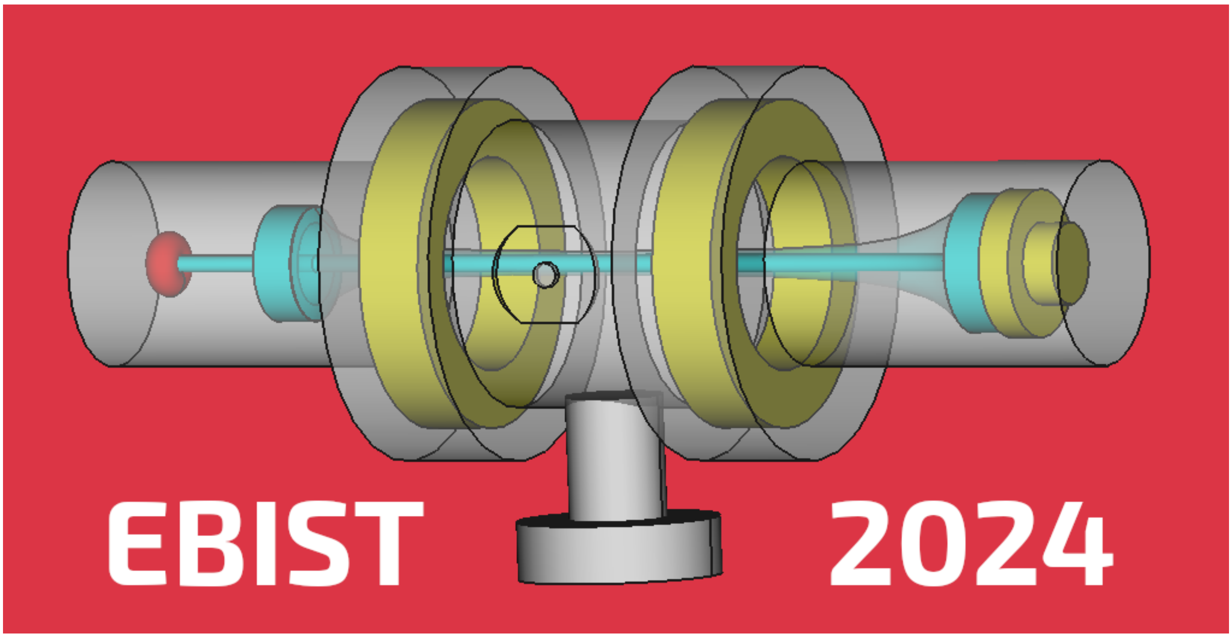

BOOK OF ABSTRACTS

The 15th International Symposium Electron Beam Ion Sources and Traps (EBIST 2024)

Jan Kochanowski University
Kielce, Poland
August 27-30, 2024

EBIST 2024 symposium was co-financed by the Minister of Science (Poland) under the "Regional Excellence Initiative" program (project no.: RID/SP/0015/2024/01).

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Welcome to EBIST 2024 in Kielce, Poland!

Welcome to the 15th International Symposium on Electron Beam Ion Sources and Traps (EBIST 2024). The goal of EBIST 2024 symposium is to discuss the design, development, applications of electron beam ion sources and traps, and the physics with highly charged ions.

The EBIST symposium has been held every three to four years since 1977. The previous two symposia took place on October 23-27, 2018 in Shanghai, China and June 14-17, 2022 in Whistler BC, Canada.

EBIST 2024 symposium is taking place in Kielce and is organized by the Institute of Physics of the Jan Kochanowski University (UJK). The entire scientific part of the conference, consisting of oral presentations and a poster session, will be held in the building of the Faculty of Natural Sciences UJK.

About 60 participants, representing 14 countries, registered to participate in the EBIST 2024 symposium, and over 50 abstracts were received, which is evidence of the great vitality of our community.

We wish all participants a successful meeting and a pleasant stay in Kielce.

Conference Program

Monday, August 26	
18:00 - 20.00	Registration
18:00 - 20.00	Welcome Reception

Tuesday, August 27			
08:00 - 12.00	Registration		
09:00 - 09:10	Opening		
Chair: Marek Pajek			
09:10 - 9:55	RL1	O. Versolato	13.5 nm LIGHT FROM TIN HCI IN LASER-PLASMA SOURCES FOR NANOLITHOGRAPHY APPLICATIONS
9:55 - 10:25	PR1	A. Niggas	HIGHLY-CHARGED-ION-INDUCED ELECTRON EMISSION FROM SURFACES
10:25 - 10:50	Coffee Break		
10:50 - 11:20	PR2	J. Tan	DEVELOPMENT OF A 0.7 T MINI-EBIT AT NIST FOR EXPERIMENTS USING TRANSITION-EDGE-SENSOR (TES) ARRAYS
11:20 - 11:50	PR3	K. Yao	PROGRESS AT THE SHANGHAI EBITS
11:50 - 12:10	ST1	C. Frank	IRRADIATION WITH HIGHLY CHARGED IONS: IMPACT OF THE KINETIC AND POTENTIAL ENERGY ON PARTICLE EMISSION
12:10 - 14:00	Conference Photo/Lunch Break		
Chair: Nobuyuki Nakamura			
14:00 - 14:30	PR4	A. Gall	MEASUREMENT OF THE EFFECTIVE ELECTRON DENSITY IN THE SAO EBIT
14:30 - 15:00	PR5	H. Guan	PROGRESS ON Ni^{12+} BASED HIGHLY CHARGED ION CLOCK
15:00 - 15:20	ST2	F. Grilo	INVESTIGATION OF THE Kα LINES FORMATION OF H-LIKE AND He-LIKE OXYGEN IONS IN AN ELECTRON BEAM ION TRAP
15:20 - 15:50	Coffee Break		
15:50 - 16:20	PR6	E. Ritter	EBIS APPLICATIONS - FROM SUPERNOVAE TO NEXT GENERATION TRANSISTORS
16:20 - 16:40	ST3	Ł. Jabłoński	TWO-ELECTRON PROCESSES IN RELAXATION OF XENON RYDBERG HOLLOW ATOMS
16:40 – 18:30	Poster Session/Lab Visit		

Wednesday, August 28			
Chair: Amy Gall			
09:00 - 09:45	RL2	M. Wakasugi	SCRIT FACILITY AND FIRST ELECTRON SCATTERING OFF ONLINE-PRODUCED RADIOACTIVE ISOTOPES
09:45 - 10:15	PR7	K. Yoo	COMMISSIONING STATUS OF EBIS CHARGE BREEDER AT RAON
10:15 - 10:50	Coffee Break		
10:50 - 11:20	PR8	F. Wenander	ATTAINING VERY HIGH CHARGE STATES WITH REXEBIS
11:20 - 11:50	PR9	R. Vondrasek	THE ATLAS ELECTRON BEAM ION SOURCE CHARGE BREEDER AND NUCARIBU
11:50 - 12:10	ST4	A. Lapierre	THE EBIS/T CHARGE-BREEDING SYSTEM OF THE REACCELERATOR AT THE FACILITY FOR RARE-ISOTOPE BEAMS
12:10 - 14:00	Lunch Break		
14:00 - 20:00	Excursion		

Thursday, August 29			
Chair: Alain Lapierre			
9:00 - 9:30	PR10	S. Kondrashev	COMMISSIONING OF EXTENDED EBIS AT BNL
9:30 - 10:00	PR11	B. Schultz	CANREB EBIS DEVELOPMENT AT TRIUMF
10:00 - 10:20	ST5	J. Rzadkiewicz	NUCLEAR EXCITATION BY NEAR-RESONANT ELECTRON TRANSITION IN $^{229}Th^{39+}$ IONS
10:20 - 10:50	Coffee Break		
10:50 - 11:20	PR12	E. Takacs	CHARGE STATE DISTRIBUTION AFFECTED BY HYPERFINE QUENCHING
11:20 - 11:50	PR13	H. Sakaue	ENERGY DEPENDENCE OF LINE RATIO IN Fe XV
11:50 - 12:10	ST6	T. Morgenroth	EXPERIMENTS ON HIGHLY CHARGED IONS FROM S_EBIT II
12:10 - 14:00	Lunch Break		
Chair: Endre Takacs			
14:00 - 14:30	PR14	Th. Stöhlker	HITRAP: TOWARDS TRAPPED AND COOLED URANIUM IONS AT HIGHEST CHARGE-STATES
14:30 - 15:00	PR15	S. Bernitt	HIGH-PRECISION X-RAY SPECTROSCOPY FOR ASTROPHYSICS USING EBIT
15:00 - 15:20	ST7	W. Biela-Nowaczyk	L-Mn DIELECTRONIC RECOMBINATION OF CERIUM IONS IN A ROOM-TEMPERATURE EBIT
15:20 - 15:50	Coffee Break		
15:50 – 16:20	PR16	Y. Yang	FIRST LABORATORY MEASUREMENT OF MAGNETIC-FIELD-INDUCED TRANSITION EFFECT IN Fe X
16:20 - 16:50	PR17	J. Richter	RESONANT X-RAY SCATTERING BY HIGHLY-CHARGED IONS EXPOSED TO MAGNETIC FIELDS
16:50 - 17:20	PR18	M. Łabuda	FRAGMENTATION DYNAMICS OF BIOMOLECULES IN THE GAS PHASE
17:20 – 19:30	Break		
20:00 – 22:30	Conference Dinner		

