonator for laser-spectroscopy of highly charged ions at highest precision

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Highly charged ions are excellent candidates for novel optical frequency standards [1] and quantum algorithms [2], since they are very unsusceptible to electromagnetic noise due to the suppression of e.g. the quadratic Zemann shift scaling with Z^{-4}[1]. However, gaining quantum control over the motional modes of cold HCI had been a challenge for the last decades since they lack of fast cycling transitions for laser cooling. Quantum logic spectroscopy of the M1 transition in Ar^{13+} which was sympathetically cooled by a single Be^{+} logic ion lowered the uncertainty by eight orders of magnitude to about 10^{-15} opening a branch for new frequency standards in near future [3]. Complementing these new types of optical clocks, a cryogenic Paul trap experiment with a quasi-monolithic superconducting quadrupole resonator with a high operating quality factor of about 30000 [4] was developed at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany to challenge some of the resulting issues: Due to the high fidelity of the radio-frequency resonance at about 35 MHz, radial mode heating of the HCI is strongly suppressed. Furthermore, the trapped ions are shielded inside the cavity due to the Meissner-Ochsenfeld effect from electromagnetic noise, reducing decoherence effects and therefore increasing interrogation times of the HCI. We will present the features of this resonator and provide first characterizations with re-trapped HCI.

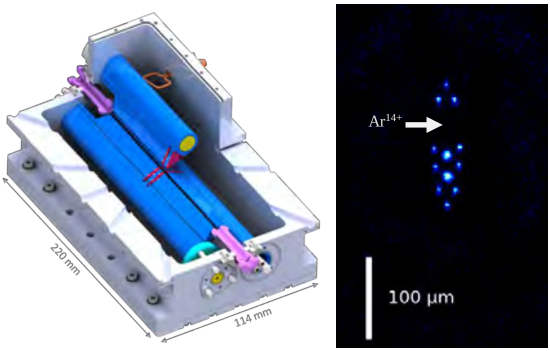

Figure 1: Left: Sliced view of the superconducting quadrupole resonator. Right: Single, crystallized Ar^{14+} trapped and sympathetically cooled beryllium ions inside it.

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Dynamics of mixed species Coulomb crystals with highly charged ions in a superconducting Paul trap

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The CryPTEx-SC project at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, is designed to perform precise spectroscopy of highly charged ions (HCIs), which are excellent candidates for the development of next-generation atomic clocks and sensitive probes in the search for new physics [1]. The spectroscopy trap is formed by merging a linear Paul trap with a superconducting radio-frequency resonator, providing ultralow-noise radial confining potentials [2]. Control and read-out of HCIs will be implemented using quantum logic spectroscopy with co-trapped Be^+ ions.

We present results from the first cold highly charged ions stored in our ion trap. After production of the HCIs in an electron beam ion trap (EBIT), they are extracted in pulses into an electrostatic beamline where they are decelerated and bunched. The HCIs are then captured in and sympathetically cooled by a Coulomb crystal of several dozen laser-cooled Be^+ ions trapped in the Paul trap beforehand. Subsequent controlled removal of Be^+ ions by exciting secular motion is used to prepare mixed species ion crystals comprising various numbers of Be^+ ions and HCIs, down to a single HCI with a single Be^+ ion, the prerequisite for quantum logic spectroscopy.

The flexible retrapping technique will be discussed, which opens up the extensive range of highly charged ion species to precision studies and additionally allows to explore the dynamics of mixed species Coulomb crystals consisting of ions with disparate charge-to-mass ratios.

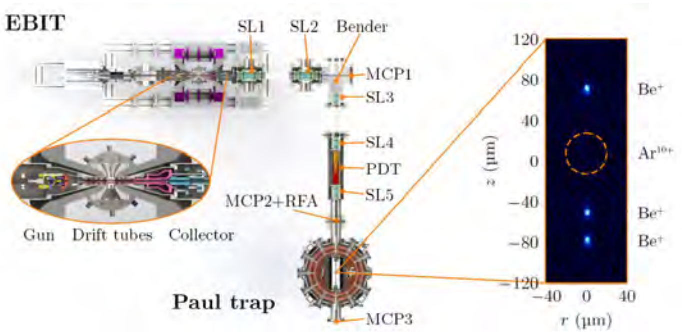

Figure 1: Overview of producing HCIs in an electron beam ion trap, transferring through a beamline and retrapping in a superconducting resonator Paul trap with example EMCCD image of a mixed species Coulomb crystal comprising three $^9Be^+$ ions and one $^{40}Ar^{10+}$ ion.

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Sympathetic cooling of highly charged ions in a Penning trap using a self-cooled electron plasma

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The amazing evolution of precision in recent Penning-trap experiments is driving the need for ever-improving cooling techniques. In this talk, the prospect of a new sympathetic cooling technique using an electron-plasma coupled to a single highly charged ion is presented. Utilizing the synchrotron-radiation of electrons in a strong magnetic field enables cooling to very low motional quantum numbers, almost to their ground state. Using a common-resonator, the motion of this self-cooled electron plasma can be coupled to an ion stored in a spatially separated Penning trap, allowing sympathetic cooling of all modes of the ion. The extremely low expected temperatures in the milllikelvin range open up an exciting new frontier of measurements in Penning traps.

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First broadband laser cooling and XUV fluorescence detection of stored relativistic HCI

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At the highly relativistic energies and high intensities of the ion beams in the new SIS100 accelerator at FAIR, conventional beam cooling techniques (*e.g.* electron and stochastic cooling) have some limitations and laser cooling is a more elaborate and efficient method for cooling. Despite one specific requirement, *i.e.* the need for a fast electronic transition in the ions, at the SIS100 many different ions (element & charge state) can be laser-cooled, owing to the large magnetic rigidity of the SIS100 (max. 100 Tm). Importantly, the use of new pulsed (rep. rate ~MHz) and tunable CW laser systems (UV and VIS wavelengths) will greatly enlarge and enhance the potential of this cooling method. However, the much higher beam energies at the SIS100 also require new approaches for *in vacuo* detection of the fluorescence emitted by the ions, as it is required for laser spectroscopy and laser cooling.

In May 2021, an improved XUV fluorescence detection system and a new tunable pulsed UV laser system were employed for laser cooling of bunched relativistic (47% of c) carbon ions at the Experimental Storage Ring of GSI Helmholtzzentrum Darmstadt, Germany. Successful broadband laser cooling was demonstrated using this powerful (~200 mW), high repetition rate (~10 MHz) and tunable (wavelength and pulse duration) UV laser system. The experiment and its results will be discussed.

In addition, we will present our new fluorescence detection and spectroscopy system for the laser cooling project at the upcoming SIS100 accelerator. The new dispersed flourescence detection system uses an aberration corrected laminar grating in grazing incidence geometry and an open face micro-channel plates detector in Chevron stack configuration (sensitive in the soft X-Ray regime) with postion and time sensitive delay-line readout. If no energy resolution is required, the system can also be used for direct detection of the fluorescence photons with a significantly larger acceptance.

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Simultaneous storage of ions and electrons in the HITRAP cooling trap

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The HITRAP decelerator facility at the GSI Helmholtzzentrum für Schwerionenforschung in Germany aims to decelerate and cool heavy, highly-charged ions (HCI) like U^{92+} [1]. After generating the high charge states at relativistic energies, HITRAP decelerates these ions via a linear deceleration stage and a cylindrical Penning trap. Within this 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 cooling trap is sympathetic cooling with a cold electron plasma. Therefore, the ions and electrons are stored simultaneously in a nested trap configuration. While the electrons constantly lose energy in the high magnetic field through synchrotron radiation, the hot ions lose energy by Coulomb interaction with the cold plasma. If the ion energy approaches the eV-regime, the electron plasma has to be ejected to prevent recombination.
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. After optimization of the local pulsed electron source we manage to produce up to 2x10^9 electrons per pulse. These pulses can be trapped by quickly switching the trap electrodes. Using the retarding field method when ejecting electrons onto a microchannel plate (MCP), it is possible to measure the energy loss due to synchrotron radiation and the space charge of the trapped electron cloud.
Besides the local electron source, HITRAP is also equipped with a small EBIT ion source for commissioning of the cooling trap. This EBIT with permanent magnets can generate different ions with medium or high charge states (e.g. Ar^{16+}) which can be transported through a low energy beamline towards the cooling trap [2]. We achieved simultaneous storage of these EBIT ions and electrons from the local source. In these experiments it has been found that the ions influence the co-trapped electrons, but so far no energy loss of the ions could be observed.
The next step is the enhancement of the ion-electron interaction and demonstration of electron cooling. This can for example be done by optimizing the injection settings or varying the ion and electron number. Furthermore, employment of non-destructive detection methods can help to further analyze the interaction.
This work is supported by BMBF under contract number 05P19RDFAA.

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Commissioning of the HITRAP cooling trap with offline ions

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The HITRAP facility at the GSI Helmholtzzentrum für Schwerionenforschung (GSI) in Germany 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 various cooling mechanisms such as electron cooling and resistive 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 [2].
We present the current status of the HITRAP cooling trap and the next steps of commissioning this setup with offline ions as well as the preparation for the next online beam time. So far a newly designed Penning trap has been commissioned and tested. The new, seven-electrode trap design is more stable and less error prone than the previous version with 21 electrodes.
We were able to investigate the storage of argon ions in various charge states, delivered by a small EBIT based on permanent magnets with an energy of 4 keV/q. Dependencies of the charge state and kinetic energy on the lifetime of the stored ions were observed. The successful manipulation of the kinetic energy of the ions, both trapped and ejected, was achieved by applying an offset potential on all trap electrodes. By ejecting the ion cloud after short storage times of a few µs, we also managed to determine the magnetron frequency of the stored ion cloud and its dependency on the trap settings. Moreover, for the first time it was possible to store ions and electrons simultaneously in the HITRAP cooling trap, although no cooling effect was observed so far.
The next steps will be the improvement of the trap settings for both electrons and ions and the proof of electron cooling. This includes the cooling of argon ions from the local ion source and commissioning the trap setup for the first time in a GSI beam time with bare ^{58}Ni. One of the main challenges during this beam time will be the separation of high energy and low energy beam as the linear decelerator stage of the HITRAP facility will only decelerate parts of the incoming 4 MeV/u beam down to the desired energy of 6 keV/u [3]. As the separation by time of flight is not possible, a new detector unit will be installed. This detector will deflect the low energy beam to an off-axis MCP detector in order to measure and optimize beam transfer towards the trap.
This work is supported by BMBF under contract number 05P19RDFAA.

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Resonant photoexcitation of trapped ions for x-ray astrophysics

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Spectroscopic observations in the UV and X-ray bands with the newest generation of high-resolution instruments onboard current and future satellite observatories have the potential to reveal previously inaccessible details of processes in astrophysical plasmas, such as the ones in galaxy clusters and active galactic nuclei. This is essential for advancing our understanding of extreme environments and the evolution of the universe.

However, what can be reconstructed from spectra is currently limited by the availability and quality of atomic data, on which plasma models are built. That is especially the case for highly charged ions (HCI), ubiquitous in hot astrophysical plasmas [1]. For many years, electron beam ion traps (EBITs) have been valuable tools for laboratory measurements with HCI, providing a wide range of atomic data, like transtion energies and rates of ionization and recombination processes.

Here, work with the novel compact PolarX-EBIT [2], based on permanent magnets, is presented, in which radiation from ultrabrilliant UV and X-ray synchrotron light sources is used to resonantly excite electronic transitions in trapped HCI. Subsequent fluorescence and changes of ion charge state are detected, which allows to gather spectroscopic data under well-controlled conditions with unprecedented resolving powers and signal-to-noise ratios. This yields atomic data valuable not only for astrophysics but also for benchmarking general atomic structure theory [3].

One such case are the two 2p-3d transitions in Ne-like Fe^{16+}, commonly labelled 3C and 3D, for which measurements and calculations of oscillator strengths seemed to disagree significantly [4], until our recent experiments uncovered previously unaccounted-for contributions to the observed intensities [5].

Furthermore, the unique off-axis electron gun of PolarX-EBIT facilitates new experimental setups, in which electronic transitions in few-electron HCI are used as accurate and reproducible wave-length references [6].

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Recent experimental and computational results on one dimensional colliding laser-produced plasmas

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In the experiment, a time-resolved ICCD camera was deployed to capture the flow behaviour of two counter-propagating laser-produced plasmas (LPPs) collimated by two face-to-face channels, which makes the plasmas close to one dimensional (1-D). Figure 1 shows the early stage of the formation of the so-called stagnation layer between the two channelled plasmas. At this stage, the plasma gathering at the collision point between the two plasmas can be clearly observed.

For interpreting and predicting the experimental results, we have built a collection of 1-D fluid modelling code based on [1] and [2] with the ambipolar electric field and collision coupling considered. Applying the code to colliding LPPs, it predicts an instant shock happens with a huge leap in plasma temperature and density when the LPPs start colliding, which is the beginning of the stagnation layer formation that is observed in these experiments. The shock may be utilized to create x-ray sources from colliding plasmas, possibly with a significant boost in the conversion efficiency from incident laser power to x-ray radiation and the stagnation layers have the potential to be used as the second target for dual-laser extreme ultraviolet sources [3].

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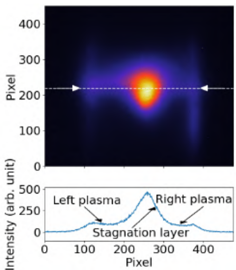

Figure 1: Upper: Stagnation layer created between two channelled colliding plasmas. White arrows show the directions of movement of the two channelled plasmas. Lower: Spatial intensity distribution along the white dash line.

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A70

Laser Produced Plasmas for Atomic Physics and Applications.

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The spectra of plasmas produced by focusing the output of high powered lasers, typically Nd:YAG lasers with pulse lengths of a few nanoseconds, on to higher Z solid elements are quasi continuous [1]. These plasmas can be used for absorption experiments to study low charge state ions present in a second laser produced plasma [2] and have potential as laboratory scale soft x-ray sources [3].

Applications involving high spatial resolution or high spectral resolution measurement typically have a photon throughput limitation where either a small region needs to be illuminated for imaging or a small slit illuminated for energy selection, and this small area bottleneck leads to very low system etendue ($<10^{-2}$ mm^{2}mrad^2). Since radiance is at best conserved in an optical system, and it is given by the photon flux divided by the etendue, these low etendue systems require a high radiance source to deliver sufficient photons to the application.

This work focuses on the development of laboratory scale soft x-ray sources (specifically in the water window between the wavelengths of 2.3 and 4.4 nm). The water window is of especial significance for applications targeted at the illumination of biological samples. Water is transparent to these x-rays, but carbon and therefore organic molecules are absorbing. The resulting transmission of water window soft x-ray photons allows for imaging of unstained, cryofixed, biological cells.

The objective is to produce sources with a brilliance up to two orders of magnitude higher than the state of the art, comparable to those achieved at bending magnets of large-scale synchrotron facilities, which will enable technological developments and scientific studies that are not presently possible on laboratory scales.

Higher radiance can be achieved by reducing the emitting area and one recent focus has been the drive to reduce the x-ray emitting area to dimensions of the order of 10μm^2. The work so far has proven that it is feasible to produce plasmas of this diameter with a relatively high conversion efficiency into the water window.

This work is supported by Science Foundation Ireland through a Frontiers for the Future Programme Award (19/FFP/6795).

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High resolution imaging of laser plasmas revealing the effects of laser spot size on plasma emission

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Laser plasmas can produce a high flux of soft x-ray radiation from a small volume, making them ideal for illumination for applications such as in EUV nano-lithography [1] and in cell imaging via soft x-ray microscopy [2].

In order to investigate the effects of the focal spot size on the plasma shape and intensity, a molybdenum target was irradiated with a Nd:YaG 1064nm driving laser. Images of the subsequently formed plasmas were generated using a 5µm pinhole which images soft x-rays through a 1µm Al filter onto a soft x-ray camera with a pixel size of 2.4µm and the imaging axis parallel to the target and perpendicular to the laser. The filter transmission combined with the camera quantum efficiency produces images in the 0.5nm to 3nm region. Such images were produced with laser energies ranging from 20mJ to 271mJ with several laser focus spot sizes.

The plasma images were simulated using a skewed pseudo-Voigt profile combined with regression techniques to generate noise reduced plasma images. The resulting areas and shapes (the ratio of the plasma widths parallel and perpendicular to the target measured through the centre of a plasma iamge) of the simulated plasma images were measured as demonstrated in Fig 1.

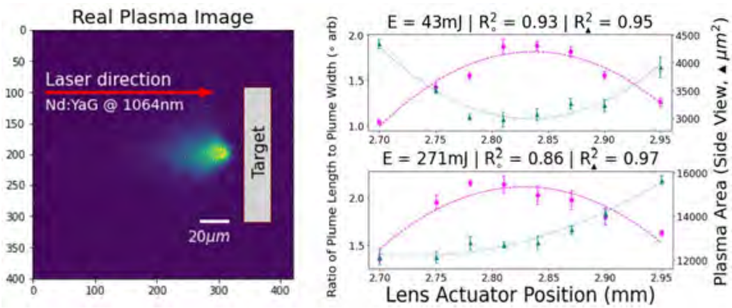

Fig 1: Left: Real plasma image with schematic target drawn. Right: Demonstration of the change in plasma area and plume shape (the ratio of the plume width perpendicular to the target and width parallel to the target) as a function of lens position fro two labelled energies.

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High-Performance X-ray Imaging Spectrometers with Ti/Au Superconducting Transition-Edge Sensor Microcalorimeter Arrays

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X-ray transition-edge sensor (TES) microcalorimeters are cryogenic non-dispersive spectrometers inhering a broad dynamic range, high quantum efficiency and most importantly a high spectral resolving power which is potentially competitive to dispersive instruments. The Athena space X-ray observatory to be launched in 2034 led by ESA will carry a large array consisting of 2376 TES microcalorimeters on the focal plane of the X-ray Integral Field Unit (X-IFU) to explore the hot and energetic universe, taking full advantage of the high energy resolution and the imaging capability. At SRON we are developing the focal plane assembly for X-IFU, and also TES detector arrays as a back-up option in the framework of a European technology development program. Our TES detectors are based on a Ti/Au superconducting thin film of which critical temperature is tuned around 90 mK. The temperature sensing elements are coupled to overhanging Au/Bi X-ray absorbers, providing quantum efficiency of 95% up to 7 keV with a pixel filling factor of 96% over the arrays. We have fabricated and tested various detector chips with 64 and 1024 TES pixels to cultivate a better understanding of how to control the properties of our detectors. We now constantly measure ~2 eV full-width at half-maximum energy resolution for 5.9 keV X-rays, encouraging realization of the full-sized TES array for the X-IFU instrument. Furthermore, the fundamental characteristics of our well-performing detectors would be potentially suitable for laboratory experiments on the physics of highly charged ions in combination with electron beam ion trap instruments and synchrotron facilities for examples. In this contribution, we will give an overview of the characteristics and capabilities of these state-of-the-art detectors.

A73

Review of recent developments in MaMFIS technology

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The standard Electron-Beam Ion Source (EBIS) employs smooth electron beam for the successive ionization of atomic targets (neutral elements and low charged ions) [1]. The highest electron current density, which is a prerequisite for the production of highly charged ions, can be attained only in the case of the Brillouin focusing. The ion extraction from the ionization region is carried out by varying the potentials on different sections of the drift tube.

In the Main Magnetic Focus Ion Source (MaMFIS), highly charged ions are produced and confined in local ion traps, which appear in crossovers of the rippled electron beam propagating in a drift tube [2,3]. The electron beam is focused by a thick magnetic lens. In a crossover, the Brillouin limit is not justified and the electron current density can exceed it by orders of magnitude. The devices are very compact and reliably operate at room temperature due to the use of permanent magnets and standard vacuum techniques. The ion extraction from the MaMFIS can be performed by means of transformation of the shape of electron beam controlled by the bias voltage on the focusing (Wehnelt) electrode, so that the local ion traps are shifted to the electron collector region. Highly charged ions can also be extracted from the local ion trap in the radial direction perpendicular to the electron beam by varying the potential applied to the extractor electrode [2]. One more possibility to extract ions confined in the local ion traps can be realized by using the EBIS technology at certain drift tube diameter-to-length ratio, electron trajectories, and extraction voltage [4].

The electron current density has been assessed indirectly through the measurement of ionization time and the utmost achievable charge state of the produced highly charged ions. The degree of ionization is determined from the high-energy part of the characteristic X-ray emission spectrum corresponding to the radiative recombination of highly charged ions with beam electrons. The most recent studies were performed in Veksler and Baldin Laboratory of High Energy Physics at the Joint Institute for Nuclear Research in Dubna. The results obtained for different elements (iridium, cerium, xenon, and bismuth) are consistent with the electron current density of the order of 10 kA/cm^2. The MaMFIS technology allows one to significantly reduce the confinement time required for an efficient ionization of bound inner-shell electrons. This is of particular importance both for heavy elements and for very short-lived radionuclides.

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A74

Theoretical study of electron-ion resonant recombination process of Si^{10+} ion

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Silicon is the eighth-most abundant element in the solar system, accurate atomic data of highly charged silicon ions are required to identify spectral lines, and derive ion abundances of solar plasma [1]. Recently, Orban et al [2] measured the rate coefficients of electron-ion resonant recombination process for Δn =0 (2s-2p) transition of Si^{10+} ions at the CRYRING electron-cooler. Bernhardt et al [3] performed a new measurement of rate coefficients for Δn = 0 and Δn = 1, 2 ($2s\rightarrow 3l$, $4l$) transitions of Si^{10+}-Si^{9+} ions at the TSR heavy-ion storage ring in MPIK. However, theoretical calculations are scarce. In this work, we systematically investigated the *L*-shell Δn =1, 2 processes of Si^{10+} ions in the ground state ($2s^2\ ^1S_0$) and metastable state ($2s2p\ ^3P_0$), found that contribution of the metastable state is not be ignored. The following reactions are considered

$$Si^{10+}(2s^2)+e^- \rightarrow \begin{cases} \left[Si^{9+}\left((2s+2p)3lnl'\right)\right]^{**} \rightarrow \left[Si^{9+}\right]^{*} + h\nu \ (\Delta n=1\ DR+TR) & (a) \\ \left[Si^{9+}\left((2s+2p)4lnl'\right)\right]^{**} \rightarrow \left[Si^{9+}\right]^{*} + h\nu \ (\Delta n=2 DR+TR) & (b) \end{cases} \tag{1}$$

We performed detailed calculations for resonance energies, resonance strengths, and state-state resolved cross sections in the isolated resonance approximation using the FAC code[4]. The strong configuration mixing among the dielectronic recombination (DR) and trielectronic recombination (TR) channels are considered, which show fewer influence on resonance energies, and a great influence on resonance strengths. The rate coefficients are obtained by convoluting the calculated cross sections with the experimental electron energy distribution $kT_{//}$=0.093 meV and $kT_{\perp}$= 0.5 eV, and compared with the TSR measurements [3], excellent agreements are obtained (see Fig.1).

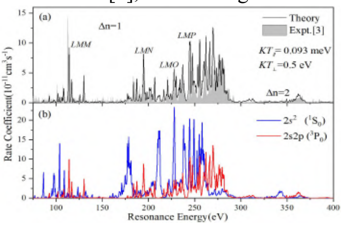

Figure 1: (a) The total theoretical rate coefficient (black curves) with considering the contributions of the ground state $2s^2\ ^1S_0$ (93%) and $2s2p\ ^3P_0$ (7%), compared to the TSR experimental results [3] (gray area). (b) the individual theoretical rate coefficient for Si^{10+} ions in the ground state $1s^22s^2\ ^1S_0$ (red line) and metastable state $1s^22s2p\ ^3P_0$ (blue line), respectively.

The work was supported by the National Key Research and Development Program of China under Grant No. 2017YFA0402300, the NSFC (Grants No. 12064041, No. 11874051)

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A75

Theoretical investigation of dielectronic recombination processes of highly charged gold ions

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Dielectronic recombination (DR) is a prominent resonant recombination process in collisions of electrons with highly charged ions (HCIs) [1]. Gold is one of the particular interest work material in the indirect laser drive of inertial confinement fusion (ICF). Accurate atomic data of highly ionized gold ions are essential and important for modelling gold hohlraum-produced plasma [2-3].
In this study, the DR process of Ne-like to Si-like gold ions (Au^{69+}-Au^{65+}) are investigated. The resonance energies, resonance strengths and cross sections are carefully calculated for L-shell Δn = 1 transitions using the FAC code based on fully relativistic configuration interaction (RCI) method [4]. Using the density matrix formular, the degree of linear polarizations of x-ray dielectronic satellite lines produced by dominant LMM, LMN DR processes are calculated, and used to obtain the differential cross section of Au^{69+}-Au^{65+} ions. Figure 1 illustrated our calculated synthesized LMM DR spectra of gold ions located at 2.6-5.6 keV energy regions, and compared with the experimental measurements of electron beam ion trap at Lawrence Livermore National Laboratory by Schneider et al [3]. Our theoretical results show an excellent agreement with the experimental values.

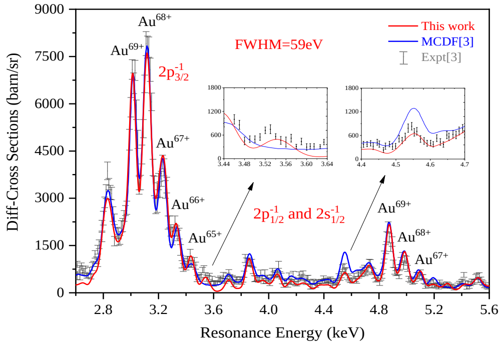

Figure 1: The calculated synthesized LMM DR spectra of Au^{69+}-Au^{65+} ions in the ground states compared to the EBIT experimental measurements [3]. The separate contributions from the different ionization stages of 41% Ne-like, 30% Na-like, 18% Mg-like, 4% Al-like and 7% Si-like target ions are considered in the calculations.

The work was supported by the National Key Research and Development Program of China under Grant No.2017YFA0402300), the Natural Science Foundation of China (Grant Nos: 12064041,11874051), doctoral research fund of Lanzhou City University (LZCU-BS2019-50).

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POSTERS B

B01

Analysis of E3 transitions in Ag-like high-Z ions observed with the NIST EBIT

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Measurements and analyses of forbidden lines in highly charged ions provide invaluable information on diverse effects including quantum-electrodynamic and relativistic effects in atomic structure as well as offer new diagnostic techniques for very hot plasmas. Recently, Sakaue et al [1] reported on observation of electric-octupole (E3) spectral lines in Ag-like W^{27+} using the compact electron beam ion trap (EBIT). The well-resolved $4f_{7/2,5/2}$-5s transitions were recorded in the extreme ultraviolet (EUV) spectrum. Using the HULLAC atomic code, the authors of Ref. [1] showed that the E3 lines are strongly enhanced for W and developed an advanced collisional-radiative model which predicts E3 line intensities for the other members of the isoelectronic sequence.

In this work we report on measurements and identifications of the E3 $4f_{7/2,5/2}$-5s transitions in W and other high-Z elements including Re (Z=75), Os (Z=76), and Ir (Z=77). The EUV spectra were recorded with the NIST EBIT using a grazing-incidence EUV spectrometer. The present higher resolution results for W and GRASP2K calculations strongly confirm the Ref. [1] findings. Our collisional-radiative model developed with the NOMAD and FAC codes offers a deep insight into the population kinetics for Ag-like ions of heavy elements. The simulation allowed the identification of new spectral lines in the spectra. We will present a detailed discussion of the observed spectra and comparisons of the measured and simulated line intensities.

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B02

Precision measurements of the $^2P_{1/2}$-$^2P_{3/2}$ fine-structure splitting in Boron-like S^{11+} and Cl^{12+} at EBIT

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Precision measurements of the fine-structure splitting of highly charged ions (HCIs) test fundamental atomic theory, including strong field quantum electrodynamics (QED) effects, electron correlation effects, and relativistic and nuclear effects. The fine-structure splitting $1s^22s^22p$ $^2P_{1/2}$-$^2P_{3/2}$ transitions in boron-like S^{11+} and Cl^{12+} were experimentally measured with a high precision spectrometer at the Shanghai high-temperature superconducting electron beam ion trap [1]. The M1 transition wavelengths for S^{11+} and Cl^{12+} were determined to be 760.9635(29) and 574.1539(26) nm (in air), respectively. Compared to the previously observed results, the accuracies of current experimental results are improved by more than ten times and 200 times for S^{11+} and Cl^{12+}, respectively. Additionally, the M1 transition energies in S^{11+} and Cl^{12+} were evaluated within the ab initio QED framework to compare with the experimental data. The present experimental results agree with the theoretical calculations and provide a possibility to test QED effects and correlation effects with high accuracy in few-electron highly charged ions. The details can be found in Ref. [2].

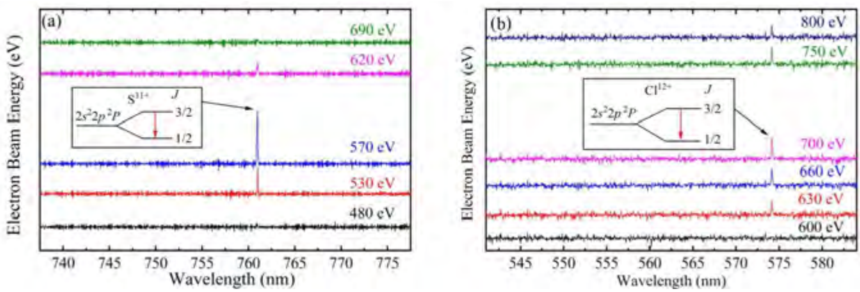

Figure 1: (a) Spectra of sulfur obtained at the SH-HtscEBIT with nominal electron beam energies of 480, 530, 570, 620, and 690 eV in the range 737–777 nm. The line is the M1 transition between the fine-structure levels in the 2s22p 2P ground term of boronlike S^{11+}. (b) Spectra of chlorine with nominal electron beam energies of 600, 630, 660, 700, 750, and 800 eV. The line is the M1 transition between the fine-structure levels in the 2s22p 2p ground term of boron-like Cl^{12+}.

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B03

Measurement and analysis of EUV emission spectrum from laser produced Zn plasma

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Highly charged ions of znic (Zn) element exist widely in astrophysical plasmas. The atomic data and parameters of plasma can be obtained by studying the spectra of these ions. In this work, the spectra from a laser-produced Zn plasma have been investigated using spatio-temporally resolved spectroscopy.

An emission spectrum of laser-produced Zn plasma in 7-14 nm wavelength region is shown in Figure 1 (a), and it is dominated by three intense banded peaks. In order to explain the structure of the spectra, the atomic structure parameters of highly charged ions of Zn are calculated using the Cowan suites of Hartree-Fock configuration interaction codes. It is found that these intense banded peaks attributed to the 3d-4f transition arrays of Zn^{6+} up to Zn^{9+} ions, as shown in Figure 1 (b).

In order to further explain the spectral structure, simulated spectra are obtained by statistical summation of atomic data and population information. Population information are calculated by the assumption of a normalized Boltzmann distribution among the excited states and a steady-state collisional-radiative model. A simulated spectrum with electron temperature $T_e = 20\ eV$ and electron density $N_e = 1.46 \times 10^{20} cm^{-1}$ are plotted in Figure 2 (a). It can be found the simulated spectrum is in good agreement with the experimental spectrum in the long wavelength region, and the dominant fractional contributions arise from Zn^{6+} and Zn^{7+} ions. However, the spectra (Figure 2 (b)) are in good agreement in the short wavelength region and Zn^{7+} and Zn^{8+} ions are predominant as $T_e = 25\ eV$ and $N_e = 1.69 \times 10^{20} cm^{-1}$. This work can provide reference for similar spectral analysis.

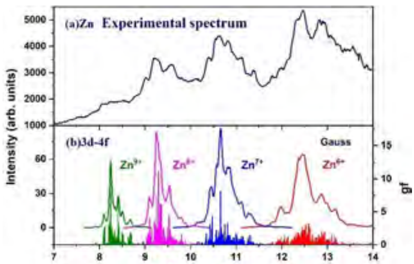

Figure 1: The line distributions of 3d−4f transition arrays of Zn^{6+} to Zn^{9+}.

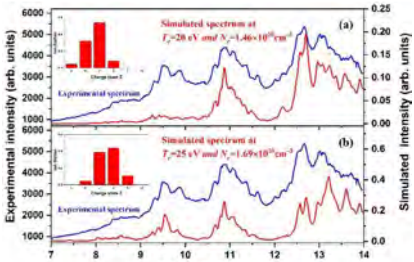

Figure 2: Comparisons between the experimental spectrum and simulated spectra.

The work is supported by the National Key Research and Development Program of China (2017YFA0402300), the Natural Science Foundation of China (11874051,11904293, 61965015).

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B04

Theoretical investigation of dielectronic recombination processes of highly charged gold ions

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In this study, the DR process of Ne-like to Si-like gold ions (Au^{69+}-Au^{65+}) are investigated. The resonance energies, resonance strengths and cross sections are carefully calculated for L-shell Δn = 1 transitions using the FAC code based on fully relativistic configuration interaction (RCI) method [4]. Using the density matrix formular, the degree of linear polarizations of x-ray dielectronic satellite lines produced by dominant LMM, LMN DR processes are calculated, and used to obtain the differential cross section of Au^{69+}-Au^{65+} ions. Figure 1 illustrated our calculated synthesized LMM DR spectra of gold ions located at 2.6-5.6 keV energy regions, and compared with the experimental measurements of electron beam ion trap at Lawrence Livermore National Laboratory by Schneider et al [3]. Our theoretical results show an excellent agreement with the experimental values.

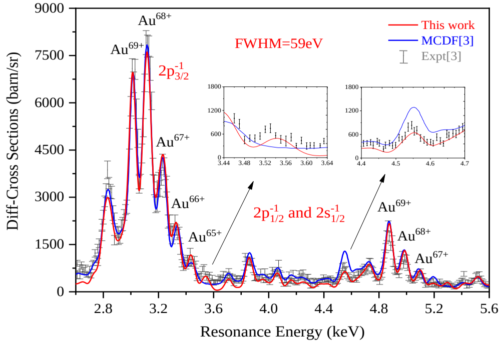

Figure 1: The calculated synthesized LMM DR spectra of Au^{69+}-Au^{65+} ions in the ground states compared to the EBIT experimental measurements [3]. The separate contributions from the different ionization stages of 41% Ne-like, 30% Na-like, 18% Mg-like, 4% Al-like and 7% Si-like target ions are considered in the calculations.

The work was supported by the National Key Research and Development Program of China under Grant No.2017YFA0402300), the Natural Science Foundation of China (Grant Nos: 12064041,11874051), doctoral research fund of Lanzhou City University (LZCU-BS2019-50).

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B05

Optical Spectroscopy of Ru^{21+}-Ru^{24+} Ions

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Spectroscopy of highly charged ions is of great interest in the diagnosis of plasma, and also in the studies of atomic physics, e.g., detection of electron correlation effects. Due to the complex structure of an open 3d-subshell, accurate atomic structure calculation of $3d^n$ configuration is still a challenge. In this work, optical spectroscopies of highly charged Ru^{21+}-Ru^{24+} ions are studied in a permanent magnet electron beam ion trap (EBIT). The charge state distribution of the Ru ions in the EBIT is analyzed for line identifications, as shown in Fig. 1. With the assistance of the large scale multi-configuration Dirac-Hartree-Fock calculations [1], more than ten new dipole forbidden lines are recognized, which could be used as reference data for further atomic structure calculations.

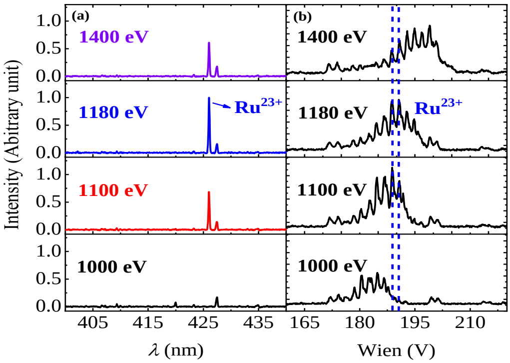

Figure 1: (a) Electron beam energy dependence of the Ru^{23+} spectra, (b) the corresponding charge state distributions.

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B06

EUV spectra of laser-produced Cu Plasmas

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The research on the radiation characteristics and dynamic evolution of laser-produced plasma (LPP) has always been a very interesting topic in the fields of atomic physics and plasma physics. Cu is one of the most concerned elements in the field of celestial bodies and fusion research. Studying the spectra of Cu plasma is very helpful for astrophysical plasma diagnosis. In this work, the time-evolving EUV spectra in the range of 8-14 nm are obtained using the spatio-temporal resolved laser-produced Cu plasma emission spectrum measurement method.

The spectral line distribution characteristics of Cu^{5+}-Cu^{9+} ($3p^6 3d^n$, n=2-6) ions from 3p and 3d transition arrays are analyzed based on Hartree-Fock configuration interaction method[1] and the normalized Boltzmann distribution. Figure 1 shows one of experimental spectrums and the theoretical spectrum of Cu^{5+}-Cu^{9+} ions under the electron temperature of 25 eV. It can be found that the theoretical peak position of each ion is in good agreement with the experimental peak position, and the spectral profile is also in good agreement.

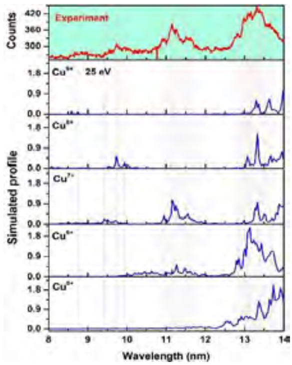

Figure 1. Comparison between experimental spectrum and theoretical spectra of Cu^{5+}-Cu^{9+} ions

This work is supported by the National Natural Science Foundation of China (11874051、12064040,11864036), the Science and technology project of Gansu Province (No. 21JR7RA122).

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B07

First Laboratory Verification of Magnetic-field-induced Transition Effect in Fe X

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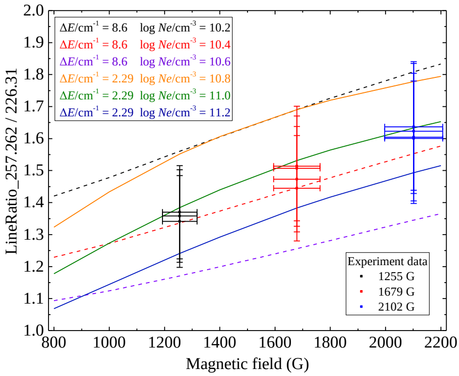
The magnetic field is extremely important for understanding the properties of the solar corona. However, there are still difficulties in the direct measurement of coronal magnetic fields. The discovery of the magnetic-field-induced transition (MIT) in Fe X, which was also observed in the coronal spectra, opened up a new method for measuring the coronal magnetic field. In this work, we obtained the Fe X extreme ultraviolet (EUV) spectra in the wavelength range of 174–267 Å in Shanghai high-temperature superconducting electron beam ion trap, and for the first time, verified the effect of MIT in Fe X by measuring the line ratios between 257.262 Å and reference line of 226.31 Å (257/226) at different magnetic field strengths. The plasma electron density that may affect the 257/226 value was also obtained experimentally and then verified by comparing the density-sensitive line ratios with the theoretical prediction, and there was good agreement between them. By comparing the simulated line ratios of 257/226 with the experimental values at given electron densities and magnetic fields, the critical energy splitting of the fine-structure levels, one of the most critical parameters to determine the MIT transition rate, was obtained. Possible reasons which may lead to the difference between the obtained energy splitting and the recommended value in previous work are discussed. Magnetic field response curves for the 257/226 value were calculated and compared to the experimental results, which is necessary for future MIT diagnostics.



Theoretical and experimental values of line ratios of 257.262 Å and 226.31 Å versus the magnetic field

B08

Towards Doppler-assisted precision laser spectroscopy of highly charged ions at the CSRe

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The combination of the storage ring CSRe and advanced laser has proven to be an excellent research platform for atomic physics of highly charged ions (HCIs) [1]. By accelerating stored ions, the ultra-short transition wavelength in HCIs can be Doppler-shifted into a convenient region, where laser light is readily available and thus making laser spectroscopy possible. There are two planned techniques to launch precision laser spectroscopy experiments at the CSRe, as shown in Fig. 1(a):

(i) Laser spectroscopy with fluorescence spectrum. An optical detector, as displayed in Fig. 1(b), has been developed for fluorescence photons detection. It is featuring a SiC-made parabolic reflector with a central slit and an MCP coated with CsI, enables a high-efficiency detection of the UV photons without affecting the normal operation of the ion beams in the ring, and the collection efficiency is improved by more than 50 times as compared to the previously installed photon detector [2].

(ii) Laser spectroscopy with Schottky spectrum [3]. Schottky resonator enables a non-destructively measurement of the revolution frequency of the ion beam with comparable precision. By resonating excitation of stored ions with a cw laser combined with ion velocity measurement, determined by the e-cooler voltage, allows a precise measurement of the transition wavelength. The determination of the $^2S_{1/2}$-$^2P_{1/2}$ transition of O^{5+} ions by using the Schottky spectrum in Fig. 1(c) and the related uncertainties analysis, including e-cooler voltage calibration, space charge effects, angular deviation, etc., are under investigation. Both the development of the optical detector and the investigation of Schottky spectrum method for the laser spectroscopy experiments at the CSRe are in progress.

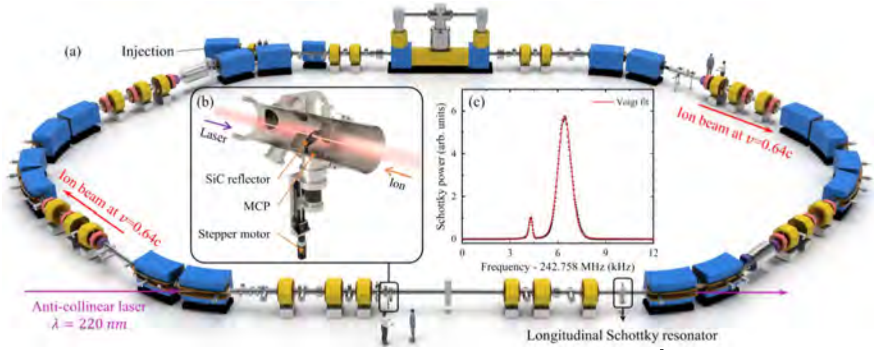

Fig. 1: (a) Schematic of the laser spectroscopy experiment of Li-like O^{5+} ions at the CSRe. (b) 3D model of the optical detector. (c) Experimental Schottky spectrum of the cw laser interaction with the coasting ion beam under electron cooling.

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B09

Re-investigation and line identifications for W^{11+} in the visible range

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We present a new investigation of unidentified emission lines in 350–660 nm from W^{11+} at a compact electron-beam ion trap in Shanghai [1]. To help the line identification, transition energies of the lowest 48 levels are calculated by the large-scale relativistic configuration interaction and multiconfiguration Dirac-Hartree-Fock calculation [2–4]. The results from the two calculations are in good agreement with each other and the deviation is 0.66% on average. By using the collisional-radiative model implemented in the flexible atomic code, six observed lines for the visible spectrum of W^{11+} are identified as magnetic-dipole transitions from $4f^{12}5s^25p^3$ and $4f^{13}5s^25p^2$ configurations.