Friday, August 30			
Chair: Thomas Stöhlker			
9:00 - 9:30	PR19	W. Nörtershäuser	LASER SPECTROSCOPY OF HE-LIKE C^{4+} AND PROSPECTS FOR OTHER HE-LIKE LIGHT SYSTEMS
9:30 – 10:00	PR20	N. Kimura	TIME-RESOLVED PLASMA-ASSISTED LASER SPECTROSCOPY OF BE-LIKE Ar^{14+}
10:00 - 10:20	ST8	S. Kumar	DELHI PENNING TRAP FOR THE STUDY OF RELATIVISTIC ELECTRON IMPACT IONIZATION
10:20 - 10:50	Coffee Break		
10:50 - 11:20	PR21	M. Togawa	XFEL STUDIES ON TRAPPED HIGHLY CHARGED IONS
11:20 - 11:50	PR22	Y. Yang	MEASUREMENT OF THE ELECTRON IMPACT IONIZATION CROSS SECTION OF HELIUM-LIKE IRON
11:50 - 12:10	Closing		
12:10 - 14:00	Lunch Break		

RL: Review Lectures **PR: Progress Reports** **ST: Special Topics**

Social events

A welcome reception, a conference dinner and a half-day excursion are planned during the EBIST 2024 conference.

Welcome reception: Monday 26/8/2024
The welcome reception is scheduled on Monday evening from 6:00 to 8:00 p.m. The reception will be held in building G of Jan Kochanowski University, Faculty of Natural Sciences, at Uniwersytecka str. 7, 25-406 Kielce, Poland.

Excursion: Wednesday 28/8/2024
A half-day excursion to the Krzemionki Prehistoric Striped Flint Mining Region, a UNESCO World Heritage Site, will take place on Wednesday after lunch. Located in the Świętokrzyskie region of Poland, Krzemionki is one of the most important prehistoric mining sites in Europe, dating back over 4,000 years to the Neolithic period.

Conference dinner: Thursday 29/8/2024
The EBIST 2024 conference dinner will be held on Thursday evening at the Wilaneska Tokarnia restaurant, located at Krakowska str. 109 in Chęciny. This restaurant offers traditional Polish cuisine prepared with the best local ingredients.

Review Lectures

13.5 NM LIGHT FROM TIN HCI IN LASER-PLASMA SOURCES FOR NANOLITHOGRAPHY APPLICATIONS

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[2]LaserLab, Department of Physics and Astronomy, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

Tin plasmas, and specifically the highly charged $Sn^{10\text{-}14+}$ ions bred therein, are the sources of extreme ultraviolet (EUV) light near 13.5-nm wavelength for state-of-the-art nanolithography, which enables the continued miniaturization of the features on chips as embodied by Moore's Law. The tin plasma is driven by powerful pulsed lasers. Generating the required EUV light from these plasmas at sufficient power, reliability, and stability is a formidable task that continues to combine industrial innovations with scientific questions at the fundamental physics level.

In this talk I will present an overview of our recent research efforts and discuss the key processes that govern the dynamics in the various steps in the process of generating EUV light. Physics aspects range from fluid dynamics responsible for forming suitable targets for the powerful lasers, over plasma physics setting the charge state balance and the ions' kinetic energies, to the quantum mechanics governing the emission of EUV photons from multiply excited states in highly charged tin ions [1].

More specifically, our research ranges from (i) advanced laser development, over (ii) studies on target formation by laser pulse impact on liquid tin microdroplets [2]; to (iii) efficiently producing EUV light focusing on 2-micrometer-wavelength drive laser light [3], and (iv) studying experimentally and theoretically the production of fast ionic "debris" [4] and its interaction with H_2 gas surrounding the plasma [5], as well as the continuing development of imaging spectroscopies [6,7].

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SCRIT FACILITY AND FIRST ELECTRON SCATTERING OFF ONLINE-PRODUCED RADIOACTIVE ISOTOPES

Masanori Wakasugi[1,2*] **and SCRIT Collaborators**[1,2,3,4]

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The SCRIT (Self-Confining RI Ion Target) facility is the first facility in the world dedicated to electron scattering experiment on unstable nuclei (RI). In 2022, we succeeded in measuring the angular distribution of electron elastic scattering off ^{137}Cs (t=30y) nuclei produced online [1]. This was the first electron-RI collision experiment. This success opened the door to the study of the internal structure of RIs using lepton probes and was also the first practical application of fixed targets of unstable nuclei.

SCRIT is an ion target forming technology that utilizes the focusing force provided by an electron beam stored in an electron storage ring. Unlike conventional EBIT, the electron beam that traps ions in SCRIT has extremely high energy and bunch structure. Although the operating principle is somewhat different from EBIT, it can be regarded as one of the advanced applications of EBIT technology and would be the only way to make rare nuclei into fixed targets with a thickness applicable to nuclear reaction research.

The overview of the SCRIT facility is shown in Fig. 1. The RI used as a target is produced in a ^{238}U photofission process driven by a 150-MeV electron beam in an ISOL-type separator (ERIS). The RI beam from ERIS is converted into a pulsed beam at the cooler buncher (FRAC) and injected into the SCRIT device inserted in the storage ring (SR2) at the appropriate frequency. Typically, the target thickness is achieved to be ~10^9 /cm^2 and the collision luminosity exceeds 10^{27} /(cm^{2}s) with the injected target nuclei of 10^8 and the stored electron beam current of 200 mA. In the ^{137}Cs experiment, a luminosity of 10^{26} /(cm^{2}s) was obtained with 2x10^7 target nuclei, and the angular distribution of elastically scattered electron in the rage of 30-60 degrees was measured at 150 MeV. In this first online experiment, the statistics were still unsatisfactory due to insufficient driver power to generate RI. An upgrade plan is therefore currently underway.

In this presentation, the details of the SCRIT facility, the ^{137}Cs experiment, and future prospects will be presented. We will also mention about the fixed RI target currently under development as a next-generation SCRIT based on EBIT technology with the aim of applying it to other nuclear reaction research.

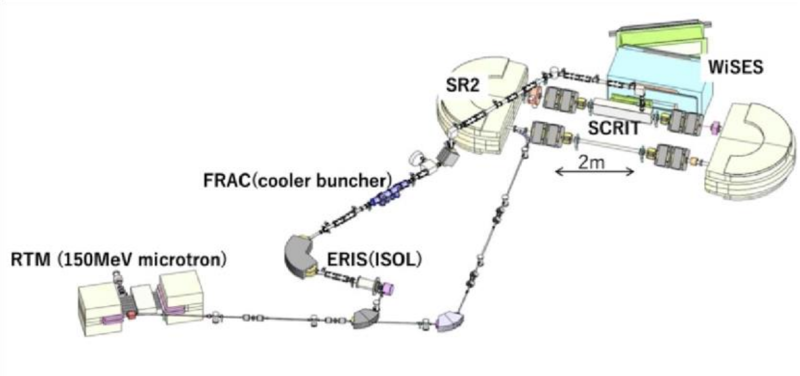

Figure 1: Overview of the SCRIT facility

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Progress Reports

HIGHLY-CHARGED-ION-INDUCED ELECTRON EMISSION FROM SURFACES

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When a highly charged ion (HCI) approaches a surface, the deexcitation of the projectile is initiated: Several Ångströms above the surface, electrons from the material are resonantly captured into high-*n* shells of the ion, forming a hollow atom [1]. Subsequently, these hollow atoms start to decay via a cascade including both radiative and non-radiative mechanisms leading to x-ray and electron emission, respectively. Close to the material, another mechanism contributes significantly to the neutralisation dynamics through emission of low-energy electrons from the surface, namely the interatomic Coulombic decay, a two-centre Auger-Meitner process [2]. In total, these deexcitation channels can lead to an emission of up to 100 electrons per ion depending on the initial potential energy of the projectile [3].