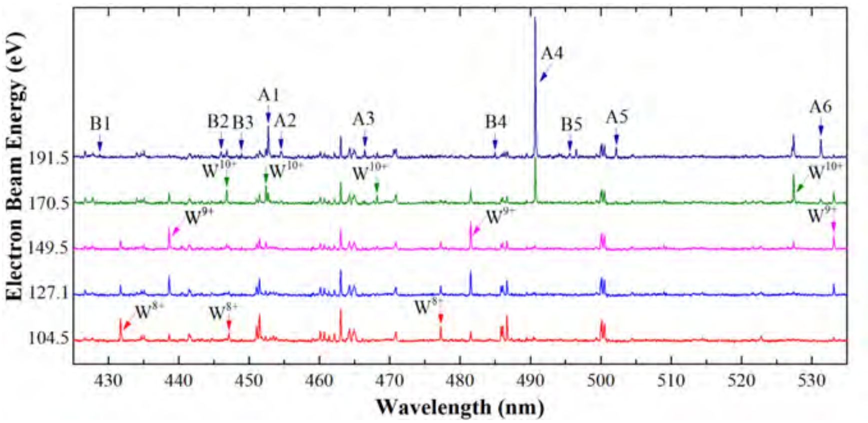

Figure 1: Spectra obtained at the SH-HtscEBIT

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B10

Dielectronic recombination for Na-like Kr^{25+} from the CSRm to the CSRe

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Storage rings equipped with electron cooling devices provide a uniquely effective technique to determine the absolute DR rate coefficients for highly charged ions. The DR experiment for Na-like Kr^{25+} in the energy range of 0-70 eV has been performed successfully at the storage ring CSRm [1]. At the beginning of 2020, the electron cooler at the CSRe has been upgraded with an embedded electron energy fast detuning system, which can support a much broader detuning energy range (±15 kV) and allow us to extend the DR spectroscopy from the CSRm to the CSRe. Therefore, more experimental candidate ions can be available at the CSRe via the stripping and selection processes in the second Radioactive Ion Beam Line (RIBLL-2) located between the CSRm and the CSRe. To evaluate the performance of the newly built experimental platform at the CSRe, we have also carried out the DR measurement of Na-like Kr^{25+} ions therein. Fig. 1 (Left) presents the comparison between the DR spectra for Kr^{25+} measured at the CSRm and the CSRe. Fig. 1 (Right) presents the details of the DR rate coefficients for Kr^{25+} measured at the CSRe within the electron-ion collision energy range of 0-150 eV, which encompass all the Δn=0 ($3s \to 3p$, $3d$) DR resonances. The experimental result was also compared with the FAC calculation, and a good agreement was achieved by considering the strong mixing among the low-energy resonances associated with 3→3 and 3→4 core excitations in the theoretical calculation. The present result demonstrates the reliability and stability for future DR spectroscopy studies at the CSRe.

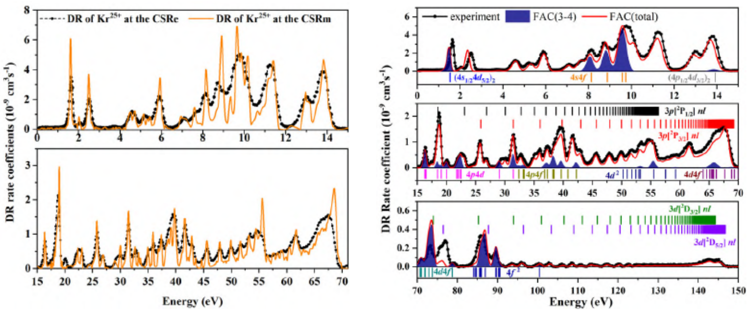

Figure 1: (Left) The comparison of the DR spectra for Na-like Kr^{25+} measured at the storage ring CSRm (Orange solid curve) and the CSRe (black dotted circles). (Right) The experimental DR rate spectrum at the CSRe. The red solid line depicts the FAC calculated total DR rate coefficients and the blue areas are the contribution from the Δn=1 DR resonances. The vertical marks indicate the resonance positions calculated by FAC calculation (Δn=1) and Rydberg formula (Δn=0).

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B11

Precision spectroscopy of 2s2p $^1P_1 \rightarrow 2s^2\ ^1S_0$ in Beryllium-like Cl^{13+} at EBIT

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Precision measurement experiment of electric-dipole transition between the 2s2p $^1P_1$ and $2s^2\ ^1S_0$ in beryllium-like Cl^{13+} have been performed in Shanghai High-Temperature Superconducting electron beam ion trap (SH-HtscEBIT) [1]. Using a portable high resolution soft x-ray and extreme ultraviolet (EUV) spectrometer [2] for spectral measurement of the extreme ultraviolet region. The E1 transition wavelength was preliminarily determined to be 237.66(2) Å (in vacuum) with an accuracy of 85 ppm at electron beam energies of 1000, 1030, 1050 and 1080 eV, respectively (as show in figure 1). It is possible to test atomic structure theoretical calculations including quantum electrodynamic (QED) effects and relativistic effects in few-electrons highly charged ions. In particular, the beryllium-like ions are very suitable for the study of electron-electron correlation effects because of the two strongly correlated 2s electrons [3]. Subsequent results are being prepared.

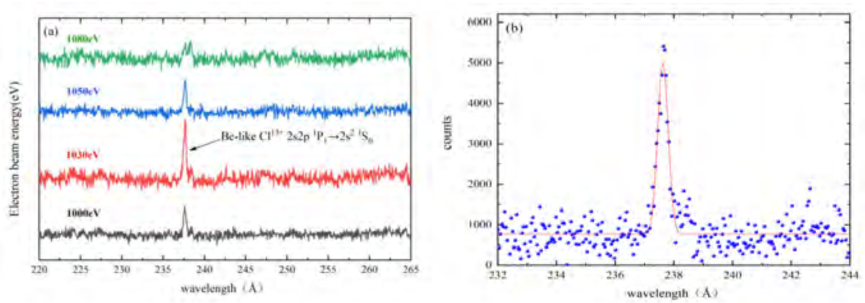

Figure 1: (a) Spectra of chlorine obtained at the SH-HtscEBIT with nominal electron beam energies of 1000, 1030, 1050 and 1080 eV in the range 220-265 Å. The line is the E1 transition between the fine-structure levels in the 2s2p $^1P_1$ and $2s^2\ ^1S_0$ of beryllium-like Cl^{13+}. (b)Expanded view of the line at 237.6 Å and its Gaussian fit.

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B12

Atomic structure and properties of Nd^{9+} for making an atomic optical clock

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Novel applications of optical transitions in highly charged ions (HCIs) for frequency metrology and tests for variation of fundamental constants have made them a subject of much interest lately [1]. The rich energy configuration of HCIs offers numerous optical transitions between the ground state and the long-lived excited states, which can be used for developing high accuracy clocks beyond the 10^{-18} precision limit [2,3,4]. 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 α_e and dark matter searches. In this work, we propose the highly charged Sb-like Nd^{9+} ions as a promising candidate for a high-accuracy optical clock. The energy levels, arising from the $5p - 4f$ orbital crossing in the Nd^{9+} ions are investigated. To comprehend Nd^{9+} as a prospective atomic clock, we determine the transition wavelengths, quality factors, lifetimes, magnetic dipole and electric quadrupole hyperfine structure constants, electric dipole polarizabilities, electric quadrupole moments of the states involved with clock transitions by using a relativistic multi-reference configuration interaction method. Relativistic sensitivity coefficients to the variation of the fine-structure constant and violation of local Lorentz invariance are determined, and various plausible systematics for the development of frequency standards are analyzed [5].

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B13

Polarization-dependent spectra of KLL dielectronic satellite lines of Ar^{17+}-Ar^{12+} ions

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Collisions of energetic electrons with highly charged ions (HCIs), abundant in hot plasmas, may lead to emission of anisotropic and polarized characteristic x-rays. Theoretical studies of polarization of x-ray lines can provide information on the directionality of the electron currents and the orientation of the magnetic-field lines in both hot astrophysical and laboratory plasmas [1].

In this work, the polarization properties of dielectronic satellite lines produced by KLL dielectronic recombination (DR) processes have been studied for highly charged Ar^{17+}-Ar^{12+} ions. The degree of linear polarization of dielectronic satellite lines, and polarization-dependent spectra at different electron beam energy from 2100 eV to 2500 eV are calculated using density matrix formalism [2] and the FAC code [3]. In the calculations, the high-order trielectronic recombination (TR) and quadruelectronic recombination (QR) processes are also incorporated, and show strong effects on polarization spectra of Ar^{13+} and Ar^{12+} ions.

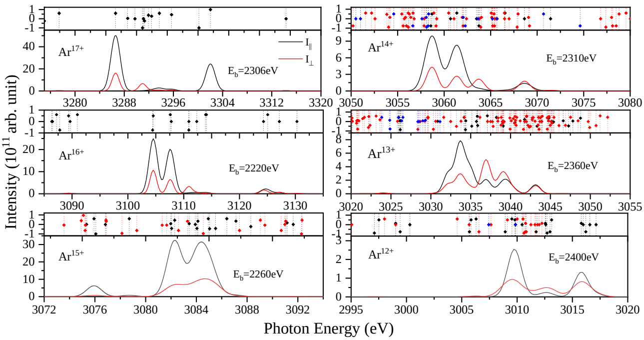

Figure 1: Theoretical polarization-dependent spectrum of Ar^{17+}-Ar^{14+} ions are calculated at different energy E_b of the electron beam. $I_{\parallel}$ and $I_{\perp}$ represent intensity associated with parallel and perpendicular polarization state. Dotted vertical line with different colors indicate the positions of dielectronic satellite lines from the DR (black), TR (red), and QR (blue) processes. The diamonds show the degree of polarization.

The work was supported by the National Key Research and Development Program of China under Grant No.2017YFA0402300, and the Natural Science Foundation of China (Grant Nos: 12064041,11874051).

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B14

Theoretical study of electron-ion resonant recombination process of Si^{10+} ion

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Silicon is the eighth-most abundant element in the solar system, accurate atomic data of highly charged silicon ions are required to identify spectral lines, and derive ion abundances of solar plasma [1]. Recently, Orban et al [2] measured the rate coefficients of electron-ion resonant recombination process for Δn =0 (2s-2p) transition of Si^{10+} ions at the CRYRING electron-cooler. Bernhardt et al [3] performed a new measurement of rate coefficients for Δn = 0 and Δn = 1, 2 ($2s\rightarrow 3l$, $4l$) transitions of Si^{10+}-Si^{9+} ions at the TSR heavy-ion storage ring in MPIK. However, theoretical calculations are scarce. In this work, we systematically investigated the L-shell Δn =1, 2 processes of Si^{10+} ions in the ground state ($2s^2$ $^1S_0$) and metastable state ($2s2p$ $^3P_0$), found that contribution of the metastable state is not be ignored. The following reactions are considered

$$Si^{10+}(2s^2)+e^- \rightarrow \begin{cases} \left[Si^{9+}\left((2s+2p)3lnl'\right)\right]^{**} \rightarrow \left[Si^{9+}\right]^{*} + h\nu \ (\Delta n=1\ DR+TR) \quad (a) \\ \left[Si^{9+}\left((2s+2p)4lnl'\right)\right]^{**} \rightarrow \left[Si^{9+}\right]^{*} + h\nu \ (\Delta n=2DR+TR) \quad (b) \end{cases} \qquad (1)$$

We performed detailed calculations for resonance energies, resonance strengths, and state-state resolved cross sections in the isolated resonance approximation using the FAC code[4]. The strong configuration mixing among the dielectronic recombination (DR) and trielectronic recombination (TR) channels are considered, which show fewer influence on resonance energies, and a great influence on resonance strengths. The rate coefficients are obtained by convoluting the calculated cross sections with the experimental electron energy distribution $kT_{//}$=0.093 meV and $kT_{\perp}$= 0.5 eV, and compared with the TSR measurements [3], excellent agreements are obtained (see Fig.1).

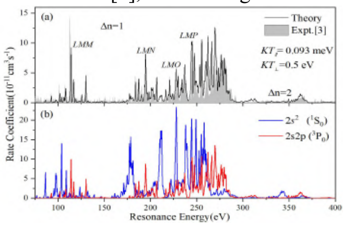

Figure 1: (a) The total theoretical rate coefficient (black curves) with considering the contributions of the ground state $2s^2$ $^1S_0$ (93%) and $2s2p$ $^3P_0$ (7%), compared to the TSR experimental results [3] (gray area). (b) the individual theoretical rate coefficient for Si^{10+} ions in the ground state $1s^2 2s^2$ $^1S_0$ (red line) and metastable state $1s^2 2s2p$ $^3P_0$ (blue line), respectively.

The work was supported by the National Key Research and Development Program of China under Grant No. 2017YFA0402300, the NSFC (Grants No. 12064041, No. 11874051)

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B15

Cascade effects on the polarization of x-ray emission following electron-impact excitation of He-like ions with Z = 10-92

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The polarization of x-ray emission from highly charged ions undergoing collisions with electron is important for spectroscopic diagnostic of the electron distribution anisotropy in high-temperature plasmas [1].

In this study, we calculated the degree of linear polarization of the $1s2p\ ^1P_1$-$1s^2\ ^1S_0$ (w) resonance line, $1s2p\ ^3P_2$-$1s^2\ ^1S_0$ (x), $1s2p\ ^3P_1$-$1s^2\ ^1S_0$ (y) intercombination lines, and $1s2s\ ^3S_1$-$1s^2\ ^1S_0$ (z) forbidden line following electron impact excitation of He-like ions with Z=10-92 using a fully relativistic distorted-wave method. The cascade contributions from the high-lying levels 1*snl* (*n*=2 and 3) to the polarization properties were investigated, including the electric-dipole (E1) allowed transitions, forbidden (M1, E2, and M2) transitions and two-photon transition (2E1). The results are compared with the existing theoretical and experimental values [2-4]. It was found that the radiative cascades dominate the degree of linear polarization of the z line. Line x shows very small contributions of radiative cascades.

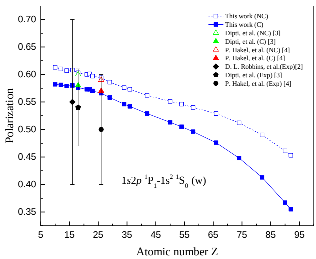

Figure 1: The calculated linear polarizations for the w line of He-like ions at electron-impact energy near the 1*s*3*l* excitation threshold, and compared with the existing theoretical and experimental values [2-4]. NC represents the values without cascade contributions, and C represents the ones with cascade contributions included.

The work was supported by the National Kay Research and Development Program of China under Grant No.2017YFA0402300), the NSCF (Grant Nos: 12064041, 11874051).

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B16

Two-electron one-photon and one-electron one-photon transition of inner shell hole state of He-like ions

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The structure and properties of inner shell hollow atoms are one of the hot topics in atomic physics[1]. The Two-electron one-photon (TEOP) transition of the double K hole atoms is essential because it was caused by the electron correlation effects and will provide a reference for the celestial bodies and laboratory plasma. He-like ions are the simplest system to investigate such complex transition process[2].

Based on the fully relativistic multi-configuration Dirac-Hartree-Fock method combined with active space method[3], the transition energy and probability of N^{5+}, Ne^{8+}, Fe^{24+}, Cu^{27+}, Xe^{54+}, and W^{72+} ions were calculated. For the TEOP transition, the spin forbidden transition is obviously enhanced with the increase of nuclear charge, which means that the relativistic effect significantly strengthened. For the OEOP transition, the transition energies of the transitions ${}^1P_1$-${}^1S_0$ and ${}^3P_2$-${}^3S_1$ are inversed with the increase of nuclear charge, which might caused by the competition between relativistic effect and electron correlation effects.

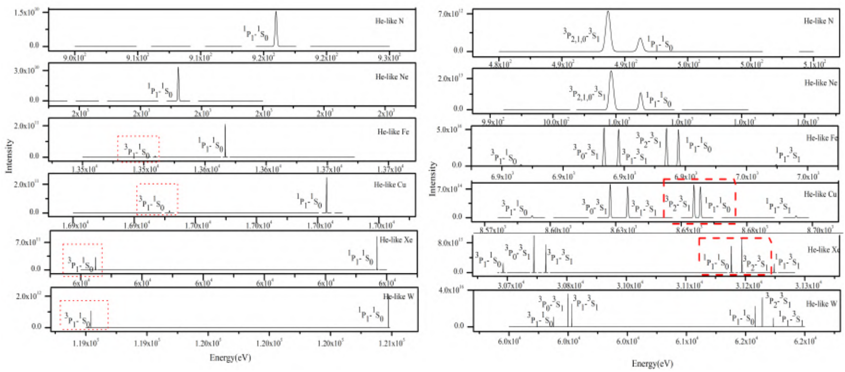

Figure 1: Transition spectra of TEOP transition 2s2p-1s^2 (left) and OEOP transition 2s2p-1s2s (right) of N^{5+}, Ne^{8+}, Fe^{24+}, Cu^{27+}, Xe^{52+}, and W^{72+} ions.

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B17

Collisional-radiative model for the spectra of M1 transition of W^{53+} ion

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The emission spectrum of tungsten ions can be used to diagnose the status of the fusion plasma[1,2]. Based on the experimental study of M1 transition spectrum of W^{53+} ion by Ralchenko et al. [3], the collisional-radiative model (CRM) were used to investigate the spectrum.

The configurations included in the present CRM are $3s^23p^63d^3, 3s^13p^63d^4$, and $3s^23p^53d^4$. In order to consider the electron correlation effects, the SD excited configurations, such as, $3s^13p^63d^34l(l = 0-2)$, $3p^63d^5$, $3p^63d^34s^2$ and $3s^23p^63d^26l(l = 0-4)$ are included as the correlation configurations.

The simulated spectrum is in good agreement with the observed spectrum on the EBIT. Five observed transitions were identified and assigned to the transitions within the multiplets of the ground configuration. The transition *m* in Fig1.(c) is predicted to be the M1 transition of W^{53+} ions which is not assigned in the previous work. This work provided the knowledge of the highly charged W ions which will be helpful for the future investigation on these ions and the fusion plasma.

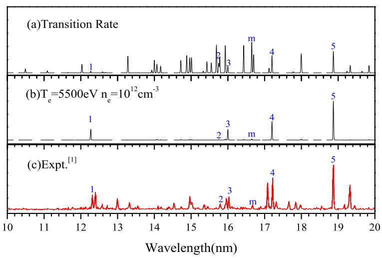

Figure 1: (a) Radiative transition rate, (b) Intensity from CRM. (c) Experimental spectra from the EBIT [3]. Each individual transition was assumed to have Gaussian profile with FWHM = 0.02nm.

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B18

Charge-state evolution from W^{5+} toW^{7+} at energies below the ionization potentials

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Experiments on an electron-beam ion trap (EBIT) and calculations using flexible atomic code (FAC) are carried out to study the charge-state evolution from W^{5+} to W^{7+}. The W^{7+} line at 574.47 nm is observed with an electron-beam energy of about 48 eV, which is far below the ionization potentials of W^{5+} (65 eV) and W^{6+} (122 eV). Multicharge-state collisional-radiative (CR) calculations for W^{5+}, W^{6+}, and W^{7+} are performed with level-to-level processes with configuration interaction (CI), including direct ionization, collision excitation, radiative recombination, charge exchange, radiative transition, and autoionization. The CI strongly influences the calculated ionization cross sections for metastable levels. The CR-simulated spectra agree well with the experiments, and the calculated effective ionization cross section for W^{6+} has the same trend as the available experimental data[1]. The metastable levels (~40 eV for W^{5+}; ~40 and ~85 eV for W^{6+}) significantly contribute to the ionization through excitation-autoionization at rather low energies (<50 eV) in the EBIT plasma. These metastable levels could have a considerable influence on the charge-state evolution of tungsten ions in edge fusion plasma.

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B19

Precise determination of $2s^2p^5 \rightarrow 2s2p^6$ transition energy in fluorine-like nickel utilizing a low-lying dielectronic resonance

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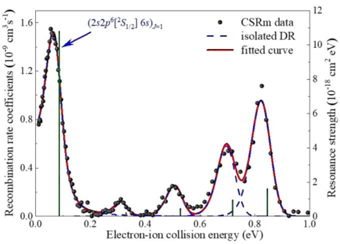
Precision spectroscopy of highly-charged ion (HCI) serves as an ideal tool to test the quantum electrodynamics (QED), relativistic and correlation effects. Dielectronic recombination (DR) occurs when a free electron is resonantly captured by the ion and the excess energy excites ion core. The doubly-excited recombined ion can decay via radiations to complete DR or via Auger back to its original state. The resonant character of DR was recognized as an ideal tool for the precision spectroscopic studies with HCIs [1-3]. Heavy-ion storage rings with an electron cooler offer a unique opportunity for measuring DR rate coefficients, in particular for the low-lying resonances. Associated transition energies in HCIs can be determined with a high accuracy when the binding energy of the captured electron can be calculated accurately. Here we present the precision DR spectroscopy of fluorine-like nickel [4]. The experimental determination of the collision energy for the first resonance via $(2s2p^6[^2S_{1/2}]6s)_{J=1}$ intermediate state at 86 meV could be performed with an uncertainty of as low as 4 meV. The multi-configuration Dirac-Hartree-Fock and stabilization methods have been applied for calculating the Rydberg binding energy of the 6*s* electron. The $2s^2p^5[^2P_{3/2}] \rightarrow 2s2p^6[^2S_{1/2}]$ transition energy in fluorine-like nickel ion is determined to be $149.056(4)_{exp}(10)_{MCDHF}$ and$149.032(4)_{exp}(6)_{SM,}$ respectively [5]. Moreover, individual theoretical contributions to the transition energy have also been evaluated by the *ab initio* calculation.



$2s^22p^5[^2P_{1/2}] \rightarrow 2s2p^6[^2S_{1/2}]$ transition energy in fluorine-like nickel ion (in eV).	
Method	Energy (eV)
experiment + theory	
Exp. + MCDHF	$149.056(4)_{exp}(10)_{theo}$
Exp. + SM	$149.032(4)_{exp}(6)_{theo}$
theory	
MCDHF	149.019(10)
Ab initio	149.046(7)

Figure 1: Background-subtracted DR rate coefficients and the fitted curves. The green vertical bars are the fitted resonance positions and strengths. The experimentally derived and theoretically calculated $2s^2p^5[^2P_{3/2}] \rightarrow 2s2p^6[^2S_{1/2}]$ transition energies in fluorine-like nickel ion are listed.

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B20

Identification of magnetic-dipole lines from W^{25+} ions in the $4f^3$ ground state

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Optical emission lines of impurity ions in fusion plasmas are useful for high-resolution measurements and particularly advantageous for fusion plasma diagnostics as mirrors and optical fibers are available to avoid direct neutron irradiation to detectors. Such magnetic-dipole (M1) transitions in the $2p^k$ configurations of highly charged iron and titanium ions have practically been used for measurements of ion temperatures, plasma rotations, and radial ion density distributions in tokamak plasmas [1,2]. The M1 transitions in the $4f^k$ configurations of highly charged tungsten ions fall into the optical range, which will be potentially useful for plasma diagnostics of ITER (International Thermonuclear Experimental Reactor).
Optical emission lines of W^{25+} have been measured using a compact electron beam ion trap (CoBIT) [3-5]. In the present work, we assigned the observed lines in 280 – 360 nm and 440 – 600 nm to the emission lines of the M1 transitions in the $4f^3$ ground state configuration based on spectra calculated using a collisional-radiative model for W^{25+} in CoBIT. Our assignments are consistent with the previous works [4,6]. Two lines at 334.16 nm and 334.58 nm measured with CoBIT were identified as the lines observed using Large Helical Device (LHD) [7]. The wavelengths calculated using HULLAC [8] agree with those calculated using GRASP2K [9], but they differ by about 3 % from the measurements.

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B21

Lifetime measurement of the microsecond-order electric-quadrupole transition: Application of plasma-assisted laser spectroscopy

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Lifetime measurements of forbidden transitions in highly charged ions (HCIs) have provided remarkable examples for evaluating atomic physics theories [1-3]. Previous measurements employed isolated HCIs in a magnetic ion storage device and observed de-excitation processes from metastable states prepared in a plasma ion source. This is a useful method for lifetimes on the order of milliseconds, and has been widely applied for various transitions. However, the conventional method cannot eliminate re-population effects due to cascade processes from upper energy levels. This intrinsic problem has prevented the broad extension of the technique to microsecond (μs)-order lifetime measurements.

Recently, we demonstrated plasma-assisted laser spectroscopy of HCIs trapped in an electron beam ion trap (EBIT) [4]. In this demonstration, we succeeded in laser excitation between the metastable fine-structure levels of Pd-like HCIs with the aid of plasma excitation processes in the EBIT. This laser spectroscopy has the potential to be applied to state-selective lifetime measurements which avoid the abovementioned problem. In this presentation, we discuss this application and its prospects by demonstrating the lifetime measurement of the μs-order electric-quadrupole (E2) transition $(4d_{3/2}^{-1}\,5s_{1/2})_{J=2}$ - $4d^{10}$ in Pd-like I^{7+}.

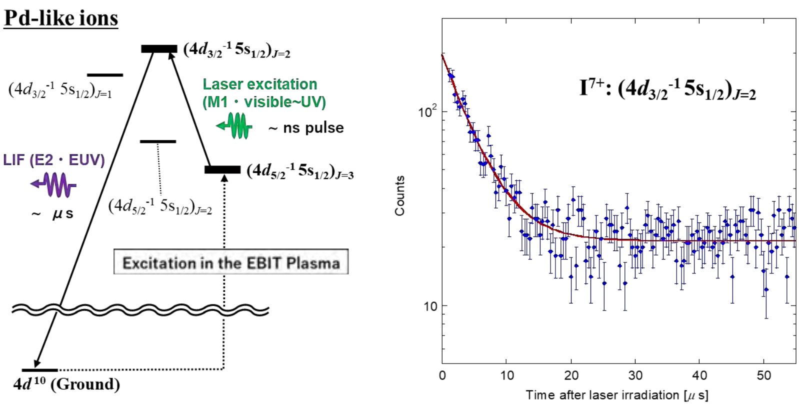

Figure 1: (Left) Concept for the lifetime measurement. (Right) Experimental decay profile.

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B22

Charge exchange spectroscopy of multiply charged erbium ions

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The “r-process” during the binary neutron star merger is regarded as the most promising candidate as the mechanism of the synthesis of heavier elements than iron in the universe [1]. For the first time, the binary neutron star merger was detected by gravitational-wave detectors Ligo and Virgo on August 17th, 2017, and the corresponding object called a kilonova was observed by optical telescopes [2]. To understand the observed spectrum from the kilonova via a radiative transport simulation, spectroscopic data of heavy elements are necessary. In the previous work, we predicted that triply and lower charged ions of heavy elements contributed to the photoemission from a kilonova. In particular, lanthanoid elements regard significantly contribute to visible and infrared emissions. However, available spectroscopic data for heavy element atoms are still limited.

In this work, we have performed spectroscopic experiments for the Er ions, one of the lanthanoid elements. The multiply charged Er ions were produced by a 14.25 GHz electron cyclotron resonance ion source with the introduction of an Er rod into the oxygen plasma at Tokyo Metropolitan University. The ion beam was extracted from the plasma by an electric potential difference of 15 kV, and directed into the collision cell after the charge state separation with a magnetic dipole. The cell was filled with a thin target gas with a pressure that satisfied the single collision conditions. A liquid-nitrogen-cooled CCD camera installed with a Czerny-Turner type spectrometer detected the photon emission spectra from the collision cell.

In this experiment, we used Er^{4+} and Er^{5+} for the projectile ions and Ar and N_2 for the target gases. Observed emission spectra show strong target dependence. Since the two targets have the almost same value as the ionization potentials, photon emissions from projectiles should be similar according to the simple understanding of charge exchange reaction between highly charged ions and neural target gases. Therefore we can easily distinguish the emission lines of Er ions from those of targets. We also identify not only the emission lines due to the single electron capture but also those due to double electron capture by comparing the spectra with different projectiles. In this conference, we report several new lines of multiply charged Er ions, especially those of Er^{3+}, and we show the candidates of the transitions by comparison between the experiments and the theoretical calculation [3].

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B23

Detailed analysis of spectra from Ga-like ions of heavy elements observed in high temperature plasmas

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Extreme ultraviolet (EUV) and soft X-ray emission spectra from highly charged heavy ions are of great interest in a variety of research fields such as nuclear fusion, industrial light source applications as well as basic atomic physics. Among a wide range of ion stages, spectra of Ga-like ions have relatively simple structure composed of a few strong isolated lines because of simple ground configuration [Ni]$4s^2 4p$ which has only one outermost electron outside the closed 4s subshell. However, experimental and theoretical investigations of spectral lines of Ga-like heavy ions are still incomplete and their atomic number (Z) dependences have not been fully analyzed yet.

In this study we focus on the experimental and theoretical studies on Z dependence of spectra from Ga-like ions of heavy elements. Experimental spectra were mainly recorded in high temperature plasmas produced in the Large Helical Device (LHD) at the National Institute for Fusion Science. In LHD, we have systematically observed EUV and soft X-ray spectra of a variety of elements with atomic numbers from 57 onward under electron temperatures of a few keV [1–3]. As a result, we have successfully obtained Z dependent wavelengths of several prominent transitions of Ga-like ions, some of which have been experimentally identified for the first time in this study.

The measured wavelengths are compared with theoretical values calculated with a multi-configuration Dirac Fock code GRASP92. Consequently, we have found that the energy level crossing of [Ni]$4s^2 4d$ and [Ni]$4s4p^2$ configurations takes place between Z=62 and 63 due to configuration interaction [4]. In addition, we have successfully identified a series of lines due to magnetic dipole transitions between two sublevels of the ground configuration, [Ni]$4s^2 4p_{1/2}$ and [Ni]$4s^2 4p_{3/2}$, which is discussed in terms of Z dependent spin-orbit splitting.

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B24

A collisional-radiative model for water window EUV spectra of bismuth ions

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Development of water window (2.2 - 4.4 nm) light sources has been motivated by its application to imaging of microscopic biological structures, such as cells and macromolecules, *in vivo* [1]. Recently, water window EUV emission spectra of highly charged bismuth ions were measured [2] using a compact electron beam ion trap (CoBIT) [3,4] at electron beam energies from 385 to 1140 eV. Emission lines due to 4f – 5g,6g transitions are observed in the spectra. We constructed a collisional-radiative (CR) model to simulate the spectra. In the present CR model, collisional excitation, de-excitation, and ionization by mono-energetic electron beams, and radiative decays via electric-dipole, quadruple, and octupole and magnetic-dipole and quadruple transitions are considered. Energy levels, collisional cross sections, and radiative decay rates of highly charged bismuth ions are calculated based on fully relativistic wavefunctions using HULLAC [5]. The present calculations agree with the experimental spectra [2]. As shown in Fig. 1, europium-like and samarium-like ions (Bi^{20+} and Bi^{21+}, respectively) emit a few strong 4f – 5g,6g lines due to 4f inner-shell excitation from the ground states of $4f^{14}5s^25p$ and $4f^{14}5s^2$, respectively. However, the emission lines of promethium-like and neodymium-like ions (Bi^{22+} and Bi^{23+}, respectively) consist of many weaker lines because they are due to the 4f inner-shell excitation from the long-lived metastable excited states of $4f^{13}5s^2$ [6,7] and $4f^{13}5s$, respectively.

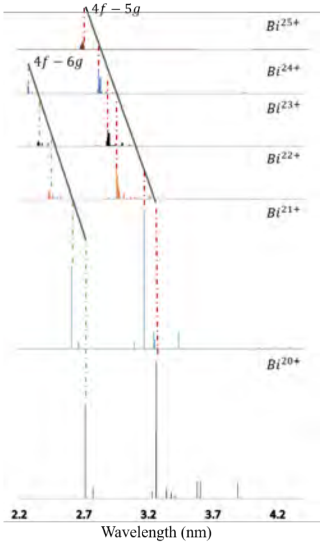

Figure 1 : CR model spectra of Bi^{20+} - Bi^{25+} in CoBIT at electron density of 10^{10} cm^{-3} and electron beam energies of 560, 600, 640, 680, 720, and 760 eV, respectively.

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B25

Soft x-ray emission spectroscopy of bismuth ions with an electron beam ion trap

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Development of plasma light sources for shorter wavelength has reached to soft x-ray region where the water window (2.3 – 4.4 nm) applied for biological microscopy of cells *in vivo*. The unresolved transition arrays (UTAs) of multiply charged bismuth (Bi) ions in laser-produced plasma (LPP) show its potential as a light source for the laboratory-scale single-shot live cell imaging [1]. From the investigation of characteristics of bismuth ions using an electron beam ion trap (EBIT), n = 4 – n = 4 UTAs contribute to the intense emission of Bi-LPP spectra in the 4 nm region [2].
In this study, we measured soft x-ray emission spectra of multiply charged bismuth ions expecting $n = 4 – n = 5$ UTAs dominated in the 2–3 nm region with an EBIT.

Bismuth ions were produced in a Compact EBIT [3] with Bi injection using an effusion cell. In the EBIT, a quasi-monoenergetic electron beam with electron energies of 385–1140 eV interacted with trapped ions. Emissions from the trapped ions in the soft x-ray region were observed with a flat-field grazing incident spectrometer equipped with a Peltier-cooled charge-coupled device [4]. Experimental spectra are compared with theoretical calculations using the flexible atomic code [5]. Observed dominant water window emissions correspond not only $n = 4 – n = 5$ transitions but also $n = 4 – n = 6$ transitions in the 2–3 nm region. Unexpected behaviour of the 4f-5g transition also observed due to the contribution of long-lived metastable excited states [6, 7]. Theoretical analysis in detail has discussed in [8] using collisional-radiative model constructed to simulate experimental spectra.

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B26

Atomic Number Dependence of Electric Octupole Decay in Electron Beam Ion Trap

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Forbidden transitions of highly charged ions in emission spectra are useful for diagnostics of fusion, astrophysical, and laser-produced plasmas since their intensities are sensitive to electron density and electron energy.

We have performed spectroscopic studies on the emission spectra of highly charged tungsten ions. Figure 1 shows a typical extreme ultraviolet (EUV) spectrum of highly charged tungsten ions with an electron beam energy of 870 eV with a compact Electron Beam Ion Trap (CoBIT). The highest charge state of tungsten ions in CoBIT was 27+ and several emission lines were observed. Characteristic two lines observed around 90 Å were identified as following transitions:

$$W^{27+}\ 4d^{10}5s \rightarrow 4d^{10}4f_{\frac{5}{2},\frac{7}{2}} \ .$$

We reported that these transitions were strongly forbidden electric octupole (*E3*) transitions in HCI 2018. Observed emission intensity of *E3* transitions is roughly the same as that of 5d-5p (*E1*) transitions observed around 125 Å even though calculated transition probability (Einstein's *A*-coefficients) of *E3* transitions is 10^{10} times smaller than that of the *E1* transition. We concluded that the observations of the *E3* forbidden emission lines were the result of an anomaly in the branching ratio to 5p from the 5d levels which caused an increase in 5s populations [1]. This conclusion suggests that there exist *Z*-dependent intensities in the *E3* transitions along the isoelectronic sequence of highly charged Ag-like ions.

Here, in order to prove the *Z*-dependence of the *E3* transition intensities, we have measured spectra of highly charged Ag-like ions for Yb, Re, Os, Ir, and Au. For Yb, Re, Os and Ir, sublimated gases of each carbonyl compound were injected into the trap of CoBIT from the gas injector. For Au, gold vapor produced in a Knudsen cell was injected into CoBIT.

We have successfully observed *E3* forbidden emission lines in Re, Os and Ir as predicted by theoretical calculations.

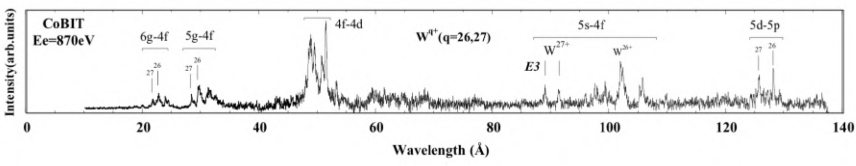

Figure 1: Observed EUV spectrum with *E3* transitions of W^{27+} ions.

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B27

Extreme ultraviolet spectra of W^{q+} ions with q=22-24

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Tungsten spectra have been studied to examine tungsten impurity behavior and the effect of radiation power loss in fusion plasmas since tungsten is used as plasma-facing material in fusion devices and is sputtered by plasma particles. However, some charge states of tungsten ions are not well studied yet due to the complexity of electron structures of the tungsten ions. Extreme ultraviolet spectra of tungsten ions have been measured in various fusion devices and electron beam ion traps (e.g. [1,2]) and examined by comparison of calculated spectra using collisional-radiative (CR) models (e.g., [3,4]). The so-called unresolved transition array (UTA) is observed at 4.5-7nm wavelength region for plasma with electron temperature ~ 1keV, which is produced by numerous overlapped 4d-4f and 4p-4d transitions of tungsten ions. The wide two-peak feature of the UTA profile is not fully understood yet [4], even though recombination processes are included in the CR model [5] for W^{q+} with q=25-39.

Recently we have extended our CR model for W^{q+} with q=22-24. Radiative, dielectronic and three-body recombination processes were included in the model as well as electron-impact excitation and ionization processes and radiative decays. All atomic data necessary for the CR model were calculated with HULLAC atomic code [6]. Electron configurations, $4p^6 4d^{10} 4f^m$, $4p^6 4d^9 4f^{m+1}$, $4p^5 4d^{10} 4f^{m+1}$, $4p^6 4d^{10} 4f^{m-1} nl$ (n=5-9, l=0-4), and $4p^6 4d^{10} 4f^{m-2} 5l nl'$($n$=5-9, l,l'=0-4) with m = 6-4 were considered as relativistic configuration-averaged levels. Fine structure levels of some of these configurations, which are important to calculate spectrum, are used in the CR model. The calculated spectra of W^{22+} - W^{24+} ions with this CR model show wide profiles at 4.5-7nm due to cascade processes from higher levels. We expect that these ions can contribute to the measured UTA profile. This result is similar to the spectrum of W^{23+} calculated in [7] without recombination processes.

We also calculated spectra of n=5-5 transitions at 10-30 nm and found wide profiles. We will compare with measured spectra of this wavelength region in plasmas of Large Helical Device to examine the validity of the CR model. Details will be presented at the conference.

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B28

Hyperfine splitting of the clock candidate transition in $^{93}Nb^{10+}$

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In the last decade, the research on optical transitions of highly charged ions (HCIs) has shown remarkable progress. Theoretical studies have revealed the advantages of high-precision spectroscopy of heavy HCIs with many electrons, *i.e.*, HCI clocks, for exploring fundamental physics beyond the Standard Model. To date, a number of transitions have been proposed as candidates and experimentally investigated [1]. Micke *et al.*, have demonstrated quantum logic spectroscopy of HCIs [2], promising realization of HCI clocks. However, there have been no experimental studies for hyperfine-structures in these candidates, though they are unavoidably demanded to develop HCI clocks.

In this poster, we present a first experimental observation for hyperfine splitting in HCI clock candidates. The magnetic-dipole transition $^2P_{1/2}$ - $^2P_{3/2}$ in $^{93}Nb^{10+}$ [3] was measured by a high-resolution visible spectrometer coupled to a compact electron beam ion trap (CoBIT) [4]. The low-magnetic field condition in CoBIT enables us to perform the hyperfine spectroscopy suppressing Zeeman and Paschen-Back effects [5]. The observed spectra show a remarkable feature consistent with the theoretical prediction considering the hyperfine splitting.

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B29

Detailed analysis of atomic processes relevant to the line intensity ratio of FeXV(233.9Å/243.8Å) in a compact electron beam ion trap

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Plasma diagnostics using EUV spectra is performed for solar plasma and fusion plasma etc. Plasma parameters can be obtained by analyzing the line spectra of ions in the plasmas using a collisional-radiative (CR) model. The CR model is obtained as a quasi-stationary state approximation to rate equations of transitions between quantum states of the ion. There are two important points to improve the accuracy of the CR model. One is to use correct probabilities of the atomic process by consulting existing data. The other is the validation of the model by comparing it with experimental spectra.

An electron-beam-ion-trap (EBIT) plasma consists of trapped ions with a narrow charge state distribution and a quasi-monoenergetic electron beam, thus the emission spectra from an EBIT provide ideal benchmarks for the CR model validation. In particular, a compact EBIT (CoBIT) operating with a low-energy electron beam is useful for measuring the EUV spectra related to the solar corona.

In this report, we present a theoretical analysis of the experimental line intensity ratios of FeXV 233.9 Å to 243.8 Å using the CR model. In the previous measurements with CoBIT [1-3], it has been reported that the experimental intensity ratios are significantly larger than theoretical predictions at electron densities of 10^{10} cm^{-3} or higher.

We constructed a CR model based on atomic data calculated by HULLAC code [4]. Atomic processes considered in the model are excitation/deexcitation by electron collision, ionization by electron collision, radiative transition, and autoionization. To have a better understanding of atomic processes relevant to the line ratio, inflow and outflow of populations of the upper levels of 233.9 Å and 243.8 Å lines are examined in detail. Then, it is shown that direct inner-shell ionization from Fe XIV, which has been omitted in the previous studies, can enhance the line intensity ratio. Since calculations of the line intensity ratio will be affected by differences in atomic data of the model, the atomic data calculated by HULLAC (e.g. excitation collision strength by electron collision, etc.) are compared with other available data and investigated impact of the differences in atomic data to the intensity ratio.

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B30

$5p$-$5s$ spectrum in highly charged WXII - WXIV Ions

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Spectral lines from highly charged tungsten ions, specially, from WIV-WXVI have been predicted to be useful in diagnostic of the ITER divertor plasma [1]. Tungsten ions having charge state WXII - WXVI are anticipated to show the transitions lines from the $5p$ to the $5s$ subshell in EUV region. These ions are highly correlated system with an open $4f$ subshell for which accurate calculations are challenging. Due to the complexity of observed spectra there was an ambiguity in charge state identification in previous study [2]. Also, there is no data available for W XII in extreme ultraviolet (EUV) range [3-4]. We present detailed theoretical analysis of $5p$-$5s$ transition of W XII–W XIV ions for the spectroscopic measurements performed at compact electron beam ion trap (CoBIT) [5-6]. The analysis of the observed spectra is based on the detailed collisional-radiative modeling with fine structure sub-levels atomic kinetics. The wavelength and rate of the transitions of W XII–W XIV ions calculated by the relativistic configuration interaction using flexible atomic code. Theoretical results are in reasonable agreement with the experimental observations ($\sim$18-28nm), which provides the clear assignment of the ionization stage and corresponding lines.

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B31

High-resolution spectroscopy of electronic *K* x rays from muonic atoms

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A muonic atom consists of a negatively-charged muon and a nucleus, sometimes accompanied by bound electrons. When a negative muon encounters an atom, the muon is captured in a highly excited state of the atom and then deexcites to lower energy levels step-by-step with the emission of Auger electrons and muonic x rays. Electron holes formed during this cascade process are immediately filled by the upper-level electrons, e.g., via characteristic x-ray emission.

We carried out high-resolution measurements of electronic *K* x rays from muonic atoms at J-PARC using a state-of-the-art x-ray detector, Transition-Edge Sensor (TES) microcalorimeters.

For muonic Fe (μFe) in a Fe metal [1], we observed an asymmetric and broad peak of electronic *K*α x rays, as shown in Figure 1. This feature reflects the dynamics of the cascade process because the energies of the *K* x rays are sensitive to the nuclear-charge screening by the muon and electron holes at the moment of the x-ray emission. In dense targets like metals, electron refilling from the surrounding follows, which is similar to de-excitation dynamics of highly-charged ions in metals [2].

On the other hand, for muonic Ar (μAr) in a gas phase [3], we found distinctively-resolved several peaks corresponding to highly-charged muonic atoms with a few bound electrons, where electron refilling is absent.

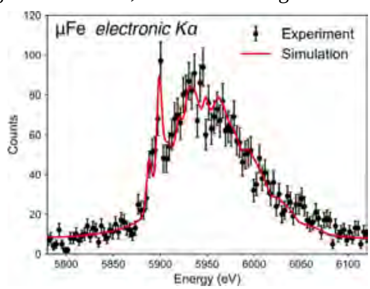

Figure 1: electronic *K* x-ray spectrum.

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B32

Up to which element the $K\alpha_1$ spectrum shows asymmetry in the experiment?