To study the deexcitation in more detail, we extract highly charged xenon ions in charge states up to q=40 from a Dresden EBIS-A and direct them towards a free-standing two-dimensional material, e.g., a single layer of graphene. This not only allows us to study the mean total electron yield but also to correlate the electron emission characteristics with the charge state of the ion after transmission. Fig. 1 shows data for 98keV Xe^{30+} projectiles. While the total electron yield for this incoming projectile amounts to ~66 electrons, the yield strongly differs depending on the particular charge exchange of the ion: More charge exchange, i.e., lower exit charge states, correspond to a higher number of emitted electrons.

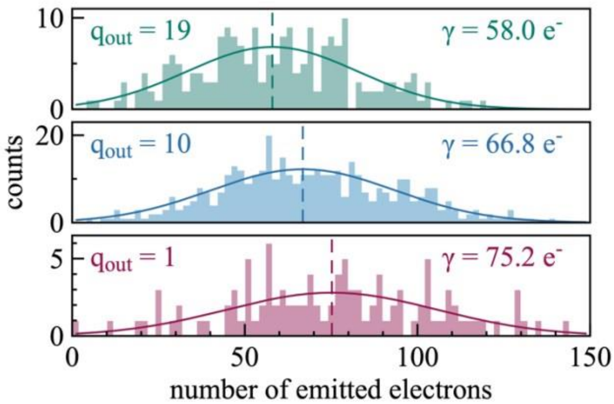

Figure 1: Electron yield spectra for 98keV Xe^{30+} transmitted through a single layer of graphene for three different exit charge states. Lower exit charge states, i.e., more neutralisation processes, are represented through higher electron yields.

In this contribution, we will outline how we apply measured electron emission statistics together with a relevant simulation package [4] to gain more insight into the deexcitation cascade of HCIs at surfaces.

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DEVELOPMENT OF A 0.7 T MINI-EBIT AT NIST FOR EXPERIMENTS USING TRANSITION-EDGE-SENSOR (TES) ARRAYS

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The electron beam ion source/trap (EBIST) has facilitated a host of experiments, including spectroscopic tests of quantum electrodynamics, ion-surface interactions, laboratory astrophysics and plasma diagnostics.[1] A number of room-temperature, compact EBITs have been introduced that proved to be very efficient sources of charge states with low ionization thresholds. The low energy regime is of particular interest for investigating certain highly ionized atoms with forbidden optical transitions (e.g., Pr^{10+} or Nd^{10+}) that have advantageous properties in searching for new physics beyond the standard model, and in developing very stable atomic clocks [2]. In addition, the well-known radiative transitions from H-like and He-like ions in an EBIT can be useful in providing very narrow spectral lines for the evaluation of x-ray quantum sensors (such as TES arrays), especially in the low energy domain where few reference lines are available from the x-ray fluorescence of metal targets.

A room-temperature EBIT can be made extremely compact by embedding strong permanent magnets in drift tubes. Such a mini-EBIT was constructed at NIST using a pair of axially magnetized NdFeB rings to obtain a peak magnetic field of 0.29 T. After a brief summary on this prototype [3,4], I will report on the progress in developing another portable EBIT designed to provide a higher peak magnetic field approaching 0.7 T. This high-field mini-EBIT will be installed on an advanced TES microcalorimeter in the Quantum Calorimeters Group, on the NIST Boulder Campus.

This work is supported by NIST Grants #70NANB19H1162 and #70NANB15H046.

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PROGRESS AT THE SHANGHAI EBITS

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Electron beam ion trap (EBIT) is a versatile instrument for conducting research in the field of highly charged ions. This abstract provides an overview of the recent progress at the Shanghai EBITs. The first category of experiments is focused on the atomic parameters essential for plasma diagnostics. Radiative recombination spectra of tungsten were measured at the Shanghai-EBIT to extract the electron impact ionization cross-sections of open *L*-shell W ions [1]. A series of experimental investigations of W optical lines were performed at the SH-Htsc EBIT [2, 3, 4, 5]. Furthermore, the magnetic-filed induced transition in Fe X, which has been proposed for coronal magnetic field measurements, was examined experimentally at SH-Htsc EBIT [6].

In the second category of experiments, we performed high-precision spectra and meta-stable state lifetime measurements at two home developed permanent-magnet EBITs. E.g., the clock transition for Mo^{11+} $4s^2 4p\ ^2P_{3/2}$-$^2P_{1/2}$ was measured directly with an accuracy level of a few ppm [7]. Employing the experimental setup depicted in Figure 1, the lifetime of Mo^{11+} $4s^2 4p\ ^2P_{3/2}$ and Mo^{15+} $3d^9\ ^2D_{3/2}$ [8, 9] meta-stable levels were measured for the test the anomalous magnetic moment effect in the magnetic dipole transitions.

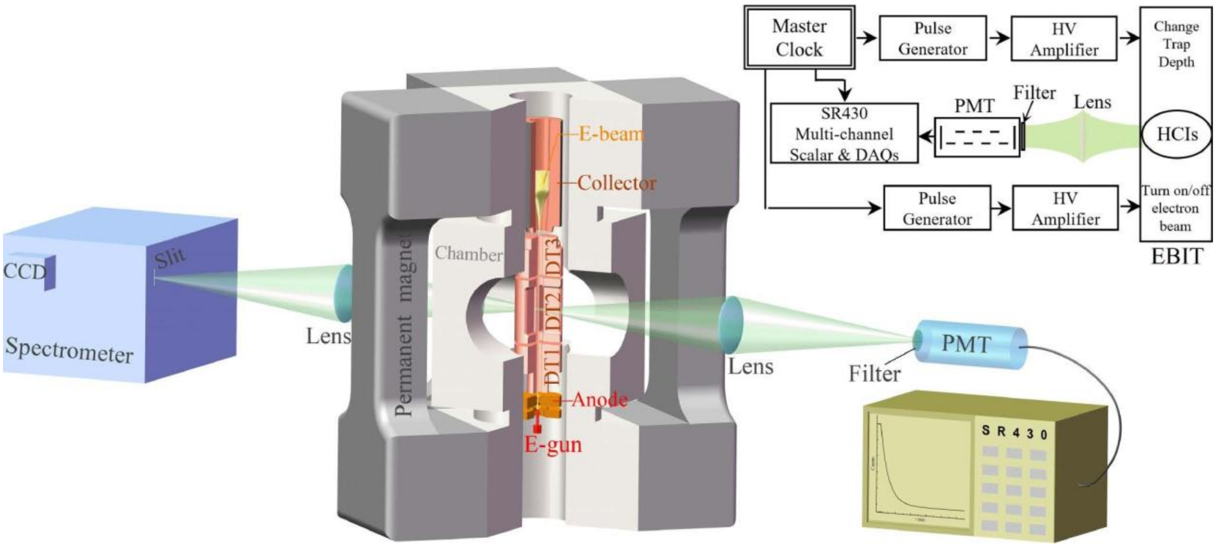

Figure 1: Schematic illustration of the lifetime measurement experiment setup. (Adopted from [9])

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MEASUREMENT OF THE EFFECTIVE ELECTRON DENSITY IN THE SAO EBIT

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The electron beam ion trap at the Smithsonian Astrophysical Observatory (SAO) has come online relatively recently and is primarily focused on astrophysically relevant studies. We present recent work to characterize the system including a measurement of the effective electron density, as an understanding of the density is necessary for modeling the plasma and will be critical for studies aimed at testing astrophysically important density diagnostics. The density was found by measuring the spatial distribution of X-ray and visible emission emanating from the electron beam and ion cloud, respectively. The distribution of emission from an Ar^{13+} forbidden magnetic dipole (M1) transition ($2s^2 2p\ ^2P_{1/2} - {}^2P_{3/2}$) at 441.2 nm was measured with two coaxial achromatic doublet lenses, a 440 nm filter with a 10 nm FWHM bandwidth, and a visible CCD camera. The spatial distribution of X-ray emission, primarily from Ar^{16+} and Ar^{17+}, was measured using a 20 mm long, 50 µm wide slit and an X-ray CCD camera. An effective electron density of 1.77 x 10^{10} cm^{-3} was found, an order of magnitude less than predicted assuming a homogeneous cylindrical beam.