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The $K\alpha,\beta$ x-ray emission spectra of the 3*d* transition metals exhibit several peculiar asymmetric line profiles not observed in other elements, whose origin has been under investigation and debate. Several mechanisms such as shake processes, conduction-band collective excitation, exchange, and final-state interactions were suggested to account for this effect. However, Deutsch *et al.*[1], Holzer *et al.*[2], Anagnostopoulos *et al.*[3], Chantler *et al.*[4], and Ito *et al.*[5] suggested that the line shapes in $K\alpha_{1,2}$ x-ray spectra could be accounted for by the diagram, and 3*s*, 3*p*, and 3*d* spectator-hole transitions. Ito *et al.* measured systematically the $K\alpha_{1,2}$ spectra in the elements from Ca to Ge, using an antiparallel two-crystal x-ray spectrometer, and elucidated the origin of the asymmetry in the $K\alpha_1$ emission profile, confirming that the broadening of the linewidths of $K\alpha_2$ spectra is due to L_2-$L_3M_{4,5}$ Coster-Kronig transitions. Combined *ab initio* Dirac-Fock calculations and high-resolution x-ray emission measurements of $K\alpha_{1,2}$ spectra for elements Ca, Ti, and Ge show that the asymmetric line shapes of these emission lines can be fully explained by considering only the diagram and the 3*d* spectator transitions [5 and references therein]. Moreover, Se, Y, and Zr $K\alpha_{1,2}$ spectra were measured using the same type of x-ray spectrometer in order to investigate the elements where the asymmetry of the $K\alpha_1$ spectrum appeared.

Our results show that the asymmetry is observed in the Se $K\alpha_{1,2}$ spectra, but no asymmetry is observed in the Y and Zr $K\alpha_{1,2}$ spectra[6]. We discuss this result in the light of a discussion by multi-electron transition processes.

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B33

Testing quantum-electrodynamics with accurate measurements of Na-like and Mg-like transitions in highly charged Os and Ir

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Some of the best tests of many-body quantum electrodynamics (QED) involve highly-charged ions having one- and two-valence electrons outside of a closed shell. For these systems, accurate theoretical calculations have been developed and measurements can be performed even in heavy elements along the isoelectronic sequence [1, 2].

Here we report on measurements and analyses of spectra from Na- and Mg-like ions of Os and Ir that were created in the electron beam ion trap (EBIT) at the National Institute of Standards and Technology (NIST). The dominant transitions observed in the extreme ultraviolet (EUV) and x-ray ranges were Na-like $3s$–$3p_{1/2}$, $3s - 3p_{3/2}$ and the Mg-like $3s^2$–$3p_{1/2}$, $3s^2 - 3p_{3/2}$ respectively.

The instruments used to measure the spectra of emitted photons were a flat-field grazing-incidence EUV spectrometer [2] and the NIST Transition-Edge Sensor (TES) x-ray microcalorimeter [3]. Calculations of wavelengths were performed with multi-configuration Dirac-Hartree-Fock (GRASP2K) [4] and relativistic many-body perturbation theory (RMBPT) [5] packages. Detailed comparisons and sensitivity to QED effects will be presented.

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B34

Absolute nuclear radius of iridium from precision measurements and calculations of EUV and X-ray transitions in highly charged ions

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The absolute nuclear radius of ^{193}Ir [1] has been determined by precisely measuring the relative difference in charge radii between osmium and iridium isotopes by novel spectroscopic observations of highly charged ions in the extreme ultraviolet (EUV) and x-ray regime. The electron beam ion trap (EBIT) at the National Institute of Standards and Technology (NIST) was used at a beam energy of about 18 keV to produce highly charged ions of Os and Ir.

The light-emission spectra generated by electron impact excitation were observed using a flat-field grazing-incidence spectrometer [2] over a range of 4 nm to 20 nm and recorded using an EUV CCD detector with a pixel resolution of about 0.008 nm. Simultaneously, x-ray photons were collected with the NIST Transition-Edge Sensor (TES) microcalorimeter [3] over a broadband energy range of roughly 500 eV to 8000 eV with an energy resolution of around 4 eV.

The dominant spectral lines of both Os and Ir observed in the EUV and x-ray range were Na-like $3s$–$3p_{1/2}, 3s - 3p_{3/2}$ and Mg-like $3s^2$–$3p_{1/2}, 3s^2 - 3p_{3/2}$ transitions respectively. The difference in the wavelength between the corresponding Ir and Os transitions was measured over the course of several days by cycling the injection of Os, Ir into the EBIT. Calibration of the instrument was regularly performed during the run by injecting Ne and observing lines from trace elements of Xe and Ba.

The observed wavelength differences are directly related to the difference in the mean square radii through the expansion of the nuclear Seltzer moment. Precision atomic structure calculations were performed using GRASP2K [4] and RMBPT [5] packages. A comparison with prior nuclear physics experimental methods will be reported.

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B35

Laboratory search for Fe IX solar diagnostic lines at an electron beam ion trap

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The Fe IX spectrum features two lines in the EUV (at 241.739 Å and 244.909 Å, respectively) that have the potential to be among the best density diagnostics in the solar spectrum. One line is an $E1$ intercombination transition, the other an $M2$ transition. However, the diagnostic interpretation of the line ratio of the two lines has been disputed intensely [1]. Density diagnostic line ratios are sensitive to uncertainties in the atomic data because they depend on many factors, such as collisional excitation and de-excitation, radiative transitions, and cascades. Observational analyses imply density uncertainties of factors of 2 to 10 from the atomic data.

It should be interesting to observe the line pair in the laboratory. The low radiative $M2$ transition rate of less than $100\,\mathrm{s}^{-1}$ [2] requires the very good vacuum of a cryogenic electron beam ion trap (EBIT) to reduce the effects of collisional quenching by charge exchange. Figure 1 shows spectra from the LoWEUS spectrograph at the Livermore SuperEBIT, obtained at two electron beam energies, both of which are well above the optimum production of the Fe IX spectrum. The lower-energy spectrum shows partly blended lines at the two Fe IX wavelengths. Higher-resolution measurements with the HIGGS spectrograph are under way.

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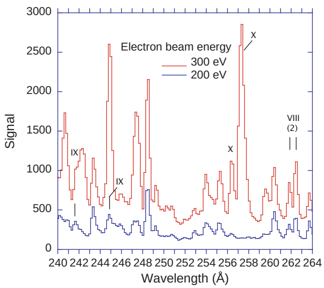

Figure 1: EUV spectra of Fe in the vicinity of the Fe IX lines of interest.

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B36

High-resolution Laboratory Measurements and Identification of Fe IX Lines near 171Å

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The Fe IX line at 171 Å dominates the spectra of many astrophysical and laboratory sources. A multitude of weaker Fe IX lines have been predicted in the vicinity of the 171 Å line (cf., the CHIANTI spectral data base [1]), but they have not been identified in the laboratory. Recently, we have presented measurements performed at the EBIT-I electron beam ion trap facility [2], which we used for tentative identification of more than a dozen new lines of the Fe IX spectrum within a 10 Å interval centered near the 171 Å line. Some of these lines had formerly been identified as arising from Fe VII, Fe XIV, or Fe XVI. Here we present new measurements that confirm these recent identifications. Our measurements carefully stepped through electron energies to clearly determine the charge state of iron associated with each observed line. Moreover, we have tried to identify additional Fe features that have previously remained unassigned, although they appeared to be either Fe VII or Fe X lines.

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B37

Measurement of the electron-impact ionization cross section of He-like Fe^{24+}

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Electron-impact ionization cross sections of He-like Fe^{24+} were measured at the electron beam ion trap (EBIT) facility of the National Institute of Standards and Technology (NIST) [1]. X-ray spectra were recorded at various electron beam energies between 9.2 keV and 18 keV by an array of 192 transition-edge sensor (TES) based x-ray microcalorimeters [2]. The ionization cross sections of He-like Fe^{24+} were determined based on the measured intensity ratio of the $Ly\alpha 1$ (1s $^2S_{1/2}$ – 2p $^2P_{3/2}$) to w (1s^2 $^1S_0$ – 1s2p $^1P_1$) and *Lyα2* (1s $^2S_{1/2}$ – 2p $^2P_{1/2}$) to w (1s^2 $^1S_0$ – 1s2p $^1P_1$) lines by considering the relevant processes affecting relative emission and ionization balance of the non-Maxwellian plasma. These processes are polarization, cascade contributions, radiative recombination, and charge exchange which were determined using the atomic kinetics simulations performed with collisional-radiative code NOMAD [3]. Comparison of the measured cross sections showed very good agreement with the relativistic convergent closed-coupling calculations [4] at all energies, while the theoretical predictions based on the non-relativistic and perturbative calculations widely used in the analysis of astrophysical spectra are higher than the measured values, particularly at energies close to threshold, illustrating the importance of relativistic effects. Uncertainty constraints show the limitation of the astrophysical temperature diagnostics capability of these transitions. The interpretation of measurements and comparison of the measured cross sections with theoretical calculations will be presented and discussed.

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B38

Electron loss in water molecule impacted by H^0 and He^0

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The study of electrons removal in collision of neutral atom with water molecule plays an important role in radiobiology. In particular, in radiotherapy during the continuous slowing-down of the ions beam, a fraction of them will change of state when its energy approaches the Bragg's peak region. In a recent work [1], the ionization of water molecule induced by neutral hydrogen has been investigated. However, the projectile electron loss process for the same collision system has been scarcely studied. In the literature, three different sets of experimental data and two semi-empirical analytical models exist, which have studied this reaction for neutral hydrogen – water molecule collisions. In this work, we present a theoretical approach to describe the electron loss process in the neutral hydrogen and helium – water collision. The total cross sections (TCSs), calculated within a quantum mechanical CDW-EIS, are presented in figure 1. The TCS computed within this approximation, that in case of neutral projectile fall down to First Born approximation, overestimates the measurements below a few hundreds of keV. To improve this, a charge corrections have been introduced [2]. As a result, the calculations with charge correction show a better agreement with experimental data and semi-empirical predictions.

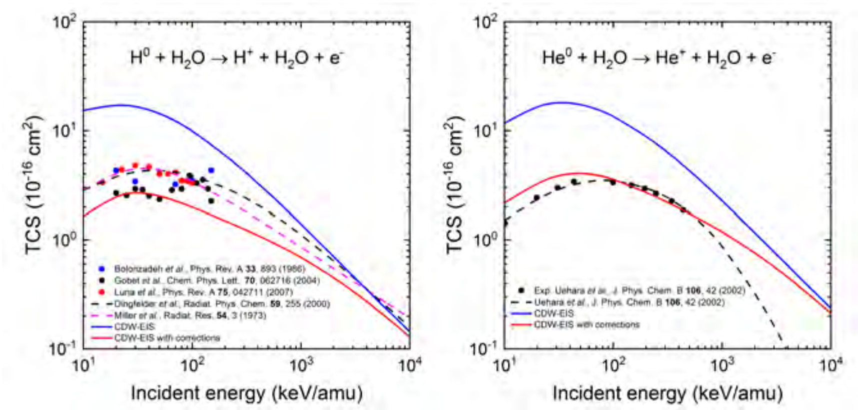

Figure 1: Electron loss total cross section for H^0 and He^0 impacted on water vapour.

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B39

Electron loss in argon atom impacted by H^0 and He^0

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The study of electrons removal in collision of neutral projectile with atom is a process of fundamental importance in many areas of science in particular, radiation damage to biological tissue, in astrophysics and the physics and chemistry of planetary atmospheres. However, neutral projectile, like neutral hydrogen or helium, induced interactions with atoms and molecule have been rarely experimentally investigated. In this work, we study the electron loss processes by using the continuum distorted wave-eikonal initial state (CDW-EIS) approximation. The results in term of total cross sections (TCSs) are shown in figure 1. To improve the CDW-EIS approximation in the case of collisions between neutral atoms, we consider the Barkas's charge in the initial channel and the dynamic effective charge in the exit one [1]. The Barkas's charge is a correction used to compute the energy loss of charged particle in the matter. On the other side, the dynamic effective charge was introduced by McGuire [2] to screen the nuclear projectile charge as a function of the momentum transfer. When both corrections are introduced into the CDW-EIS approximation, the obtained TCSs are in better agreement with the experimental data.

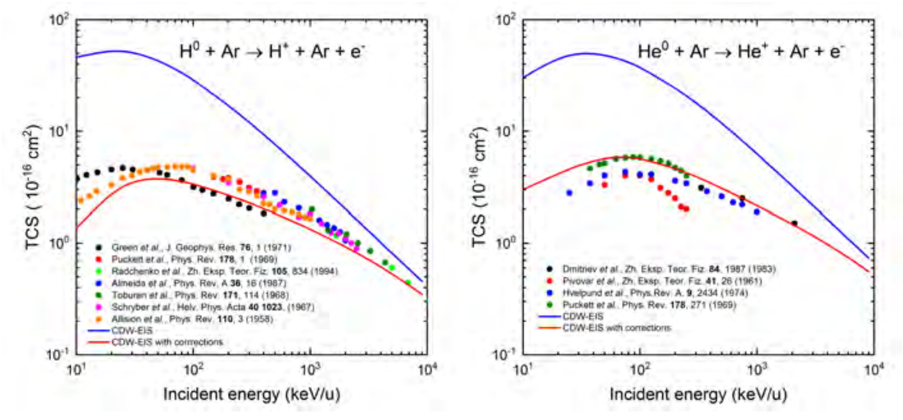

Figure 1: Electron loss total cross section for H^0 and He^0 impacted on argon.

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B40

Projectile dynamic screening and binary encounter electron emission

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The so called binary-encounter (BE) electrons are emitted from the target as a result of an energetic collision where the projectile velocity is higher than the electrons initial orbital velocity. Therefore, the interaction between the emitted electron with the projectile has a dominant role over the interaction among the electron and the target. BE collisions are associated to a low impact parameter so high momentum transfers are involved. In the case of a dressed projectile, the impact parameter lies within the radius of its K-shell so it could be expectable that the projectile-electron interaction is governed by the projectile's unscreened nuclear charge Z_P. However, the BE peak magnitude in the electron emission DDCS at 0° does depends on the ionization degree q of the projectile ion. The BE peak magnitude increases with decreasing q [1,2].

In a previous work [3] we have presented a correction to the continuum distorted wave with eikonal initial state model, CDW-EIS, based on a dynamic effective charge in the projectile distortion of the exit channel. Depending on the momentum transfer, this correction takes into account situations of full screening or no screening of Z_P by the projectile's bounded electrons. In this work we study in greater detail the CDW-EIS projectile dynamic charge corrections on the BE emission from an He target. We found a radically different behavior compared to the previous version of the CDW-EIS model, obtaining now a better agreement with the BE peak q-dependence, up to the measured q's.

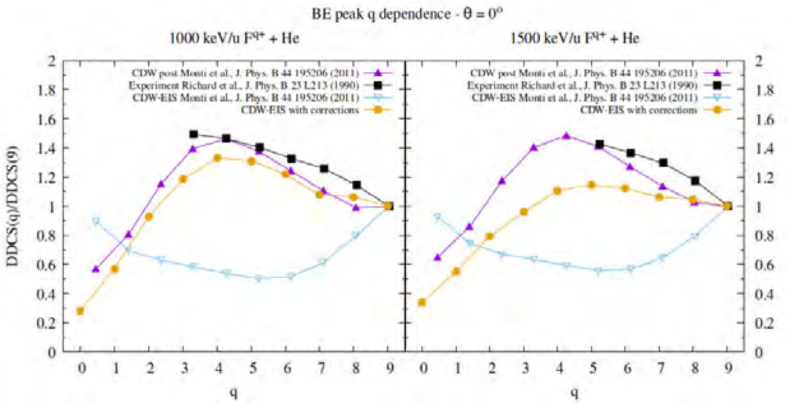

Figure 1: Projectile charge-state q dependence of BE peak DDCS's relative to bare-ion BE peak DDCS's.

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B41

State-selective electron capture in Ne^{10+} + H(1s) collisions

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Collisional data for highly charged ions like Ne^{10+} are important for astrophysical and fusion plasma research. We model electron capture and ionisation in fully-stripped neon ion collisions with ground-state atomic hydrogen using the two-centre wave-packet convergent close-coupling (WP-CCC) method over the energy range from 1 keV/u to 2 MeV/u. The calculated total electron-capture cross section agrees very well with the molecular and atomic orbital close-coupling calculations at low and intermediate energies. However, our results slightly overestimate the experimental results by Meyer *et al.* [1], and underestimate the measurements by Panov *et al.* [2] available only below 10 keV/u. At higher energies, where there are no measurements, the results also agree well with the classical trajectory Monte-Carlo results. Partial nl-resolved electron-capture cross sections, important for fusion plasma diagnostics, have also been calculated for final states up to $n = 10$ [3], where n and l are the final state principal and angular momentum quantum numbers, respectively. The results for the dominant channels are generally in good agreement with the atomic-orbital close-coupling calculations. However, by using a finer energy grid, we detect pronounced oscillations in the state-selective cross sections for $n \geq 8$ at energies below 10 keV/u. Our results for the total ionisation cross section differ from previous close-coupling calculations. However, they are overall in good agreement with the latest classical trajectory Monte-Carlo results. Previous WP-CCC calculations for collisions of fully-stripped carbon [4] and beryllium [5] ions with atomic hydrogen suggested that the maximum principal quantum number of bound states $n_{\max}$ on the projectile centre required for convergence was roughly equal to the charge of the incident ion. However, we find this not to be the case for highly-charged ions, such as Ne^{10+}. All the results reported in this work have converged within a few percent over the entire energy range mentioned above. To maintain such accuracy, in the most challenging intermediate energy region we had to set $n_{\max} = 15$. In particular, at 100 keV/u the n-resolved cross section peaks at $n = 7$ and then drops towards 0 very slowly with increasing n. Therefore, to achieve convergence in the total electron-capture cross section within a percent, we had to increase $n_{\max}$ to 23. This is more than twice the charge of the projectile.

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B42

State-selective single electron capture in slow N^{6+}-He collisions

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The charge exchange process of highly charged ions colliding with atoms or molecules plays an important role in different fields, such as X-ray emission from comets, which is attributed to the charge exchange of the solar wind ions with the neutral components of the comet [1, 2].

In the present work, the state-selective single-electron capture in collisions of N^{6+} ions with He was systematically studied at impact energies range from 0.9 to 8.6 keV/u. Our experiments were conducted at EBIS platform combined with COLTRIMS [3, 4] at the Institute of Modern Physics in Lanzhou. The fully differential cross sections have been obtained. From the longitudinal momentum spectrum of the recoil ions, the single electron captured into n=3 states of the projectile ion is dominant, while the capture n=4 states have a small contribution, and increase gradually with the increase of the projectile energy. Also, the two-peak structure of the angular differential cross sections was observed. The continuum distorted wave (CDW) approach was used to calculate the angular differential cross sections [5]. The inclusion of the projectile-nucleus target-nucleus (N-N) interaction, produces better the two-peak structure of the angular differential distribution. The results show that the nucleus-nucleus interaction plays an important role in slow ion-atom collisions.

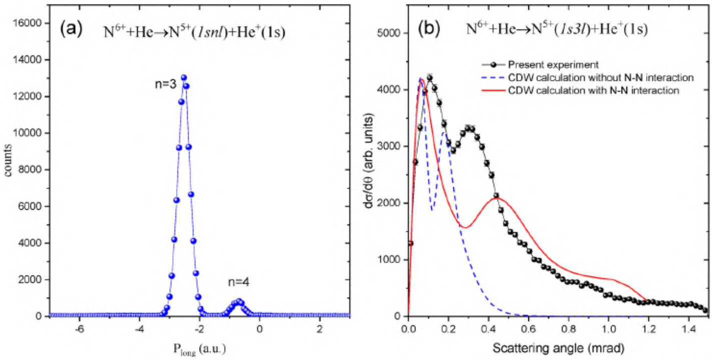

Figure 1. (a) The longitudinal momentum spectra and (b) differential cross sections as a function of the scattering angle of the single electron capture in collisions of 6 keV/u N^{6+} ions on helium. Blue dashed and red solid curves are the CDW calculations without and with N-N interaction, respectively.

This work is supported by the National Key R&D Program of China under Grant Nos. 2017YFA0402400 and 2017YFA0402300.

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B43

Simultaneous *K*-shell double ionization of target and ion in symmetric collision between Kr^{26+} and Kr atom at 152 MeV/u

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In collisions between energetic heavy ions and atoms, the strong Coulomb field of one of collision partners can cause double *K*-shell ionization of the second one [1]. The production of *K*-shell vacancy in atoms is typical accompanied by the creation of *K*-shell vacancy in ions. The production mechanism of *K*-shell vacancy in collision partners could not be studies for fully symmetric systems in low collision energy, since target and projectile *K* radiation could not be resolved at small Doppler shifts [2]. The development of heavy-ion storage ring provides us an opportunity to study *K*-shell vacancy under symmetrical ion-atom collision, in which the desired energy and charge state of ion could be conveniently achieved.

Simultaneous *K*-shell double ionization of target and ion in symmetric collision between Kr^{26+} ions and Kr atom at 152 MeV/u was studied experimentally at HIRFL-CSR. The *K* x-rays emitted from ions and atoms were detected by Silicon Drift Detectors (SDD) mounted at 35°, 60°, and 90° observation angles with respect to the ion beam direction. Figure 1 shows the typical spectra of Kr Kα rays recorded by the SDD at the 35° observation angle. The *K* x-rays from projectiles and targets are effectively separated on account of large Doppler shift at small observation angle. Both the *K*α hypersatellite ($K\alpha^{h,s}$) lines from ions and target appear as shoulder on the high-energy side of the corresponding *K*α satellite ($K\alpha^{s}$) peaks, and are visibly distinguished from the satellite transitions. The *K*β line of projectile is almost invisible since the ion without electron in *M*-shell was employed. The current experimental results are expected to eliminate the influence of *M*-shell and higher shell electrons on the collision process as well as cascade process by measuring the relative intensity of ions and target lines and their respective structures.

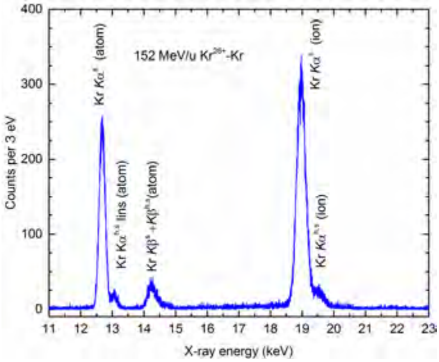

Figure 1: the typical spectra of Kr Kα rays recorded by the SDD at the 35° observation angle.

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B44

Electron-impact ionization of tungsten ions

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Tungsten is being considered as a plasma-facing material in magnetically confined fusion devices, such as ITER. Electron collision ionization is a dominant atomic process in fusion plasma which determines the ionization balance of the non-local thermal equilibrium plasmas. However, the effect of long-lived excited states in low charged ionic stages need to be investigated[1-2]. Moreover, reliable EISI data are not available for many tungsten ions[3].

We used the flexible atomic code (FAC) in the distorted-wave approximation method to calculate electron-impact single ionization cross sections for tungsten ions. Comparison between the previous experimental measurement results and present calculation show a prominent contribution of metastable states in low charged states such as W^{7+}-W^{10+} ions[4].

Moreover, we performed calculations of detailed electron- impact single ionization cross sections for tungsten ions, spanning charge states W^{38+} - W^{45+}. We demonstrate the importance of radiative damping on the total electron-impact ionization cross section. The data obtained are expected to be useful for modelling plasmas for fusion applications, especially for the ITER community.

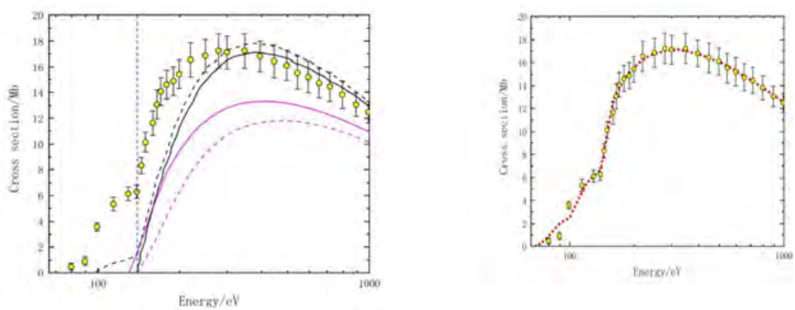

Figure 1: (a) Comparison of the present theoretical calculations to the previous experimental and theoretical data for single ionization from the ground levels of the W^{7+}. (b) Include the contributions from 29 long-lived metastable states.

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B45

Target atomic number dependence of the electron capture into H-like Cs ions

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Various x-ray transitions of Cs^{q+*} (q is the charge state of the ions) produced by the electron capture in collisions of 66.4 MeV/u Cs^{54+} ions with N_2, Ar, Kr and Xe atoms have been experimentally studied at the Heavy Ion Research Facility at Lanzhou–Cooling Storage Ring (HIRFL-CSR). It is found that the experimental intensity ratio I(K-α)/I(Ly-α) for the possible transitions from the excited states Cs^{53*}(1s2p-1s^2) and Cs^{54*}(2p-1s) for 66.4 MeV/u Cs^{54+} ions increases as the increase of the target atomic number. The obtained results are compared with the ratio of the capture cross sections to the excitation cross sections of the projectile electrons, calculated with the relativistic eikonal approximation and symmetric eikonal approximation, respectively. The obvious deviation has been found between the experiments and the theoretical calculations. Also, it is found that the experimental intensity ratio of I(K-β)/I(K-α) for the de-excitaion of Cs^{53*} from the state-selective nonradiative electron capture of 66.4 MeV/u Cs^{54+} ions in collisions of N_2 to Xe gas target shows an independence on the target atomic number. This is different from the calculations with the relativistic eikonal approximation, where the obvious increase of the ratio of the theoretical cross sections for the low atomic number of the target is expected. Also, the experimental intensity ratio is at least 3 times lower than the calculated ratio from the relativistic eikonal approximation. The possible explanations of the deviations between the experiments and theoretical calculations will be discussed.

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B46

Dielectronic recombination rate coefficients of C-like Kr^{30+}

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Dielectronic recombination (DR) rate coefficients for C-like Kr^{30+} have been measured in the energy range of 0-60 eV by employing the merged-beam technique at the heavy-ion storage ring CSRe at the Institute of Modern Physics in Lanzhou, China. The measured spectrum covers the DR resonances associated with the $2s^22p^2 \rightarrow 2s^22p^2$, $2s2p^3$ and $2p^4$ core excitations. The corresponding DR resonance energies and strengths were calculated by the flexible atomic code (FAC) to understand the experimental results. An overall good agreement has been achieved between the experiment and theory, except for the data below 8 eV. In particular, the contributions from the trielectronic recombination (TR) to $2p^4[^1D_2]6l$ states have been identified with the help of the theory. Temperature-dependent plasma recombination rate coefficients were deduced from the measured DR spectrum in the temperature range 10^3-10^7 K and compared with the present FAC calculations as well as previous AUTOSTRUCTURE data from the literature. The AUTOSTRUCTURE calculation substantially underestimates the rate coefficients below 10^4 K, indicating that the low energy resonances were poorly understood before.

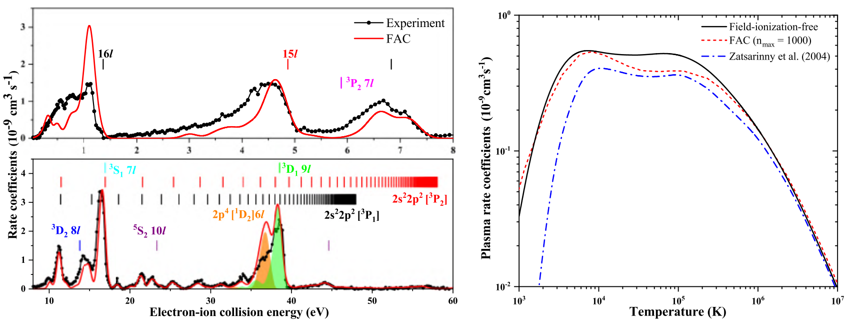

Figure 1: (left) Experimental and theoretical DR rate coefficients for the C-like Kr^{30+}. The colourful vertical bars represent the corresponding resonance positions calculated by the Rydberg formula. The shaded areas with the same colours as the text boxes show the corresponding DR contributions. Note that the prefix text ($2s2p^3$) of the core excitations to $2s2p^3$ is omitted. (right) Experimentally derived plasma rate coefficients for C-like Kr^{30+} in the temperature range 10^3-10^7 K along with the present FAC calculations and the data from Zatsarinny [2].

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B47

Dielectronic recombination of Li-like Ar^{15+} using a newly self-developed detuning system at the CSRm

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A self-developed detuning system for the dielectronic recombination (DR) experiment was installed on the electron cooler of heavy-ion storage ring HIRFL-CSRm. To test the stability of this detuning system, a DR calibration experiment using the Li-like argon ions was performed at the CSRm. As shown in Figure 1 (a), the experiment was carried out over the energy range of 0 –37 eV, including all the DR resonance associated with the core excitations of $2s_{1/2} \rightarrow 2p_{1/2,3/2}$. Figure 1 (b) presents the fitting result of the measured low-energy DR spectrum, i.e., 6 components were used to fit the DR resonance structure of $2p_{1/2}10l$. The longitudinal and transverse temperatures of the electron beam obtained as the fitting parameters are $kT_{\|} \approx 0.25$ meV and $kT_{\perp} \approx 30$ meV, respectively, which yields an energy resolution of about 30 meV (FWHM) at the electron-ion collision energy of around 1.2 eV. Compared with the previous DR experiment of Li-like argon at the CSRm (2015, Huang et al) [2], a higher energy resolution was achieved in the present measurement. By comparing the measured DR spectrum with FAC calculation, the angular momentum quantum numbers for the resolved resonance peaks associated with $2p_{1/2}10l$ were well distinguished and the attributed electron configurations have been indicated in Figure 1 (b) with black vertical bars. The present work provides an important technical reserve and lays the solid foundation for the DR precision spectroscopy in the future High Intensity heavy ion Accelerator Facility (HIAF).

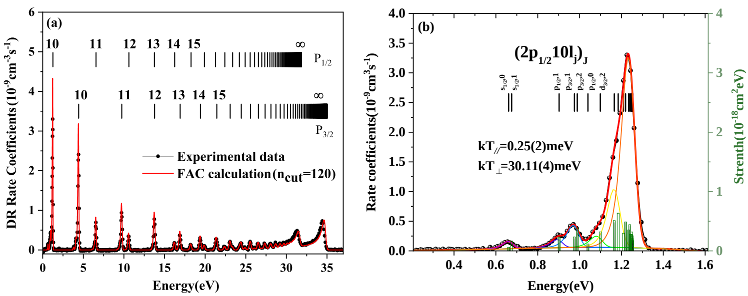

Figure 1: (a) The comparison of the experimental and FAC calculated DR rate coefficient of Ar^{15+} ions. The short line in the figure indicates the distribution of Rydberg energy levels in $1s^22p_{1/2}nl$ and $1s^22p_{3/2}nl$ configurations. (b) Fitting of the resonance structure of $1s^22p_{1/2}10l$ (black point). The black vertical bars are the calculated resonance positions of $1s^22p_{1/2}10l$. The heights of the short green lines indicate the resonance strengths at the corresponding resonant energies.

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B48

State-selective capture in Ar^{8+} collision with He at 1 keV/u

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In slow highly charged ion-atom collisions, principal *n* and orbital angular momentum *l*-resolved state-selective capture cross sections are important due to its applications in hot plasma diagnostics. Additionally, the *nl*-resolved state selectivity is important for understanding few-body collision dynamics, which control the bound quantum-state transition between two-centres.

We report the measurement of state-selective capture between 1 keV/u Ar^{8+} and He with a cold target recoil ion momentum spectroscopy at electron beam ion source laboratory in Institute of Modern Physics, Chinese Academy of Sciences. The state-selective capture has been resolved for one 1s electron of He capture into 4s, 4p, 4d + 4f and 5s states of Ar^{7+} ion, where 4d + 4f capture dominates over others. The present measurement qualitatively agrees with the previous result [1].

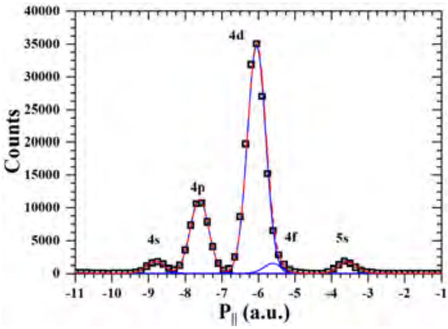

Figure 1: Longitudinal recoil ion momentum $P_{||}$ in 1 keV/u Ar^{8+} -He single capture. The open squares represent the measurement; lines are results from gaussian fitting.

This work is supported by the National Key R&D program of China under Grant Nos. 2017YFA0402400 and 2017YFA0402300, and Strategic Key Research Program of the Chinese Academy of Sciences (XDB34020000).

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B49

Theoretical Investigation of Collision strengths for Fe X

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We present here a detailed study of electron impact excitation of Fe X, focusing on the need to model the extreme ultraviolet (EUV) spectrum of interest for measuring coronal magnetic field strengths using the magnetic-field-induced transition method [1-4]. The energy structures were calculated using the relativistic GRASP code [5] for 100 jj fine-structure levels from 8 configurations (up to n=5). The energies belonging to the $3s^23p^5$, $3s3p^6$, and $3s^23p^43d$ configurations were shifted to their predicted National Institute of Standards and Technology values. The relativistic parallel Dirac atomic R-matrix codes [6] were employed in the scattering calculations to generate the collision strengths and subsequently the Maxwellian-averaged effective collision strengths for temperatures in the range of 10^4 to 10^7 K. The present effective collision strengths when compared with previous theoretical studies, are found an overall good agreement for the EUV transitions of interest in the wavelength range from 170 to 260 Å. In addition, the new collision data were adopted to model the EUV spectrum of Fe X and obtain the intensity ratios of the diagnostic line pairs used to derive the magnetic field strength. Comparisons were made between the spectra modelled using the present data with solar observations and other theoretical studies.

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B50

Charge-sharing dynamics of dissociating highly charged acetylene ions after electron-capture by highly charged ions

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After multi-electron capture from covalent molecules, charge-rearrangement occurs until dissociation. However, it is still unclear where or when the rearrangement is finished and charge-sharing is determined. In order to study the charge-sharing dynamics, we observed dissociation of highly charged acetylenes ($C_2H_2^{n+}$, n = 5, 6). The H^+ ions in the acetylene ions dissociate quickly, which are utilized as probes; that is, the kinetic energy distributions (KED) of two H^+ ions reflects charge distribution of two inner carbon ions. We observed four-body dissociation events of highly-charged acetylene ions by collision with Ar^{8+} ions at an energy of 120 keV [1].

The experiments were carried out using an apparatus consisting of a position-sensitive time-of-flight (PSTOF) device with a large position-sensitive detector (120 mmϕ) for fragment ions and a charge analyzer for scattered projectile ions. The trigger of the TOF measurements was detection of scattered Ar^{5+} ions passing through the collision region, corresponding to five- and six-electron capture processes with two and three Auger electron emissions from the scattered ions, respectively.

Fig. 1 (a) shows KEDs of H^+ ions for the $H^+C^{2+}C^+H^+$ channel. The KEDs on the C^{2+} and C^+ side are quite similar, indicating equal sharing of the charges in the C_2^{3+} ion when both the H^+ ions dissociated from the ion. Fig. 1 (b) shows KEDs of H^+ ions for the $H^+C^{3+}C^+H^+$ channel. The KED on the C^{3+} site is higher than its counterpart. However, the difference is much smaller than the pure Coulombic value for C^{3+} and C^+ sharing at the initial stage of dissociation. In order to estimate a C-C distance where charge-sharing was finalized and the corresponding charge distribution of the two carbon ions, we performed numerical simulations based on the pure Coulomb explosion model. For the $H^+C^{2+}C^+H^+$ channel, the charge-sharing is finalized at the distance longer than about 200 pm. For the $H^+C^{3+}C^+H^+$ channel, the finalized distance is almost same as that for the $H^+C^{2+}C^+H^+$ channel, but initial charge distribution is slightly asymmetric.

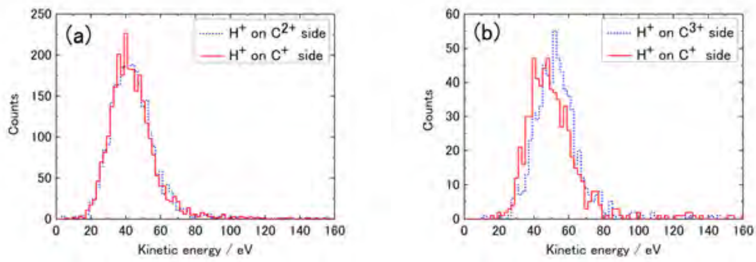

Fig. 1: (a) KEDs of H^+ for the $H^+C^{2+}C^+H^+$ channel. One from near the C^{2+} site is shown by a blue dotted line, and the other from near the C^+ site is shown by a red solid line. (b) KEDs for the $H^+C^{3+}C^+H^+$ channel.

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B51

Charge-state evolution for 1.0-MeV/u W ions passing through C-foils

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Equilibrium and pre-equilibrium charge-state distributions for 1.0-MeV/u tungsten ions after passing through carbon foils are investigated following those for 2.0-MeV/u sulfur [1] and carbon ions [2]. Variety of incident charge states of W ions are as extensive as 13–38+ and target-foil thickness 2.1–20 μg/cm^2. The present charge-state evolution establishes the equilibrium at C-foil thickness 9.9 μg/cm^2, showing asymmetrical distribution with its mean charge state 31.3 and width 2.29 (Fig. 1). For 2.0-MeV/u S and C ions, a *quasi-equilibrium* was observed, *i.e.*, mean charge states for projectile ions with filled K-shell merged before establishing the real-equilibrium and evolved simultaneously to the real-equilibrium as target thickness increased, whereas those for projectile ions with K-shell hole(s) evolved directly and monotonously to the real-equilibrium not showing such pre-merger. [1, 2] For the present equilibrium and pre-equilibrium charge-state distributions or their mean charge states, no shell-effect or quasi-equilibrium is observed between Kr-like W^{38+} and Rb-like W^{37+} (or N- and O-shells). Theoretical calculations based on the balance rate equations do not satisfactorily reproduce the measured charge-state distributions or their evolution for W, although those for 2.0-MeV/u S ions could successfully be reproduced [3].

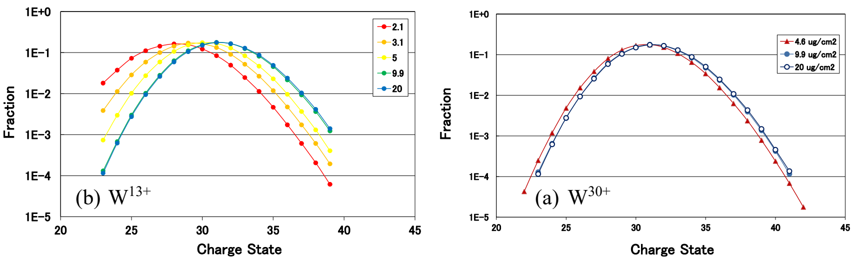

Figure 1: Charge state distributions for 1.0-MeV/u (a)W^{13+} and (b)W^{30+} incident ions after penetrating C-foils of 2.1–20 μg/cm^2 in thickness.

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B52

Simulation study to aim to elucidate biological effect due to fast highly-charged ion irradiation

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In fast highly-charged ion irradiation, a distinguishing feature appears, that is, energy deposition concentrates near this ion path (IP). Because we think that there is a possibility to produces high relative biological effectiveness (RBE) owing to this feature, we have developed a new simulation model [1] to study physical phenomena produced near the IP. This model will allow us to analyze the motion of the secondary electrons and spatial resolusion for energy deposition of these electrons on the target in the irradiation of a highly-charged ion closer to reality than conventional models.

Owing to this irradiation, huge number of molecules are ionized along the IP and huge number of molecular ions are produced. In our simulation model, we incorporated strong electric field created by these molecular ions and the effect of this electric field on the motion of secondary electrons. Note that only our model succeeded to reproduce the trend of the measurement of secondary electron yield by Kimura et al. [2]. In our previous study, we treated protons and carbon ions as incident ions where $\sigma_i \leq 4 \times 10^{-15}$ cm^2, because only these ions are employed in heavy ion beam cancer therapy, where σ_i is the incident ion impact ionization cross section. Because we found some experiments of more highly-charged ion such as Ar and Fe ions to elucidate the biological effect, σ_i is extended up to 2×10^{-14} cm^2 in this study. Figure 1 shows (a) P_{se} vs. τ (= $1/n_M\sigma_i$) and (b) D_r distribution in the case of σ_i = 1, 1.5, and 2 ($\times 10^{-14}$ cm^2), where P_{se}, r, τ, n_M, and D_r are probabilities of seconadary electrons escaping this electric field, the distance from the IP, the mean path between ionization events, the number density of molecules in the target, and the local dose as a function of r, respectively.

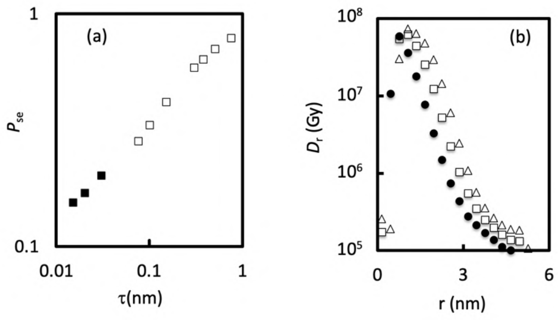

Figure 1: (a) P_{se} vs. τ; □ and ■ are the results shown in Ref. [1] and simulated here, respectively. (b) D_r vs. r ; ●, □, and △ corresponds to σ_i = 1, 1.5, and 2 ($\times 10^{-14}$ cm^2), respectively.

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B53

Delayed fragmentation of nucleobases following MeV ion collisions

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Many studies have been performed on dissociation processes of gas-phase biomolecules induced by energetic ion collisions. One of the characteristic features of dissociation of large polyatomic molecules, including biomolecules, is delayed fragmentation arising from the increased number of degrees of freedom [1–3]. Studies of delayed fragmentation processes provide rich information about the stability of intermediated ions and the dissociation mechanism, which can even involve neutral fragments [1]. So far, delayed fragmentation of nucleobases has focused on the adenine molecule with keV ion collisions. This study performs MeV ion irradiation of various gas-phase nucleobase molecules to explore delayed fragmentation pathways in more detail.

The experiments were performed using a 1.7-MV Cockcroft–Walton-type tandem accelerator. Gas-phase nucleobase targets of adenine, guanine, cytosine, and thymine were irradiated with pulsed beams of 0.5-MeV H^+ and 0.6–4.0-MeV C^{q+} (q = 1–3). Fragments were analyzed by time-of-flight (TOF) mass spectrometry. The TOF data were recorded in list mode to analyze the correlation among the detected fragments.

Figure 1 shows the TOF correlation maps between the first and second TOFs of the two fragments produced in the same dissociation event of adenine. Delayed processes are observed as long tails. Some processes were not observed in other experiments with keV ions, probably owing to the low statistics. We evaluated the lifetime for some dissociation channels. To derive the lifetime of dissociation from singly charged molecules, we estimated the absolute detection efficiency of the micro-channel plate detector for neutral fragments using a novel method. The lifetimes were determined to be of the order of hundreds of ns to μs.

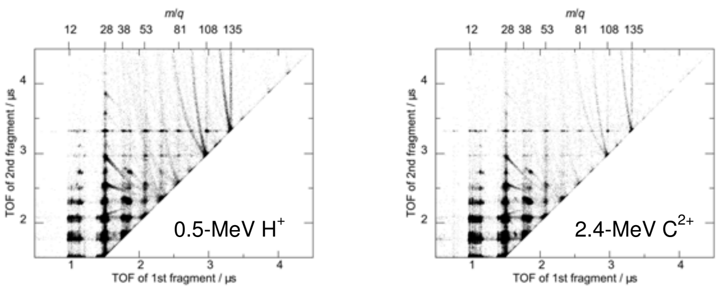

Figure 1: Time-of-flight correlation maps of the two fragments generated from adenine.