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PROGRESS ON NI^{12+} BASED HIGHLY CHARGED ION CLOCK

Hua Guan[1*], **Shaolong Chen**[1], **Zhiqiang Zhou**[1,2], **Guosheng Zhang**[1], **Jiguang Li**[3], **Tingxian Zhang**[4], **Chengbin Li**[1], **Tingyun Shi**[1], **Yao Huang**[1], **Kelin Gao**[1*]

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

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

Source of error	Shift (pm)	Error
Line centroid determination	511582.05	0.21
Calibration system	/	0.42
Isotope shift	0.06	0.06
Stark shift	/	<0.01
2nd -order Zeeman effect	/	<0.01
Total	511582.11	0.47

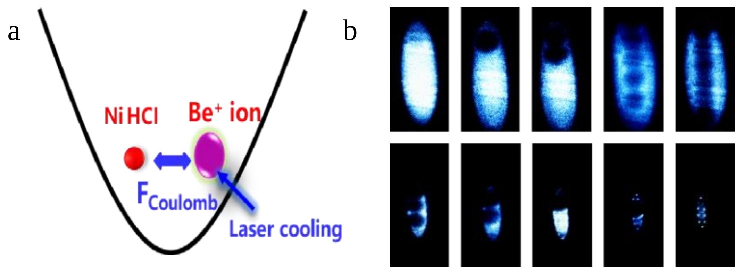

Fig. 1. The sympathetic cooling of HCIs. a : Sympathetic cooling Schematic Image ; b : Coulomb crystal of Be^+ and Ni HCI (the dark circular shapes) --The process of HCI from being injected and trapped and subsequently lost one by one.

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EBIS APPLICATIONS - FROM SUPERNOVAE TO NEXT GENERATION TRANSISTORS

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The Dresden EBIS-A is a table-top sized facility for ion production and acceleration with multiple application areas ranging from astrophysics to materials science and information technology. Every ion source built by DREEBIT, a Pfeiffer Vacuum company, is customized to meet the specific demands required by the individual application. In this presentation, we give an overview of recent Dresden EBIS-A installations at various institutions worldwide to demonstrate their capabilities and inspire future projects.

Using colinear laser spectroscopy like it is done at the COALA apparatus at TU Darmstadt, it is possible to determine transition frequencies and fine-structure splitting in He-like low-Z Atoms, which are highly charged (e.g. C4+-Atoms [1]). To reach the highest possible accuracy, the line shape of the fluorescence response function was studied for pulsed and continuous ion extraction modes, as the Dresden EBIS-A can provide both. Thus, the symmetry and linewidth could be optimized and a high accuracy could be reached.

Moreover, EBIS-A machines can be used to study the interior of stars and supernovae by means of x-ray and optical spectroscopy, measuring characteristic x-rays form highly charged metal ions. The challenge here is the production of highly charged ions from rare earth elements. The solution provided by Dreebit is the technique of Metal Ions from Volatile Compounds (MIVOC) [3] in combination with a Metal Alloy Ion Source with the possibility to inject ions produced by both methods into the EBIS-A.

For materials research in solid state physics, highly charged ions (HCI) can be used to obtain permanent modifications of surfaces and to obtain next generation transistors [4,5] Those modifications range from isolated point defects to phase transitions. Ion induced surface features are widely studied, but the theoretical understanding of the mechanisms is difficult. Since the EBIS allows for production of ions with different charge states and a tunable kinetic energy, contributions from potential and kinetic energy deposition can be studied independently, gaining a deeper understanding of the interaction details.

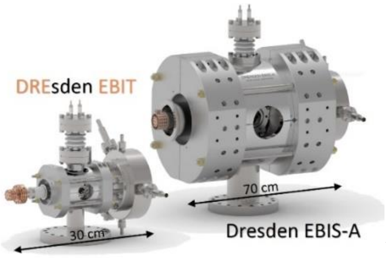

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Figure 1: Dresden EBIS and EBIS-A machines

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COMMISSIONING STATUS OF EBIS CHARGE BREEDER AT RAON

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The RAON heavy ion accelerator in Korea was constructed to facilitate experiments that produce and utilize more exotic rare isotopes, employing both the ISOL (Isotope Separation On-Line) and IF (In-Flight) methods [1]. Within the RAON ISOL facility (RISFAC), rare isotopes (RIs) are generated in the Target/Ion Source (TIS) module using a proton beam and subsequently extracted to the ISOL beamline [2]. The RI ion beam must meet the injection conditions required by the post-accelerator to the SCL3 (Super-Conducting Linac), which include an A/q ratio of less than 6 and an energy of 10 keV/u. To meet these specifications, an Electron Beam Ion Source (EBIS) charge breeder, operating with up to 2 A of the electron beam within a 6 T magnetic field, was installed to produce highly charged RI ions within the ISOL system [3].

Stable ions, including Cs, Sn, Rb, and Na ion beams, have been used to confirm the matching of the required conditions during the commissioning of the EBIS [2, 4]. Using an electron beam of up to 1 A, 133Cs27+ (A/q=4.93), 120Sn24+ (A/q=5), 85Rb17+ (A/q=5), and 23Na7+ (A/q=3.29) have been produced and transported to the A/q separator magnet to identify the A/q value of each ion. For the preparation of RI beam acceleration by the SCL3, stable 40Ar8+ ions (A/q=5) have been used for the commissioning of the SCL3. The first RI generation commissioning in the RISFAC used the SiC target, and RI Na and Al ions were extracted from the TIS system. To match A/q of ions used in its commissioning, 25Na5+ (A/q=5) among the generated RIs was targeted to be transported to the post-accelerator. 25Na1+ ions were separated in the pre-mass separator and injected into the EBIS. After charge breeding to 25Na5+ ions, they were transmitted to the post-accelerator. Progress on the commissioning of the RAON EBIS will be reported, along with the charge breeding and beam transportation results with stable and rare isotope beams.

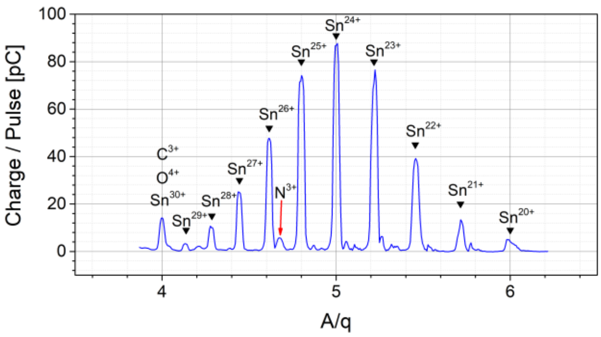

Figure 1: A/q (mass-to-charge ratio) distribution of charge-bred 120Sn ions with residual gas [2].

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ATTAINING VERY HIGH CHARGE STATES WITH REXEBIS

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At the REX-ISOLDE charge breeder, a higher electron current density allows for increasing the repetition rate and ion throughput, and extending the physics reach towards short-lived ions. However, this must not come at the expense of deteriorated beam purity and breeding efficiency. At REXEBIS, this goal was pursued by introducing a non-adiabatic electron gun as previously reported in ref. [1]. Since then, further breeding characterization experiments have been carried out, particularly focusing on reaching very high charge states. The lower mass-to-charge ratio allows for acceleration to higher energies, even exceeding the HIE-ISOLDE linac design value of 10 MeV/u for light ions, and for the heavy elements, the requested beam energies can still be attained, notwithstanding a decline of the field gradient with the years in the superconducting linac. The results will be discussed, and extensively compared with predictions from the EBISIM charge breeding code. In addition, experience from the operation with the IrCe cathode will be shared.

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THE ATLAS ELECTRON BEAM ION SOURCE CHARGE BREEDER AND nuCARIBU

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The Californium Rare Isotope Breeder Upgrade (CARIBU) ^{252}Cf source is being replaced with a new system that provides neutron-induced fission on actinide foils. The nuCARIBU system utilizes a 6 MeV cyclotron producing a 0.5 mA proton beam delivered to a ^{7}Li target. The resultant neutrons are moderated to thermal energies to induce fission in an actinide foil, providing neutron-rich fission products. During this time, the EBIS has been operating in a standalone mode. A new Ba/W dispenser cathode has replaced the IrCe cathode with no degradation in performance. Efforts are underway to lower the electron energy in the trap to achieve closed-shell breeding for the mid-mass species typical of nuCARIBU.

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COMMISSIONING OF EXTENDED EBIS AT BNL

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The Extended Electron Beam Ion Source (EEBIS) has been installed and commissioned at Brookhaven National Laboratory (BNL) hadron accelerator complex in the spring of 2023. EEBIS has replaced its predecessor, Rhic EBIS, which provided ions for BNL hadron facilities for over a decade since 2009. The main motivations for the source upgrade were related to the demand for higher intensities of the Au^{32+} ion beam for the Relativistic Heavy Ion Collider (RHIC) and to the necessity of an intense source of polarized $^{3}He^{2+}$ ions for a future Electron Ion Collider (EIC). EEBIS is now and will continue to be in the future the primary source for a variety of different ions for the RHIC, NASA Space Radiation Laboratory (NSRL), and a future EIC at BNL.