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B54

Occurrence scattering time for electron-ion collision in nonextensive plasmas

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The occurrence scattering time advance [1] for the electron-ion collision is investigated in a non-extensive plasma including Tsallis *q*-entropy. The eikonal analysis and the *q*-distribution function [2] are used to derive the occurrence scattering time as a function of the impact parameter, collision energy, scattering angle, and Tsallis entropic index. It is found that the occurrence scattering time advance decreases with increasing Tsallis entropic index. It is also shown that the effect of Tsallis *q*-entropy on the occurrence scattering time advance increases with an increase of the scattering angle. In addition, it is found that the effect of Tsallis *q*-entropy on the occurrence scattering time advance decreases in forward scattering domain in nonextensive plasmas.

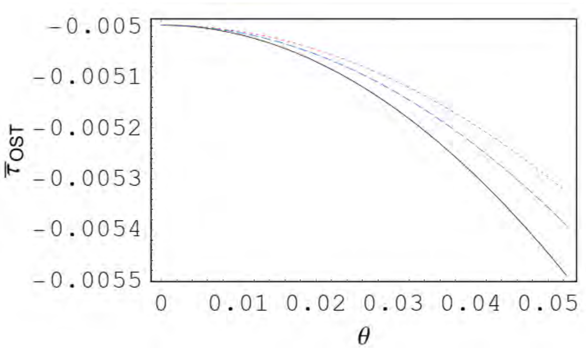

Figure 1: The scaled occurrence scattering time in nonextensive plasmas.

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B55

Radiative Double-Electron Capture by Highly-stripped Ions on Graphene

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Radiative double-electron capture (RDEC) occurs when the capture of two electrons by an ion is accompanied by the simultaneous emission of a single photon. This process, fundamental in atomic collisions, is considered the inverse of double photoionization by a single photon. RDEC has been successfully studied with $F^{9,8+}$ ions on gas [1] and thin-foil [2] targets. Only recently has it been investigated for single-layer graphene [3]. This work was done at WMU with the 6-MV tandem van de Graaff accelerator. For the graphene, a target (~0.35 nm thick) was mounted on a silicon nitride grid (200 nm thick) consisting of ~6400 holes of 2 μm diameter on a 200 μm thick substrate. A Si(Li) spectrometer placed at 90° to the beam detected emitted x rays in coincidence with magnetically separated outgoing charged particles counted with silicon surface-barrier detectors.

In preliminary work for RDEC with graphene [3], results for 2.11 MeV/u $F^{9,8+}$ ions suggested very large cross sections, approaching values found for thin-foil targets when the thickness of the graphene was about a hundred times smaller. In the present work, the RDEC measurements have been repeated with single-layer graphene as well as identical targets that had no graphene on them.

Figure 1 shows new results for RDEC for 2.11 MeV/u $F^{9,8+}$ incident on graphene where the number of counts is plotted against the time difference between the x rays and particles detected. The upper panel shows the results for F^{9+} on graphene, the middle panel for F^{9+} with no graphene, and the bottom panel for F^{8+} incident on the graphene. The top panel for F^{9+} shows about 7-8 counts in the peak (near a time difference of 1950 ns) after background subtraction, the middle panel exhibits no counts for the target without graphene as expected, and the bottom panel for F^{8+} displays counts but none in the peak, a reasonable expectation for this one-electron ion when compared with earlier results for F^{8+} on gas targets [1].

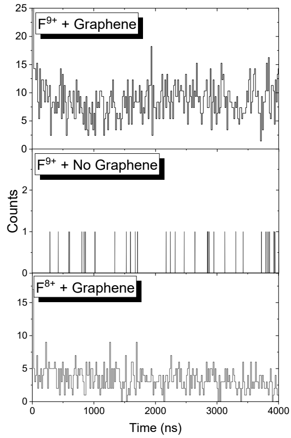

Figure 1: RDEC results for $F^{9,8+}$ on single-layer graphene

A tentative cross section can be calculated for the F^{9+} projectile, and the differential value at 90° is 1.3 b, corresponding to a total cross section (assuming isotropy) of 11 b. These values are more in line with the earlier values found for F^{9+} incident on gas targets, but larger by about a factor of 4, and are reasonable in view of the target thickness for the graphene compared to gas.

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B56

Probing the plasmon resonance in PAHs upon highly charged ion impact

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The polycyclic aromatic hydrocarbons (PAH) are established to be present in the interstellar medium [1-2] and have attracted a lot of attention in the last few decades. The PAHs are in general planar molecules having delocalized π-electron cloud that can oscillate collectively upon external perturbation. The collective excitation are also known as giant plasmon resonance (GPR), which results from strong e^--e^- correlations. We studied the absolute double differential cross section (DDCS) of electron emission using electron spectroscopy as well as the ratio of double-to-single ionization (DI-to-SI) by using TOF RIMS techniques in collisions with highly charged ions (HCI).

The GPR primarily decays via electron emission. However, observation of the GDPR in the e-emission channel is challenging due to the presence of large Coulomb ionization background of low-energy electrons. A novel idea is demonstrated of using the highly charged ions to create large perturbation strength in order to excite the plasmons effectively. For the first time, the GPR in a PAH molecule has been observed as a characteristic peak in the DDCS of electron emission [Fig. 1 (a)] and its angular distribution has been studied [3-4].

The DI-to-SI ratios for PAHs upon HCI impact have been found to be substantially large [Fig. 1 (b)] as compared to the atoms and smaller gas molecules such as CH_4 [5]. The detailed projectile charge (q_p) and velocity (v_p) dependence of the ratio has been studied for three different PAH molecules. The influence of GPR in these PAH molecules resulting from the strong e^--e^- correlations has been shown by modeling the q_p and v_p dependence of the ratio. The detailed results of the e-emission, as well as the DI-to-SI ratio will be presented.

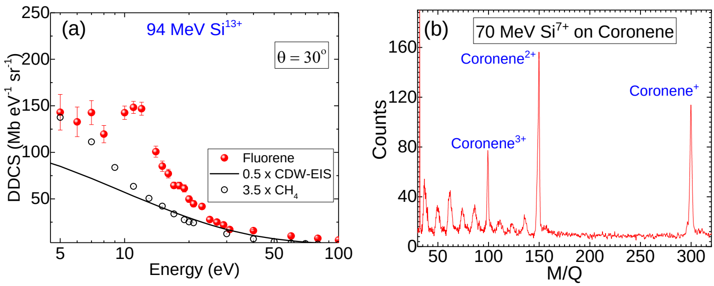

Figure 1: (a) DDCS of e-emission from fluorene and CH_4 at 30° in collisions with 94 MeV Si^{13+} ion impact, (b) Typical TOF spectra for coronene molecule in collisions 70 MeV Si^{7+} ions.

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B57

Theoretical and experimental studies on the captured electron population probability of hydrogen-like O ions in collision with metal surface

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The interaction between highly charged ions and solid surfaces is a complex many-body process, and the population of electron capture into different Rydberg states is important information to study this process. Based on the two-state vector model (TVM) [1,2] proposed by Nedeljković et al., we calculated the probability of hydrogen-like O ions incident on metal targets capturing conduction band electron to different Rydberg states and gave the most likely ion-surface distance for charge exchange during the neutralization. It is found that a smaller principal quantum number n_A corresponds to a larger Rydberg state probability, and the smaller the neutralization distance, the smaller the principal quantum number n_A arranged by the ion trapped electrons. Therefore, the X-rays emitted as the hydrogen-like O ions impinging on the metal surfaces mainly originate from the de-excitation of the smaller n_A to the ground state. In addition, in order to verify the calculation results of the model, based on the ECRIS of the Institute of modern physics, Chinese Academy of Sciences, the X-ray emission spectra of hydrogen-like O ions incident on the surface of metal targets (including Al, Cu, Ni and Fe) were measured, and the transition energies from different high Rydberg states to ground states were calculated in combination with FAC program. It is found that the *K*-X rays of O ion measured in this experiment mainly come from the 2*p*-1*s* transition, which is consistent with the probability calculated by the TVM theory.

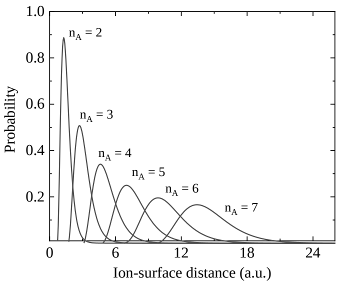

Fig. 1. Probability for the electron captured into the different Rydberg states ($n_A = 2-7$).

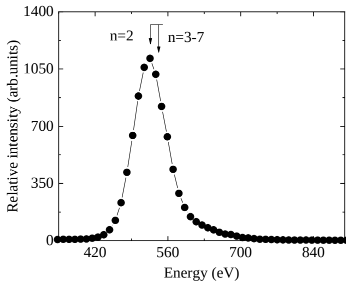

Fig. 2. X-ray spectra induced by 10 keV/q hydrogen-like O ions impact on copper surfaces.

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B58

Observation of extreme ultraviolet to visible spectra of tungsten ions with a compact electron ion beam trap

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For the spectroscopic diagnostics of the ITER plasma in the near future, spectroscopic data of tungsten ions are important. Since the temperature of the ITER plasma spans a wide range from the edge to the core regions, the charge state of tungsten ions required for the diagnostics also spans a wide range. An electron beam ion trap (EBIT) is an ideal device for observation and identification of previously unreported lines of tungsten ions and thus tungsten spectral data have been obtained at several EBIT facilities [1-4]. However, there is still a lack of data, and further observations and identifications are thus strongly needed.

So far, we have observed spectra of tungsten ions using a compact electron beam ion trap (CoBIT) [5] with a visible spectrometer useful for the 300 to 1000 nm range and an extreme ultraviolet (EUV) spectrometer useful for the 5 to 30 nm [6]. In order to fill a part of the gap between 30 and 300 nm, we have recently built a new spectrometer [7], which is useful for the 11 to 124 nm range. Spectra of tungsten ions obtained with these three spectrometers are presented.

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B59

HCI-surface collision experiments with an electron beam ion source

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In the collisions of slow highly charged ions (HCIs) with material surfaces, the large potential energy of the ions causes characteristic interactions that are essentially different from those caused by low-charged ions or fast ions. The characteristic modification of surfaces caused by HCIs is expected to be applied for nano-scale surface treatment, surface analysis, and so on. Thus the study of HCI-surface interactions has been one of the most interesting and important subjects in the physics of HCIs for many years.

For performing HCI-surface collision experiments, an electron beam ion source (EBIS) was built in 2005 at Kobe university [1]. It has been operated since then for studying characteristic processes caused by the potential energy of HCIs [2-7]. The Kobe EBIS has recently been moved to the University of Electro-Communications in Tokyo. The current status of the EBIS and the experimental plans in near future are presented.

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B60

Observation of vacuum ultraviolet transitions relevant to astrophysical plasmas with a compact electron beam ion trap

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For the spectroscopic diagnostics of astrophysical hot plasmas, spectroscopic data for transitions in highly charged ions are important. For example, the solar observation satellite *HINODE* observes emissions in the extreme ultraviolet (EUV) range with an EUV imaging spectrometer (EIS) for the diagnostics of the solar corona. In order to obtain the spectroscopic properties of transitions relevant to the diagnostics with EIS, we observe EUV transitions of HCIs [1-3] with the Tokyo electron beam ion trap (Tokyo-EBIT) [4] and a compact electron beam ion trap (CoBIT) [5].

As a follow-on of EIS/HINODE, the Solar-C_EUVST mission is currently proposed. In this mission, transitions of HCIs are planned to be observed for a wavelength range wider than that in EIS for investigating not only the solar corona but also the chromosphere to the transition region. The planned wavelength range spans from 17 to 285 nm, whereas the available wavelength range of the EUV spectrometer that has been used for the Tokyo-EBIT and CoBIT is 5 to 30 nm. In order to extend the observation range to a longer wavelength range, we have recently built a new vacuum ultraviolet (VUV) spectrometer useful up to 124 nm [6]. The performance of the new spectrometer and the spectra of ions relevant to the Solar-C_EUVST mission, such as 46.5 nm of Ne VII, are presented.

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B61

Observation of extreme ultraviolet spectra relevant to the electron density diagnostics of solar corona active regions

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Extreme ultraviolet (EUV) emission line intensity ratios of highly charged ions can be used for the density diagnostics of the solar corona. For active regions such as flare plasmas, density-sensitive emission line pairs that can be applied to the high-temperature and high-density ranges are needed. Ions such as Ar XIII-XIV and Ca XV-XVII are candidates that are useful for the temperature range $T_{\mathrm{e}} > 3$ MK [1,2].

We present EUV spectra of Ar XIV and Ca XV observed with two electron beam ion traps (EBITs), the Tokyo-EBIT [3] and CoBIT [4]. The applicability of EUV line ratios in these ions to the density diagnostics is examined through the comparison of collisional radiative model calculations with the spectra obtained with a well-defined EBIT plasma.

This work was supported by JSPS KAKENHI grant No. JP19H00665.

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B62

Laser cooling of relativistic O^{5+} ions at CSRe: experiment and simulation

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Laser cooling of O^{5+} ion beams with an energy of 275.7 MeV/u was successfully achieved at the storage ring CSRe in Lanzhou, China [1, 2]. To the best of our knowledge, the Li-like O^{5+} ions are the highest charge state and highest transition energy ions that have ever been laser-cooled. To explain the experimental results, we simulate the Schottky spectrum of bunched O^{5+} ions with and without laser cooling by employing the multi-particle tracking method. In the simulation, both the transverse oscillation and the photon-ion resonant interaction process are considered. For bunched ion beams, the power of the central peak is about several orders of magnitude higher than that of the sidebands, which was attributed to the 'coherent effect'. The simulation systematically studied the dependence of the Schottky power on the ions number at different bunching and observation harmonics, and the 'coherent effect' has been interpreted for the first time [3]. For laser-cooled bunched ion beams, both the experimental and simulation Schottky spectra are shown in Fig. 1. The simulation result shows good agreement with the experimental result, providing a precise method to extract the momentum spread of the laser-cooled O^{5+} ion beams. In the experiment, the dynamics of laser cooling processes have been investigated systematically by detuning frequency between the bucket and the laser. With most of the ions laser-cooled to the center of the bucket, the relative longitudinal momentum spread of the O^{5+} ion beams reached $\Delta p/p \approx 1.5 \times 10^{-6}$, which is limited by the diagnostic resolution of the Schottky diagnostics for bunched ion beams. The experiment and simulation will benefit the further laser cooling and precision laser spectroscopy experiments at the storage rings and also Gamma Factory at CERN [4].

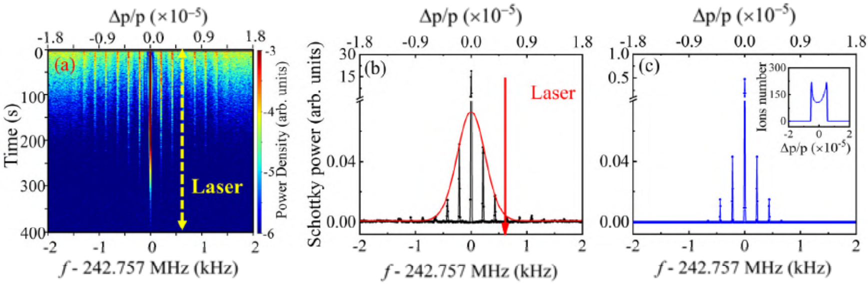

Figure 1 (a) The Schottky spectrum of laser-cooled bunched O^{5+} ions at the CSRe. (b) The Schottky spectrum extracted from figure (a) at 150 s. (c) The corresponding simulated Schottky spectrum of figure (b), in which the inset shows the momentum distribution used in the simulation.

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B63

EUV emission and charge-separated suprathermal ion from a laser-produced tungsten plasma

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Tungsten (W) is a promising material for plasma-facing components in future magnetic confinement fusion (MCF) reactors such as ITER. This is because tungsten has desirable properties as plasma-facing components, for instance low hydrogen retention. However, since tungsten is a high-Z heavy element its multiply ionized ions will still have bounded electrons even in the centre of ITER plasmas in an electron temperature range of less than 1 keV [1]. Highly charged tungsten ions radiate intense emissions in the extreme ultraviolet (EUV) regions, and this results in a large energy loss of confined plasma. Then it is important to diagnose not only the EUV emission but also the suprathermal ion generation as contamination.

We observed the EUV spectra and the charge-separated ion spectra from a laser-produced tungsten plasma. Figure 1 shows the spectral comparison by optical thickness due to the critical density difference of 1×10^{21} cm^{-3} and 4×10^{21} cm^{-3}, which are the laser wavelengths of 1064 nm and 532 nm. We found that the increase emission in 1 nm – 3 nm under optically think condition. Some peaks in 1.3 nm – 1.5 nm were attributed to W XXXVIII ions. In addition, shorter wavelength peaks appeared for optically thick condition, as compared to lower optical thickness. Figure 2 shows the tungsten ion spectra by use of a Faraday cup and an electrostatic analyser (ESA) at laser wavelength of 1064 nm and the laser intensity of 1×10^{14} W/cm^2. The maximum kinetic energy was observed to be 2 MeV due to heavy element of tungsten. We would show some dependences of the spectral behaviors of the EUV emission and the suprathermal ions.

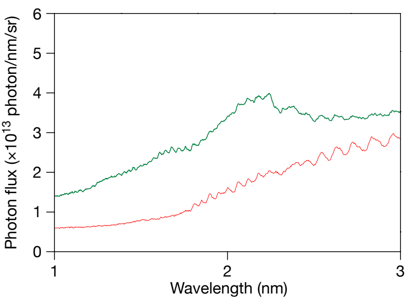

Figure 1: EUV spectra.

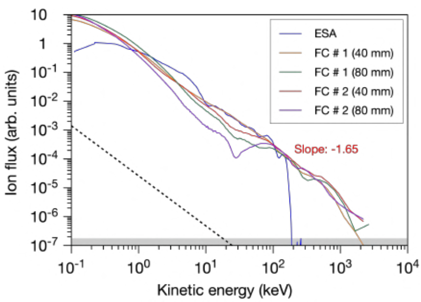

Figure 2: Suprathermal ion spectra.

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B64

Status and future perspectives of the U^{89+} resonant coherent excitation (RCE) experiment at GSI/FAIR

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We have been working on the high-precision spectroscopy of the Li-like U^{89+} 2s - $2p_{3/2}$ transition (4459.37(21) eV) using resonant coherent excitation (RCE) in a thin silicon target. This transition is a well-known target for precise tests of two-loop QED and is often used as a reference line for heavy-ion x-ray spectroscopy. After the first successful experiment using the 190 MeV/u U^{89+} provided by the SIS at GSI [1], we have focused on improving the spectroscopic precision of this method by using the electron-cooled U beam from the Experimental Storage Ring (ESR) [2]. With the upgraded voltage divider [3], the transition energy is expected to be measured with a reduced uncertainty of several parts per million on the absolute transition energy. A new attempt to measure the 2s - $2p_{1/2}$ transition energy (280 eV) is developed using a silicon drift detector with an extremely thin window. The status of the developments and possible plans for future experiments at the Facility for Antiproton and Ion Research (FAIR) will be discussed in the poster.

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B65

Far-UV emission from the laser-produced plasma of Al, Cu, Fe, and Inconel alloy targets

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Laser-produced plasma (LPP) has been intensively studied during past decades as a promising light source in a wide range of wavelengths. In particular, the EUV and soft X-ray emission from LPP has attracted considerable attention in the prospect of applications lithography and microscopy. On the other hand, experimental and theoretical studies of LPP in the far-UV region (50-200 nm) are quite limited compared to those in EUV and soft x-ray region, partly because of the few industrial applications expected in this region. Nevertheless, photo processes in the far-UV region are crucial in natural sciences since they trigger the electronic transition of atoms and molecules and promote chemical reactions. In this contribution, we report on a spectroscopic study of LPP in the far UV region using a second harmonics of a high-power Nd:YAG laser and various metal targets; Al, Cu, Fe, and Inconel 600 alloy (Ni/Cr/Fe/Mn). The emission from LPP was analyzed by a vacuum monochromator with a toroidal grating (1200 G/mm) and a photodiode detector. In Figure 1, the solid line shows an example of the LPP spectra from the Fe target obtained at the laser pulse energy of 520 mJ. We analyzed the laser-power dependence of the spectral shapes and intensities for various target elements with the help of the LIBS (Laser-Induced Breakdown Spectroscopy) database from NIST (https://physics.nist.gov/PhysRefData/ASD/LIBS/). The dotted lines show the LIBS simulation for Fe, Fe^{+}, and Fe^{2+} calculated for the electron temperature $T_e = 6.5$ eV and the density $n_e = 6 \times 10^{21}$ cm^{-3}. The spectrum is composed of many lines, including transitions between excited states of Fe^{+} and Fe^{2+}. Also, to increase the photon flux at the end of the monochromator, we have developed a parabolic mirror system, which enhanced the spectral intensity by more than an order of magnitude.

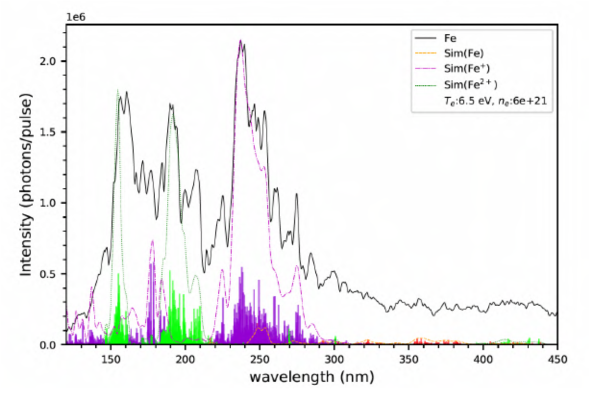

Figure 1: The LPP spectrum of Fe observed at the laser pulse energies of 520 mJ. The dotted lines show the simulation using the LIBS database from NIST.