EEBIS utilizes two identical two meter long unshielded 5T warm bore superconducting solenoids, and it is operated with electron beam current up to 10 A providing a high capacity of ion traps to fulfill the requirement of high ion output. The upstream solenoid contains a "short ion trap" with a length of 95 cm, while the "long ion trap" with a length of 178 cm is located inside the downstream solenoid bore. The main features of EEBIS are:

- Gas injection and ionization cell equipped with Lorenz pulse valve
- High-capacity ZAO non-evaporable getter (NEG) custom linear pumping units
- In situ apparatus for pumping speed measurements to monitor NEG activation and saturation
- "External drift tube" construction with differential pumping stages to provide space for Lorentz pulse valve and He high field polarization cell
- New electron gun cathode.

The design of EEBIS as well as the results of its commissioning and first-year operation will be presented and discussed.

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CANREB EBIS DEVELOPMENT AT TRIUMF

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As part of the new Advanced Rare Isotope Laboratory (ARIEL) currently under construction at TRIUMF, the Canadian Rare isotope facility with Electron Beam ion source (CANREB) can deliver high purity beams of highly charged ions (HCI) to experiments. Stable or rare isotope beams are prepared in an RFQ cooler/buncher and energy matched into an EBIS charge state breeder using a pulsed drift tube. The EBIS was designed to produce an electron beam current up to 500 mA which is transported through a magnetic field of up to 6 Tesla. Ions are charge bred to $3 < A/q < 6$ and the resulting HCI are transported through a Nier-type mass separator prior to injection into the linac. In past years EBIS performance has been impaired due to limitations in high voltage and electron gun operation. Progress in addressing these issues, along with recent charge breeder development, will be discussed.

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CHARGE STATE DISTRIBUTION AFFECTED BY HYPERFINE QUENCHING

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The electron beam ion trap (EBIT) of the National Institute of Standards and Technology (NIST) was used to confine and probe Pr and Nd lanthanide ions at different electron beam energies and densities near their Ni-like ionization potentials [1]. Time resolved spectra were recorded by a transition edge sensor (TES) broadband, high energy-resolution x-ray microcalorimeter array of detectors [2]. The non-Maxwellian plasma was modeled by collisional-radiative calculations to reliably predict the spectral emission of the ion cloud [3].

Our analysis shows that the finely tuned charge state distribution near the Ni-like charge state is strongly affected by a metastable population fraction at 10^{10}-10^{12} cm^{-3} electron densities. The equilibrium intensities of Ni-like and Co-like spectral lines in Fig. 1. show that isotope-dependent hyperfine interaction strongly influences the population dynamics in these systems. The comparison of the time evolution of the measured and simulated x-rays spectra also indicates that the charge state distribution is affected by the hyperfine mixing of the $3d^94s$ $^3D_3$ and $^3D_2$ metastable energy levels.

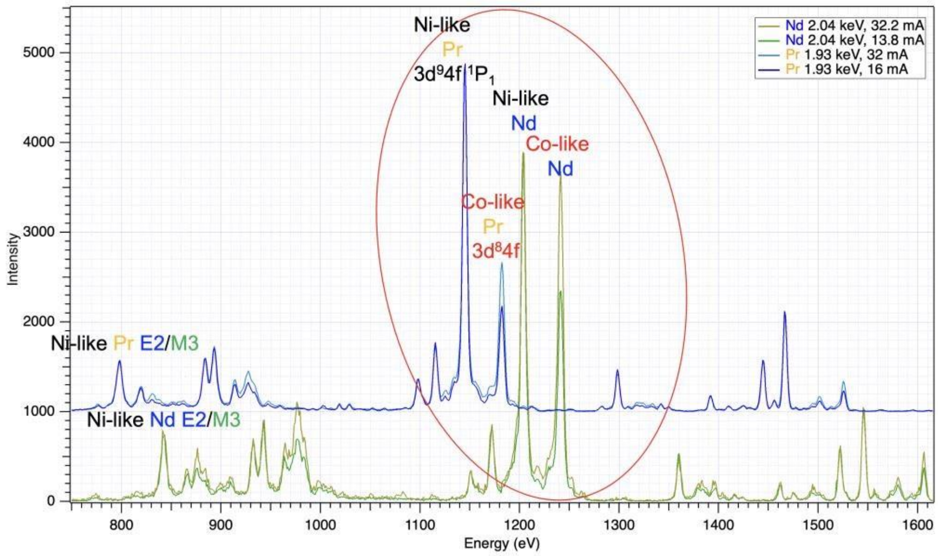

Figure 1: X-ray spectra of Nd and Pr at electron beam energies below their Ni-like ionization thresholds recorded by the NIST TES microcalorimeter array

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ENERGY DEPENDENCE OF LINE RATIO IN FE XV

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We present the energy dependence of the intensity ratio between the 3s3p $^3P_2$—3s3d $^3D_3$ transition at 233.9 Å and the 3s3p $^1P_1$—3s3d $^1D_2$ transition at 243.8 Å in Fe XV studied with an electron beam ion trap over an energy range that spans resonance excitation regions.

The line ratio I(233.9)/I(243.8) of Fe XV has often been reported to deviate from calculations in previous solar observations, and there have been various arguments that the discrepancy is due to the unreliability of the theoretical value or to the blending of other emission lines. We explored the cause of the discrepancy, using laboratory plasmas, and pointed out that there is a discrepancy between the experimental and theoretical values, even if there is no emission line blending inthe previous experiments [1].

We observed the extreme ultraviolet spectrum of Fe XV in the electron beam ion trap over a wide electron energy range of 400-600 eV and observed a clear resonance structure [2].

The observed line ratio between the 233.9 and 243.8 Å lines showed strong enhancement at someelectron energy regions, due to resonance excitation processes. The enhancement has reasonably been reproduced by the collisional-radiative model calculations. The present experimental and theoretical results have shown that the population of the 3s3p $^3P_2$ metastable state is important for the 233.9 Å line intensity, and thus for the ratio.

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HITRAP: TOWARDS TRAPPED AND COOLED URANIUM IONS AT HIGHEST CHARGE-STATES

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A unique selling point of the GSI/FAIR accelerator facilities is the storage and cooling of ions up to the heaviest species for precision experiments to study the physics of extreme electromagnetic fields as well as electronic processes subject to such extreme conditions. The related physics program, promoted by the international SPARC collaboration [1], builds on the ESR storage ring, the only storage ring worldwide which offers unparalleled experimental capabilities and allowing to decelerate ions to energies much below the injection energy (typical beam energy range between 400 and 4 MeV/u). Recently special focus was given to extend the physics potential by extraction the beams towards the dedicated low-energy storage ring CRYRING@ESR (extraction at typically 10 MeV/u) [2] and towards HITRAP (extraction at 4 MeV/u) where ions will be provided at rest in the laboratory, enabling experiments with utmost precision [3,4]. Whereas CRYRING@ESR is under full user operation since 2021 [2], HITRAP is currently still under commissioning, but substantial progress has been achieved very recently [5].

HITRAP consists of two linear stages for deceleration ions provided by the ESR down to several keV/q and subsequently trapping and cooling down to sub-eV energies [5], before guiding the ions for further use. We will present the current status of the HITRAP project with a focus on the very first experiments currently under preparation. Special emphasis will be given on first precision experiments with cooled ions confined in precision Penning traps such as at ARTEMIS [6] where laser-microwave double-resonance spectroscopy will be used to measure the intrinsic magnetic moments of both electrons and nuclei in highly charged ions.

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HIGH-PRECISION X-RAY SPECTROSCOPY FOR ASTROPHYSICS USING EBIT

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Instruments onboard satellite x-ray observatories, like Chandra, XMM-Netwon, or XRISM, record high-resolution x-ray spectra from hot astrophysical objects. These spectra are often dominated by line features originating from highly charged ions. Line intensities and apparent transition energies can provide valuable insights into temperatures, densities, and dynamics of different components of stellar atmospheres, accretion disks, intracluster media, and many more [1]. However, the amount of information that can be reliably extracted from spectra frequently depends on and is limited by the availability and quality of atomic data, like transition energies at rest, transition rates, branching ratios, or cross-sections. EBITs have proven to be invaluable tools in the field of laboratory x-ray astrophysics, providing this urgently needed atomic data, which is crucial for the success of current and future satellite missions.

We give an overview of recent developments and present experiments carried out with the compact, permanent-magnet-based PolarX-EBIT [2], in which we measured transition rates and energies of astrophysically relevant highly charged ions with unprecedented precision [3].

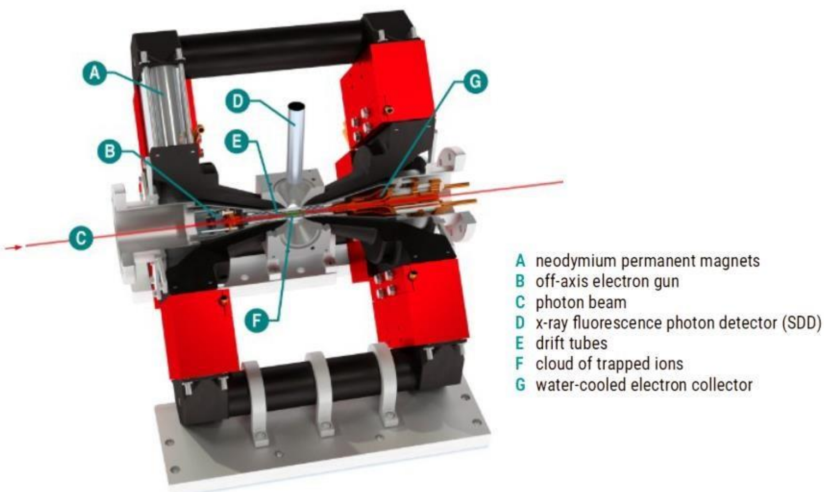

Figure 1: The compact transportable PolarX-EBIT.

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FIRST LABORATORY MEASUREMENT 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[1]. 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.

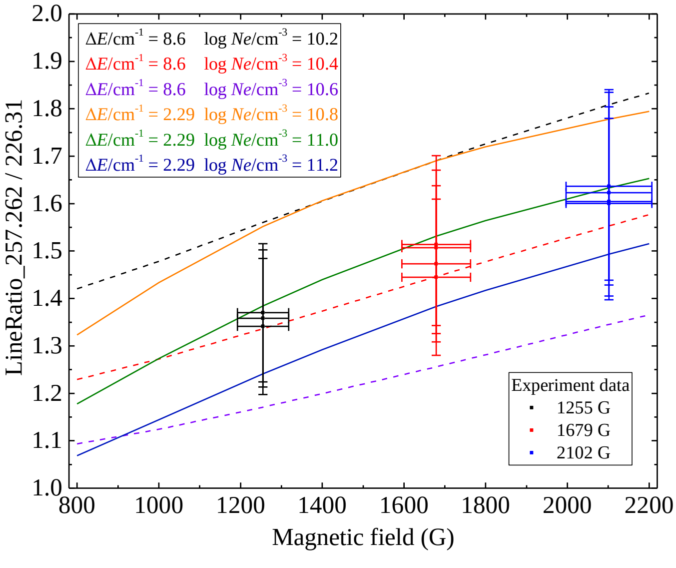

Figure 1: Theoretical and experimental values of line ratios of 257.262 Å and 226.31 Å versus the magnetic field.

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RESONANT X-RAY SCATTERING BY HIGHLY-CHARGED IONS EXPOSED TO MAGNETIC FIELDS

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The interaction of X-rays with highly charged ions is an important tool to study and characterize many astrophysical plasmas. Such interactions can also be studied under laboratory conditions, by employing electron beam ion traps (EBITs) and synchrotron radiation. Recently, for example, the elastic resonant scattering of linearly polarized x-rays on helium-like nitrogen ions was measured at the Elettra synchrotron radiation facility in Trieste using the portable PolarX-EBIT. In this experiment, one observed $1s^2\ {}^1S_0 + \gamma \rightarrow 1s\ np\ {}^1P_1 \rightarrow 1s^2\ {}^1S_0 + \gamma$ transitions for various excited states with $n = 2\ldots7$, and paid special attention to the probabilities of the photon scattering either in parallel ($W_\parallel$) or perpendicular ($W_\perp$) direction to the linear polarization vector of the incident radiation. It was shown, in particular, that the ratio $W_\parallel / W_\perp$ is highly sensitive to the principal quantum number n of the intermediate state $1s\ np\ {}^1P_1$ through which the resonant scattering occurs. In order to explain this n-dependence, we present a theoretical study of resonant photon scattering by ions. We demonstrate that a Zeeman splitting of the magnetic sublevels of the $1s\ np\ {}^1P_1$ states, induced by the EBIT's magnetic field, may drastically affect the angular distribution of scattered photons. This observation is closely related to the well known Hanle effect, which was observed first in 1924 and since then became a practical tool for lifetime determinations of optical transitions. In contrast to the conventional Hanle effect, in which one varies the magnetic field, the here presented 'soft X-ray Hanle effect' works also in static magnetic fields. By comparing experimental data with theoretical predictions we were able to determine femtosecond lifetimes of the $1s\ np\ {}^1P_1$ excited levels.

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FRAGMENTATION DYNAMICS OF BIOMOLECULES IN THE GAS PHASE

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The main focus of our work is to examine the mechanism and qualitative characteristics of different processes that occur in molecular interactions, mainly induced by ion-atom and ion-(bio)molecule collisions [1-4]. Such processes like ionization, fragmentation and charge transfer are essential in systems with biological interest, where approaches at the molecular level are crucial to model and control the effect of radiations on the cell to improve medical treatments, such as cancer disease and cell repair. Recently, based on the rapid development of the numerical tools and protocols we formulate *"step-by-step"* methodology to investigate collision-induced (eV energy range) fragmentation in the family of ring structures to identify the patterns for possible reaction channels [5-6]. A novelty in our treatment lies in the use of the state-of-the-art modern quantum chemistry and molecular dynamics methods, numerical implementations as well as in the use of machine learning methods to predict the patterns of possible fragmentation for the small size molecules.

To examine the electronic structure of the projectile and target involved we performed calculations of minima and transition states on the PES using wave function based approaches and Density Functional Theory, which allow to determine different accessible products of dissociation. Moreover, we introduced Atom-Centered Density Matrix Propagation method where calculations of the electronic PES are crossed over the classical nuclei movement *„on the fly"* to study molecular dynamics and to determine possible dissociation channels for the several values of energy (of eV range) being applied to the system. In this contribution I will discuss in details different scenarios currently developed and report on recent results of the fragmentation mechanism of model molecules (such as i.e. furan-C_4H_4O [5-6], hexachlorobenzene-C_6Cl_6 [7] and dihydropyran-C_5H_8O) with complementary photoionization and particle collision experiments data obtained by our collaborators to unravel the redistribution of internal energy of the molecules and their dissociation pathways.

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LASER SPECTROSCOPY OF HE-LIKE C^{4+} AND PROSPECTS FOR OTHER HE-LIKE LIGHT SYSTEMS

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Nuclear charge radii of radioactive isotopes are typically referenced to a stable nucleus in the isotopic chain through atomic isotope shift measurements. Elastic electron scattering, muonic atom spectroscopy, and their combined data analysis are the usual sources for those reference radii. In some cases, their accuracy limits the uncertainty of the charge radii of the whole chain of radioactive nuclei. This is particularly the case for the light elements and considerably hampers exploitation of the nuclear information that will be obtained by measuring the charge radius of ^{8}B, which is currently prepared at Argonne National Laboratory [1]. This isotope is considered a proton halo nucleus, and a direct comparison to the charge radius of ^{7}Be [2] would best allow for determining the halo-proton orbit's size. However, isotope shift measurements provide only changes in mean-square charge radii $\delta\langle r^2\rangle$ in the isotopic chain of one element. Hence, the difference in charge radii of two nuclei of different elements always includes the uncertainty of both reference radii. In the case of boron, the charge radii of the stable isotopes ^{10,11}B are known with relatively low precision that is much worse than for all other light elements and already limits the interpretation of a precise isotope shift measurement for tests of ab initio nuclear structure calculations [3]. Therefore, we have explored an all-optical approach for a charge radius determination purely from laser spectroscopy measurements and non-relativistic QED calculations [4] with the well-known ^{12}C nucleus through laser excitation of helium-like $^{12}C^{4+}$ from the metastable 2^3S_1 state with a lifetime of 21ms to the 2^3P_J states [5, 6]. High-precision collinear laser spectroscopy was performed at the Collinear Apparatus for Laser Spectroscopy and Applied Physics (COALA) [7] at TU Darmstadt in the Institute of Nuclear Physics and meanwhile extended to $^{13}C^{4+}$ [8]. We will give an overview of the project and present the results, including the all-optically extracted uclear charge radius of ^{12}C. An outlook on planned measurements at COALA and a potential application on short-lived isotopes at ISOLDE/CERN will be provided.