B66

Generation of highly charged Au ion in laser-produced plasma for water window X-ray radiation sources

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Highly ionized plasma generated by a high-power laser pulse radiates bright and short-pulse X-rays. Since X-rays have much shorter wavelength than conventional visible/UV lights, diffraction limit becomes shorter, making it possible to observe nanoscale objects with higher spatial resolution. Particularly, X-rays in the water-window (WW) region (2.3-4.4 nm) have shown a considerable difference in absorption between carbon and oxygen (water), which are the two main constituents of living organisms. Therefore, X-ray microscope using WW region has a substantial potential for nanoscale living cells diagnostic.

One of the methods to develop a WW soft X-ray source is to use laser-produced Au plasma. Due to the *4d-5f* transition in the highly ionized Au ion attributed to Au^{24+}~Au^{29+}, there is a strong unresolved transition-array (UTA) emitted from the plasma, which mainly contributes to the emissions at the WW region (Fig. 1). Besides, an enhancement of WW emission has also been observed, when a Au plasma is generated by a commercial Nd:YAG laser (1064 nm, 7 ns, 1 J) under a low-pressure nitrogen gas atmosphere [1]. Based on these facts, the Au laser plasma scheme has become an attractive candidate for the WW X-ray source with ns or less pulse duration.

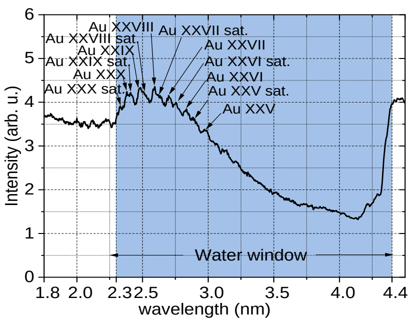

Figure 1 Au UTA spectrum

However, considering the cost and the repetition rate for a practical WW X-ray generation, a thin tape target is more favorable when compared to the usual planar targets. Not only because thinner targets can readily be supplied at a repetition rate of >100 Hz, but also they produce less debris from the vicinity of the plasma, which effectively prevents optics from been damaged [2]. Therefore, it is necessary to optimize the target thickness as thin as possible, while still holding the conversion efficiency at a high level. In addition, since the precise gold opacity has not been disclosed, a reliable opacity table is craved in the indirect inertial confinement fusion (ICF) science. In addition, an optimization of the laser focusing spot size under fixed laser energy has also been investigated. More details will be presented in the poster.

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B67

Charge-separated ion spectra from a laser-produced plasma

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Extreme-ultraviolet (EUV) lithography at 13.5 nm is expected to be introduced in high-volume manufacturing of integrated circuits (ICs) having node sizes less than 10 nm. Lithography at this wavelength is capable of reaching feature sizes below 5 nm. Beyond that, switching to a shorter wavelength of around 6.*x* nm, while maintaining or increasing throughput in the lithography system, would improve resolution by a further factor of two and extend the technology to feature sizes less tha 2 nm. Plasmas of the rare-earth elements gadolinium (Gd) and terbium (Tb) produce strong resonant emission due to the presence of an intense unresolved transition array (UTA) around 6.*x* nm in the spectra of their ions. Because the emitting ions in Gd and Tb, plasmas have an electronic structure largely similar to Sn, they are expected to exhibit a similar spectral behavior, and emit an intense UTA due to $4p - 4d$ and $4d - 4f$ transitions at shorter wavelengths [1]. Recently, the suitability of CO_2 laser-produced plasma (LPP) EUV sources based on Gd and Tb has been demonstrated for efficient, high power operation [2].

We observed the ion debris using an electrostatic analyser (ESA) to separate the charge states. Figure 1 shows the charge-separated ion energy spectra. The maximum charge state was Gd^{17+} (not shown) with a most probable energy higher than 20 keV. We show some dependence of the laser intensity and its pulse duration.

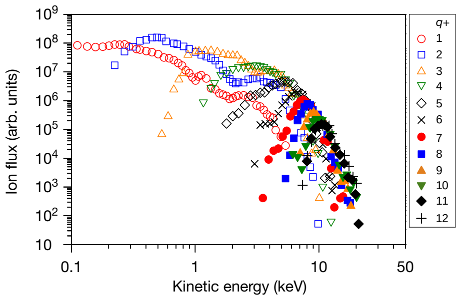

Figure 1: Charge-separated ion spectra from a laser-produced Gd plasma.

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B68

Spatial Profile Measurement on Line Emissions from Highly Ionized Tungsten Ions of W^{41+} to W^{46+} in the EUV Wavelength Range in the Large Helical Device

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Tungsten is a candidate material for plasma-facing components in the divertor region of the international thermonuclear experimental reactor (ITER) and future fusion reactors because of its high melting point, low sputtering yield, and low tritium retention [1]. On the other hand, there is a concern that tungsten ions with a large atomic number of Z = 74 will cause large energy loss by radiation and ionization when the plasma is contaminated by the tungsten impurity. Therefore, it is very important to investigate the behavior of tungsten in high temperature plasmas in order to control tungsten transport and establish reliable operation scenarios for fusion reactors.
Spectroscopic studies for emissions released from tungsten ions have been conducted in the Large Helical Device (LHD), which is a superconducting plasma confinement device with a heliotron magnetic configuration, for contribution to the tungsten transport study in tungsten divertor fusion devices and for expansion of the experimental database of tungsten line emissions [2,3]. Tungsten ions are distributed in the LHD plasma by injecting a pellet consisting of a small piece of tungsten metal wire enclosed by a carbon tube.
In this study, the spatial profiles of highly-ionized tungsten ions from W^{41+} to W^{46+} are measured via space-resolved extreme ultraviolet (EUV) spectroscopy. By superposing electron cyclotron resonance heating with continuous neutral beam injection heating after the tungsten pellet injection, the electron temperature at the plasma center can be maintained above 3 keV, and the emission lines of W^{41+} to W^{46+} were observed in the EUV wavelength region as follows; W^{41+} at 131.2 Å, W^{42+} at 129.4 Å, W^{43+} at 126.3 Å, W^{45+} at 127.0 Å [4], and W^{46+} at 7.93 Å [5]. The ions with higher charge states are localized in the central region of the plasma where the electron temperature is higher. W^{41+}, W^{42+}, and W^{43+} were distributed in the electron temperature region of about 2 keV, while W^{45+} and W^{46+} were distributed in the electron temperature region of about 3 keV.
This work was partially supported by JSPS KAKENHI grant number 20K03896.

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B69

Study on non-Maxwellian electron energy distribution in ECRH plasmas via Helium-like argon and the satellite lines

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The motivation of this study is understanding electron energy distribution function (EEDF) in hot plasmas. EEDF represents a nature of energy transfer and dissipation processes in collisionless plasmas, e.g. astrophysical objects and thermonuclear fusion plasmas. In fusion plasmas, non-Maxwellian electron energy distribution function (EEDF) is expected during electron cyclotron resonance heating (ECRH), lower hybrid heating, dc heating, and so on. Muto et al. [1] investigated x-ray bremsstrahlung emission from ECRH plasmas in the Large Helical Device (LHD), and they discovered high-energy electrons up to 200 keV with a bulk plasma of T_e ~4 keV by the x-ray spectra. Another possible method to diagnose EEDF is population kinetics of ions, i.e., line spectra. X-ray lines emitted from helium-like ions and their satellite lines have been used as a temperature diagnostics, and intensities of lines that are formed especially by inner-shell excitation and ionization are affected by high-energy electrons [2]. Therefore, x-ray line spectroscopy with high spectral resolution can be a good diagnostics of EEDF.

In the 23rd LHD experimental campaign, we observed helium-like argon lines and the satellite lines around 3.98 Å in ECRH plasmas. Electron densities of the plasmas were scanned shot by shot in the range of (0.5 - 1.5)×10^{19} m^{-3}. Data taken by a Thomson scattering measurement and an electron cyclotron emission measurement show a sign of suprathermal electron inside the last closed flux surface under conditions of electron densities of less than 10^{19} m^{-3}. The x-ray measurement between 3.973 Å and 4.001 Å was performed by a crystal spectrometer whose spectral resolution is 0.028 mÅ. We also obtained spatially-resolved extreme ultraviolet spectra emitted from lithium-like argon at 23.5 Å, and confirmed that lithium-like argon ions were populated around the region where a sign of high-energy electron is confirmed.

In the observed x-ray spectra, we find a strange emission line at 3.988 Å, which has not been discussed observationally in fusion plasmas so far. Its intensity got significant under condition of electron densities of less than 10^{19} m^{-3}, and disappeared when the density got higher. According to calculated energy levels by Saloman [3], the line seems emitted from a doubly excited state $1s2s3p$ of lithium-like argon. We perform calculations of collisional excitation and ionization cross section, radiative decay and recombination rates, and autoionization rate by the Flexible Atomic Code [4]. We setup a collisional-radiative model by taking high-energy electrons with isotropic velocity distribution into account, and compared intensity ratios among the observed emission lines with the measurement results. We found that the observed intensity of the emission line at 3.988 Å is too high to be explained by the calculated intensities.

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B70

Commissioning of the UNIST-EBIT: X-ray Resonant Spectroscopy of the Highly Charged Ions at PAL-XFEL

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UNIST (Ulsan National Institute of Science and Technology)

To study highly charged ions (HCIs), UNIST (Ulsan National Institute of Science and Technology) built an electron beam ion trap (EBIT) to acquire spectral data of individual elements in their highly charged states. The use of permanent magnets maximizes portability to move in and out of the accelerator beamline. Preliminary experiments on connecting the EBIT with the PAL-XFEL (Pohang Accelerator Laboratory X-ray Free Electron Laser) hard X-ray beamline have been carried out over two R&D beam times. During these shifts, X-ray resonant spectroscopy of the highly charged argon ions with the aid of a monochromatic photon beam from the PAL-XFEL has been performed. In this work, we present highly charged argon spectroscopic measurements as well as the preparation of our next experiment with the iron.

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B71

Enhancement of gain coefficient of Li-like Al ion 3*d*-4*f* soft X-ray laser oscillation by a single resonator

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We have tried to develop a compact, high-repetition rate, intense soft X-ray laser (3*d*-4*f* transition, 15.47 nm) in Li-like Al ion (Al^{10+}) generaed by laser plasma. In a recombination plasma scheme, rapid cooling of the plasma due to an adiabatic expansion creates a favorable condition for a population inversion due to a three-body recombination process. The faster cooling of the electron temperature leads to a higher recombination rate and thus to a larger population inversion. By irradiating Al target with 16-pulse train of a joule class Nd:YAG laser (1064 nm, pulse width 400 ps, total energy: ~3 J), we have succeeded in increase of the gain coefficient to g=8.6 /cm. In order to obtain higher gain coefficient, we optimized the pulse interval of the pump YAG laser, by which we can control the plasma heating and cooling rates and thus increase the gain. In addition, to realize further enhancement of the gain coefficient, we employed a single resonator, which had a Mo/Si multilayer flat mirror (reflectitity@15.5nm and 86°: 45%).

In the experiment, Al line shaped plasma was generated by focusing the YAG laser beam by utilizing a prizm lens array. The focus size having a homogeneout spatial intensity distribution was 50 μm and 11 mm in height and length, respectively. We installed a temporal delay stage to control the pulse interval of each drive laser. Soft X-ray spectra were collected by a toroidal mirror and focused onto an entrance slit of a grazing incident spectrometer (flat-field, 1200 grooves/mm). Spectra were was measured by a CCD camera. By varying the plasma length (laser medium), we evaluated the gain coefficient for Li-like Al ion 3*d*-4*f* transition. On the other hand, the Mo/Si mirror was installed at 20 mm from the target edge. The laser beam radiated into both target sides and one of them was reflected by this Mo/Si mirror and subsequently returned in the lasing medium, resulting in increase of the X-ray intensity sigfinicantly due to double path effect.

As a result, the highest gain coefficient was obtained at a pulse interval of 250 ps, and the gain coefficient reached 9.84 /cm. Figure 1 shows the typical X-ray laser spectrum. When the plasma lengths were over 3 mm, the intensity increased linearly in terms of the plasma length, implying that the amplification seems to be classified into a gain saturation regime. As for the single resonator experiment, the intensity of 15.47 nm X-ray laser was increased by only 1.5 times, although the geometrical estimation and mirror reflectively expected the value of 2.57 times. The reason for this is insufficient alignment of the reflected X-ray beam, by which the reflected laser was not passed through the lasing plasma medium appropriately.

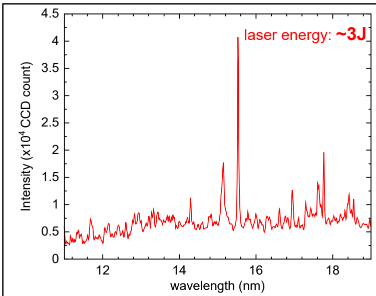

FIG. 1 Lasing spectra of 15.47 nm Li-like Al ion 3*d*-4*f* trainstion.

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Measurements of highly charged Si and Ba ions from the SAO EBIT

Amy Gall [a], Adam Foster [a], Yang Yang [a,b], Endre Takacs [b,c], Nancy Brickhouse [a] ,
Eric Silver [a] , Randall Smith [a]

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The electron beam ion trap (EBIT) facility at the Smithsonian Astrophysical Observatory (SAO) has been recently brought back online after a silicone coolant leak compromised the vacuum system. During the recommissioning process the trapping electronics, gas injection, control, and thermal systems were updated or redesigned to improve performance. Despite the ultra-high vacuum pressure, background gases become highly ionized through electron impact ionization during EBIT operation and are observable if the ion trap is not periodically dumped, as is the case for all EBITs. As part of our efforts to characterize the updated EBIT system, the background contaminants were observed using a broadband solid-state X-ray detector while systematically scanning the electron beam energy over a broad energy range. Spectral features resulting from radiative recombination, direct excitation, and the resonant dielectronic recombination processes are reported for various elements including Si from the initial coolant leak, and Ba from the electron gun cathode. A collisional radiative model was used to help identify features and a comparison of the modelled and measured spectra are presented.

B73

Selective Field Ionization of Rydberg Atoms for Blackbody Sensing

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Electromagnetic radiation sensing is at the core of modern physics. A ubiquitous source of incoherent radiation is blackbody radiation (BBR): electromagnetic radiation emitted by a body in thermal equilibrium with its environment. It follows that characterizing BBR is an appropriate technique to accurately assess the temperature of a distant entity. A thermal radiation detector integrating an invariable quantum system represents the next technological leap in radiation thermometry while being directly traceable to the new International System of Units (SI).

Rydberg atoms are highly polarizable, and therefore extremely sensitive to electric fields such as BBR. Remarkable advances in vapor cell technology and laser systems have facilitated the efficient production of Rydberg states in atoms such as Rb. Efforts are underway at NIST to use Rydberg atoms as calibration-free, SI-traceable sensors of thermal radiation, thereby characterizing reference blackbodies at the 100 ppm level [1] and greatly reducing the calibration uncertainty for classical thermal radiation sensors. Furthermore, these sensors may serve to reduce the Stark shift uncertainty in atomic clocks due to BBR, the largest systematic error in those systems to date.

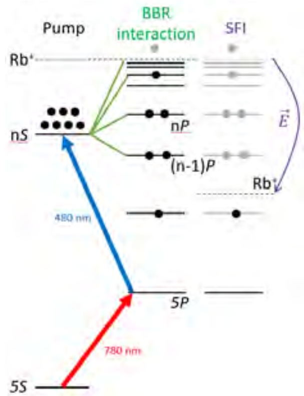

Figure 1: Procedure for selective field ionization (SFI) of Rydberg Rb atoms following blackbody radiation (BBR) interaction.

Selective field ionization (SFI) [2,3] of Rydberg states is the measurement technique to be employed. Parallel plates will be mounted in a Rb vapor cell. The Rb atoms will be pumped to Rydberg states via a two-photon process using counter-propagating lasers: a 780 nm laser will induce a $5S \rightarrow 5P$ transition and a 480 nm laser will bring the Rb to the final nS Rydberg state. The atoms will then evolve for a variable amount of time in the BBR field absent one laser field, where they will populate neighboring P states or photoionize (much smaller population). An electric field will be applied between the plates and ramped up to 10 kV/cm to selectively ionize high-lying energy levels in the Rydberg atoms as the field intensity increases. The ions will then be collected on a cathode, with the time of arrival determining the state energy and the signal size determining the state population. Measuring the transition rate across many states in the Rydberg atom should give the ability to measure BBR frequency components from $\sim$ 0.1 - 10 THz ($\sim$ 0 - 100 °C).

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B74

A Compact 0.7 Tesla Electron Beam Ion Trap using Radial NdFeB Arrays[†]

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We report on the progress at NIST in building a compact electron beam ion trap (EBIT) using drift tubes embedded with radially magnetized NdFeB arrays to produce a peak field of 0.7 Tesla for intensifying the electron beam at the trap center. This room-temperature EBIT is designed to facilitate experiments involving highly charged ions with low ionization thresholds, including tests of quantum sensors and development of high-accuracy optical atomic clocks. Although EBIT devices using superconducting magnets are very versatile, they tend to be costly to operate. It has been demonstrated that permanent magnets can be suitably configured to replace the B-field generating solenoid in an EBIT. An early effort at NIST employed a pair of axially magnetized NdFeB rings yoked by soft-iron drift tubes to produce a peak field of 290 mT at the trap center; observed highly charged ions extracted from this prototype[1] included Ne^{8+}, Ar^{9+}, Ar^{13+}, Kr^{17+}, as well as other species with ionization potential up to 900 eV. To enhance the magnetic field we have redesigned the architecture along the lines of a similar compact Penning trap[2] which utilizes three pairs of radially magnetized rings to yield an axial B-field of approximately 700 mT at the trap center.

[†]Supported in part by NIST Grants 70NANB19H162 and 70NANB15H046.

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B75

Observation of extreme ultraviolet spectra relevant to the electron density diagnostics of solar corona active regions

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Extreme ultraviolet (EUV) emission line intensity ratios of highly charged ions can be used for the density diagnostics of the solar corona. For active regions such as flare plasmas, density-sensitive emission line pairs that can be applied to the high-temperature and high-density ranges are needed. Ions such as Ar XIII-XIV and Ca XV-XVII are candidates that are useful for the temperature range $T_\mathrm{e} > 3$ MK [1,2].

We present EUV spectra of Ar XIV and Ca XV observed with two electron beam ion traps (EBITs), the Tokyo-EBIT [3] and CoBIT [4]. The applicability of EUV line ratios in these ions to the density diagnostics is examined through the comparison of collisional radiative model calculations with the spectra obtained with a well-defined EBIT plasma.

This work was supported by JSPS KAKENHI grant No. JP19H00665.

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Observation of vacuum ultraviolet transitions relevant to astrophysical plasmas with a compact electron beam ion trap

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For the spectroscopic diagnostics of astrophysical hot plasmas, spectroscopic data for transitions in highly charged ions are important. For example, the solar observation satellite *HINODE* observes emissions in the extreme ultraviolet (EUV) range with an EUV imaging spectrometer (EIS) for the diagnostics of the solar corona. In order to obtain the spectroscopic properties of transitions relevant to the diagnostics with EIS, we observe EUV transitions of HCIs [1-3] with the Tokyo electron beam ion trap (Tokyo-EBIT) [4] and a compact electron beam ion trap (CoBIT) [5].

As a follow-on of EIS/HINODE, the Solar-C_EUVST mission is currently proposed. In this mission, transitions of HCIs are planned to be observed for a wavelength range wider than that in EIS for investigating not only the solar corona but also the chromosphere to the transition region. The planned wavelength range spans from 17 to 285 nm, whereas the available wavelength range of the EUV spectrometer that has been used for the Tokyo-EBIT and CoBIT is 5 to 30 nm. In order to extend the observation range to a longer wavelength range, we have recently built a new vacuum ultraviolet (VUV) spectrometer useful up to 124 nm [6]. The performance of the new spectrometer and the spectra of ions relevant to the Solar-C_EUVST mission, such as 46.5 nm of Ne VII, are presented.

This work was supported by JSPS KAKENHI Grant Number JP19H00665.

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AUTHOR INDEX

HCI 2022 Timetable

Aug 28 (Sun)	Aug 29 (Mon)	Aug 30 (Tue)	Aug 31 (Wed)	Sep 1 (Thu)	Sep 2 (Fri)	Sep 3 (Sat)
	9:10 Opening	9:00 RL-2 Versolato		9:00 RL-5 Safronova	9:00 PR-11 Wolff	
	9:30 RL-1 Matsushita	9:45 ST-8 Higashiguchi		9:45 PR-9 Berengut	9:30 PR-12 Yan	
	10:15 ST-1 Yang	10:05 ST-9 Sokell		10:15 PR-10 Borschevsky		
		10:25 ST-10 Lyu	9:00-12:00 Poster session Virtual B			9:00-12:00 Networking
	10:35 coffee	10:45 coffee		10:45 coffee	10:00 coffee	
	11:05 PR-1 Rajput	11:15 PR-6 Wei		11:10 ST-19 Priti		
	11:35 PR-2 Jorge	11:45 PR-7 Rousseau		11:30 ST-20 Ding	10:30-12:30 Poster session (onsite only)	
	12:05 ST-2 Tribedi	12:15 ST-11 Yadav		11:50 ST-21 Wang		
				12:10 ST-22 Ueberholz		
	12:25 lunch	12:35 lunch	12:00 lunch		12:30 luch	adjourn
	14:00 PR-3 Hu	14:30 RL-3 Blaum	14:30 RL-4 Schmidt		14:30 RL-6 Rangama	
	14:30 ST-3 Kimura	15:15 ST-12 Herkenhoff	15:15 ST-14 Warnecke		15:15 PR-13 Oreshkina	
	14:50 ST-4 Takács	15:35 ST-13 Kromer	15:35 ST-15 Dijck		15:45 PR-14 Okada	
	15:10 ST-5 Strnat			Excursion + Banquet	16:15 ST-23 Okumura	
	15:30 coffee	15:55 break	15:55 coffee		16:35 coffee	
	16:00 PR-4 Niggas		16:25 PR-8 Lestinsky		17:05 PR-15 Bernitt	
17:00-19:00 Registration Reception	16:30 PR-5 Skopinski	17:00-20:00 Poster session Virtual A	16:55 ST-16 Isberner		17:35 ST-24 Hosier	
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	17:20 ST-7 Hillenbrand		17:35 ST-18 Loetzsch		18:15 Summary	