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TIME-RESOLVED PLASMA-ASSISTED LASER SPECTROSCOPY OF BE-LIKE AR^{14+}

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Be-like Ar^{14+} is a crucial spectroscopic research target for various motivations. For instance, extreme ultraviolet emissions of Be-like Ar^{14+} have been extensively observed in astrophysical plasmas. The simple energy level structure provides the prominent emission lines in a plasma, and they are useful for the diagnostics of its plasma condition. The simple atomic system with four bound electrons also gives an advantage for verifications of relativistic atomic structure calculations. Draganić *et al.* suggested that the visible transition $1s^22s2p\ ^3P_1 - {}^3\mathrm{P}_2$ is sensitive to the quantum electrodynamics (QED) effect, and they precisely measured its transition wavelength using emission spectroscopy with an electron beam ion trap (EBIT) [1]. Laser spectroscopy for this transition has also been proposed by the Oxford and Stockholm EBIT groups [2, 3]; however, the spectroscopic result has not been reported yet, to the best of our knowledge.

In this talk, we present our recent spectroscopic result on Be-like Ar^{14+} using a compact electron beam ion trap (CoBIT) at the university of electro-communications [4]. By employing the time-resolved plasma-assisted laser spectroscopy, which we recently demonstrated [5, 6], we succeeded in measuring the QED-sensitive transition wavelength of $1s^22s2p\ ^3P_1 - {}^3\mathrm{P}_2$. We also measured the transition-rate of the extreme ultraviolet intercombination line $1s^22s^2\ ^1S_0 - 1s^22s2p\ ^3P_1$, which is useful for the temperature diagnostics of astrophysical plasmas [7, 8].

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XFEL STUDIES ON TRAPPED HIGHLY CHARGED IONS

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The spectroscopic study of highly charged ions allow for benchmarking of atomic structure theory, particularly in predicting electron behavior in strong fields. This research provides insights into bound-state quantum electrodynamics (QED), nuclear effects, and electron correlation. Electron Beam Ion Traps (EBITs) as standalone experiments [1], along with studies using highly monochromatized light from synchrotrons [2,3], facilitate the experimental investigation of these effects in the X-ray regime.

We further extend these techniques making use of the ultrahigh intensities and short pulses provided by X-ray Free-Electron Laser facilities. These facilities offer intensities several orders of magnitude higher than those of contemporary third-generation synchrotrons. We make use of these properties and go beyond established X-ray absorbtion spectroscopy at FELs [4] and study nonlinear multiphoton processes in highly charged ions within the X-ray regime. Such multiphoton interactions are of fundamental scientific interest as they enable the investigation of the production of transient electronic states. Here, we present ultrafast ionization processes that traverse transient double core-hole states.

Furthermore, we present preliminary results from an experiment utilizing the novel two-color X-ray mode at EuXFEL [5]. This mode was applied in a pump-probe experiment aimed at determining the lifetimes of astrophysically relevant transitions, which are on the order of tens of femtoseconds. These lifetimes are typically challenging to measure, even with high-resolution spectroscopy.

The presented results originate from the newly commissioned compact EBIT, SQS-EBIT, which is now available for user experiments at the Small Quantum System Instrument (SQS) at the European XFEL.

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MEASUREMENT OF THE ELECTRON-IMPACT IONIZATION CROSS SECTION OF HE-LIKE FE^{24+}

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The Hitomi mission revealed the insufficiency of current atomic data in astrophysical databases for the era of high-resolution X-ray missions. In 2023, the XRISM mission, optimized in the Fe K band, was launched to use strong spectral lines to probe plasma conditions. To assess the accuracy of existing atomic data, measurements of electron impact ionization (EII) cross sections of He-like Fe were conducted at the cryogenic Electron Beam Ion Trap (EBIT) at the National Institute of Standards and Technology (NIST) [1]. The X-ray spectra were recorded with an array of 192 transition-edge sensor (TES) based X-ray microcalorimeters [2]. The EII cross sections of He-like Fe^{24+} were determined based on the measured intensity ratio of the resonance w line in Fe XXV to the Lyα lines in Fe XXVI at various electron beam energies. Measurements were compared with simulated spectra generated by a detailed collisional-radiative model [3] of the non- Maxwellian EBIT plasma. Measured cross sections show agreement with most theoretical predictions. We estimated the impact of measured results on the ionization fraction for a collisional ionized plasma in equilibrium.

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Special Topics

IRRADIATION WITH HIGHLY CHARGED IONS: IMPACT OF THE KINETIC AND POTENTIAL ENERGY ON PARTICLE EMISSION

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Ion beams are a strong tool for tailored modification of various solid properties, e.g. for manipulating a surface both structurally on the nanometer scale as well as chemically regarding its stoichiometry. Since these modifications are relevant inter alia for applications such as doping of two dimensional (2D) semiconductors by ion irradiation [1] or fabrication of membranes by pore creation [2], the investigation of ion-solid-interaction and understanding of its underlying fundamental effects are crucial for technological progress.

It is well known that both the kinetic energy and the potential energy of an ion have an influence on created defects regarding e.g. pore diameters. Highly charged ions provide enormous potential energies up to several hundred keV which enable high energy density deposition at the surface and in a surfacenear volume. There are various models in literature describing kinetic and potential sputtering of the sample due to ion impacts in accordance with experimental data such as the linear cascade theory [3]. However, there is no generally admitted universal model considering all experimental observations especially for the influence of the potential energy. A well-founded analysis of an ion's energy deposition in a solid requires a *separate* analysis of the influence of the ion's kinetic and potential energy, respectively.

Our HICS (highly charged ion collisions on surfaces) setup located at the university of Duisburg-Essen is designed to vary the kinetic energy and the potential energy independently over a broad range. The highly charged ions are provided from an EBIS (Dresden EBIS-A from DREEBIT GmbH, Germany) and their potential energy i.e. charge state is selected via a magnetic sector magnet followed by an acceleration/deceleration unit ("ion lift") [4].

We present time-of-flight secondary neutral mass spectrometry (ToF-SNMS) studies on the influence of the potential and kinetic energy on the sputter yield of a semiconductor (WS_2) and thin metal films (25 nm Au). In our studies we used highly charged Xe ions with potential energies between 12 keV and 40 keV and kinetic energies spanning from 20 keV to 260 keV. Our experiments show a linear dependence of the sputter yield on both the kinetic and potential energy in these ranges. Nevertheless, the influence of the potential energy is more dominant than the influence of the kinetic energy for both systems. Comparing the sputter yields of Au and W (from WS_2) shows a qualitatively larger influence of the kinetic energy on the sputter yield of Au.

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INVESTIGATION OF THE KA LINES FORMATION OF H-LIKE AND HE-LIKE OXYGEN IONS IN AN ELECTRON BEAM ION TRAP

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Atomic data from Highly Charged Ions (HCI) are fundamental for diagnostics of astrophysical observations [1] and nuclear reactor plasmas [2]. Most of the data comes from old calculations and has yet to be benchmarked in the laboratory. Unreliable atomic calculations can lead to wrong interpretations when included in the diagnostics and plasmas models. Such atomic data is often benchmarked in Electron Beam Ion Traps (EBIT), devices capable of producing, storing, and probing HCI [3].

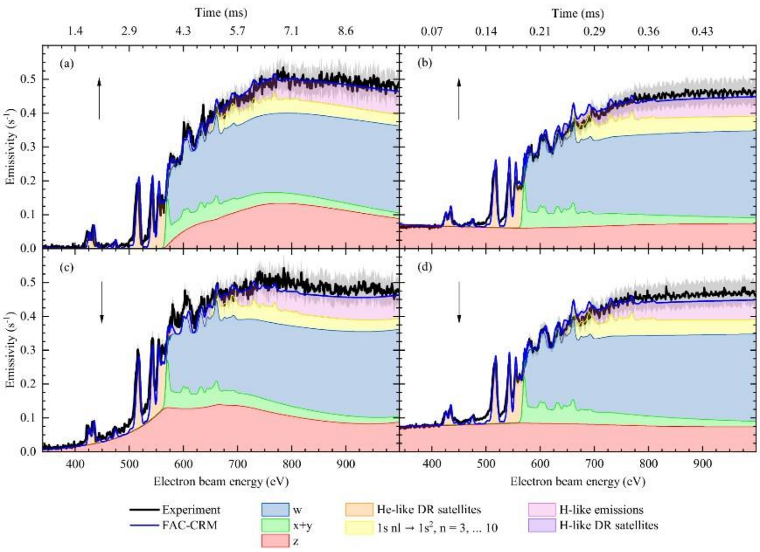

Figure 1: Experimental observations of He-like O emissions compared with the CRM simulations for different experimental

The Kα formation of He-like Oxygen was studied in the FLASH-EBIT, in Heidelberg, by ionizing and trapping oxygen ions and probing with the electron beam. In this experiment, the emissions were observed after to direct impact and resonant excitation, while the satellite lines of dielectronic recombination were also recorded. We developed a Collisional Radiative Model (CMR) capable of simulating energy level populations over time with a changing electron beam energy. Several energy scanning speeds produced different results due to 1s2s $^3S_1$ metastable state population. We were able to benchmark the code, obtaining a good agreement between the simulated spectra and the experimental observations. Our code also allowed the decomposition of the channels that feed the different emission lines and be applied to other more complex atomic systems.

Furthermore, The KLL dielectronic recombination structure of H-like oxygen was also observed. In this case, as the ion can recombined into a metastable state, an effective suppression of the dielectronic recombination structure was observed, with different magnitudes for different scanning speeds. The suppression was analytically modeled and verified with the experimental data.

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TWO-ELECTRON PROCESSES IN RELAXATION OF XENON RYDBERG HOLLOW ATOMS

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In slow collisions of highly charged ions Xe^{q+} ions ($q >> 1$) with surfaces the highly excited Rydberg ($n \approx q$) hollow atoms (RHA) are formed [1]. They rapid relaxation to the ground state in solids was a subject of intense debates in last years. In particular, in the experiments with monoatomic layers [2, 3] it was demonstrated that relaxation of RHA proceeds in a femtosecond time scale [2] and it was proposed [3] that ICD process [4] is responsible for a successive deexcitation of RHA, but only between the highest Rydberg states. Consequently, further relaxation of RHA down to ground state needs more investigations.

In this experiment, the X-rays emitted during the deexcitation of RHA were investigated. RHA were formed by interaction of ~8 keV×q highly charged Xe^{q+} ions (q=23-36) with metal surfaces. The pulsed ion beams were generated in the EBIS facility and the emitted X-rays were observed with a silicon drift detector. The measured M-X spectra were interpreted based on MCDHF calculations, as dominated by Paschen series of the strongest electric dipole transitions nf→3d along with their hypersatellites. In addition, the analysis showed an important contribution of two-electron processes to the mechanism of deexcitation of RHA including the exotic processes of internal dielectronic excitation (IDE) [5], two-electron one-photon transition (TEOP) and interatomic Coulombic decay (ICD).

The IDE process was identified as being responsible entirely for the emission of M-X radiation in the interaction of Xe^{q+} ions (q=23-26) with the Be surface, as for $q \leq 26$ the ions did not have initial vacancies in the M shell. This process was analyzed quantitatively for the first time, through the interpretation of energy spectra based on MCDHF calculations, and the proposed model of X-ray emission (q-XEM) explaining a dependence of the absolute intensity of M-X radiation on the charge state of the ion. In the measured M-X spectra for Xe^{35+} ions, transitions above the M-series limit were observed and interpreted as exotic two-electron one-photon transitions (TEOPs). Branching ratios for this process were determined in two dedicated experiments. In the spectrum recorded for Xe^{35+} ions, a sharp "cutoff" of the Paschen series of radiation transitions above the state $n_{cut} = 23$ was found, which indicates the presence of the ICD mechanism for higher states $n > n_{cut}$ in the initial phase of RHA relaxation. Based on the measured absolute intensities of the emitted M-X radiation, the fluorescence yield $\omega_M = \Gamma_X/\Gamma_A$ was determined, which was used to estimate the relaxation time of hollow atoms in their "radiative" deexcitation phase. Estimated lifetime is about 2 fs which shows that the relaxation of RHA in metals takes place on a femtosecond scale.

Acknowledgments

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THE EBIS/T CHARGE-BREEDING SYSTEM OF THE REACCELERATOR AT THE FACILITY FOR RARE-ISOTOPE BEAMS

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The Reaccelerator (ReA) of the Facility for Rare-Isotope Beams (FRIB) at Michigan State University (MSU) uses a helium gas-filled Radio-Frequency Quadrupole (RFQ) ion trap and an electron-beam ion trap (EBIT) as a charge-breeding system. Rare isotopes produced via projectile fragmentation or inflight fission are selected by the Advanced Rare Isotope Separator of FRIB and stopped in a helium gas cell before transport at low energy to ReA. Continuous ion beams are injected into the RFQ trap, which cools and bunches the ions, that are then ejected as ion pulses. The ion pulses are injected into the EBIT, captured, charge bred, ejected, and accelerated by the superconducting LINAC of ReA to several MeV/u.

The electron current of the EBIT (300 - 600 mA) limits its capacity to ~$2x10^{10}$ charges, yielding maximum rates of less than ~10^{10} pps for light ions. An upcoming upgrade to the EBIT electron gun is expected to provide 2 A in current. In parallel, a high-current electron-beam ion source (HCEBIS) is being commissioned in a test area. In its present configuration, the HCEBIS can provide an electron current of 2 A. An upgrade will increase the current to 4 A. The implementation of these two upgrades is expected to allow for maximum rates of ~10^{11} pps, compatible with FRIB projected rates. This will also provide redundancy of the breeders. We present the status of the upgrades and recent results of the EBIS/T charge-breeding system and future plans to upgrade the ReA injection system which will also integrate the HCEBIS to ReA.

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NUCLEAR EXCITATION BY NEAR-RESONANT ELECTRON TRANSITION IN $^{229}TH^{39+}$ IONS

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There is a strong interdisciplinary interest for the ^{229}Th isotope arising from its possible applications, such as nuclear clock frequency standard [1] and precise determination of the temporal variation of fundamental constants [2]. The nuclear excitation from the ground state to the 8eV ^{229m}Th isomer by near-resonant electron transition is considered theoretically for Sb-like (q = 39+) thorium ions. The multiconfiguration Dirac–Hartree–Fock method with configuration interaction has been employed in order to analyze the rich structure of $[Kr]4d^{10}4f^{5}$ configuration of Th^{39+}. The promising electronic transition has been found, which energy is very close to the new reference value of the ^{229m}Th nuclear isomer energy, 8.338±0.024eV [3]. It was found that within uncertainty range of both atomic and nuclear excitation energies, the rate of nuclear excitation by electron transition varies by more than two orders of magnitude. Our results indicate that the upper theoretical limit for the ^{229m}Th isomer excitation rate reaches at resonance (Δ = 0 meV) an enormous value of $\sim 10^{16} s^{-1}$. It was also shown that using an electron beam ion trap, the production of the ^{229}Th isomer can reach rates ranging from tenths to $\sim 10^{19} s^{-1}$. Thus, such an experiment would constitute an extremely sensitive tool for independent verification of the excitation energy of the isomeric state in the ^{229}Th nucleus.

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EXPERIMENTS ON HIGHLY CHARGED IONS FROM S-EBIT II

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Electron beam ion trap (EBIT) are versatile instrument for investigating electron-ion interactions, which shed light on atomic structures and plasma behaviours. Dielectronic recombination (DR) is one of the crucial processes determining ion charge state balance in hot plasma. It's knowledge not only improves theoretical understanding but also is vital for accurate plasma diagnostics [1]. Ions are at the center of experiments at GSI facilities such as CRYRING, ESR, and HITRAP. Currently, ion supply is dependent on the accelerator at GSI, but demand for ions has increased recently. To meet this demand and facilitate offline experiment operations at GSI, local ion sources will be essential. S-EBIT II can not only act as an ion source for HITRAP [2], but also can operate autonomously in standalone mode for separate experiments. This makes it a versatile tool for cutting-edge experiments with extracted highly charged ions, measurements of charge-changing processes such as DR and X-ray spectroscopy. It also opens up new opportunities for local experiments like ARTEMIS [3], independent of the GSI accelerator. DR measurements with argon have been carried out as a primary step towards completing commissioning of S-EBIT II, as well as an investigation of strategies to connect it to HITRAP. Integration of S-EBIT II with the HITRAP beam line, addresses the dynamic requirements of evolving experimental research with highly charged ions at GSI.

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L-Mn DIELECTRONIC RECOMBINATION OF CERIUM IONS IN A ROOM-TEMPERATURE EBIT

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Dielectronic Recombination (DR) is a fundamental process in ion-electron collisions and holds significant importance, particularly in astrophysical applications. Here [1], we explore the DR with experimental results obtained at the Electron Beam Ion Trap at Jagiellonian University in Cracow. There, an electron beam is generated by a high-current cathode made of iridium and cerium. Small amounts of these elements evaporate from the cathode and form low-intensity admixtures within the electronion plasma in the EBIT. Their presence and specific ionic population can be particularly observed by examining their spectral characteristics from the DR process. Results have been compared with FAC calculations, working in Unresolved Transition Array mode, allowing identification of the charge state of observed active cerium ions. These observations highlights which the DR features and respective charge states that should be present in spectra obtained in EBITs with similar cathode specifications.

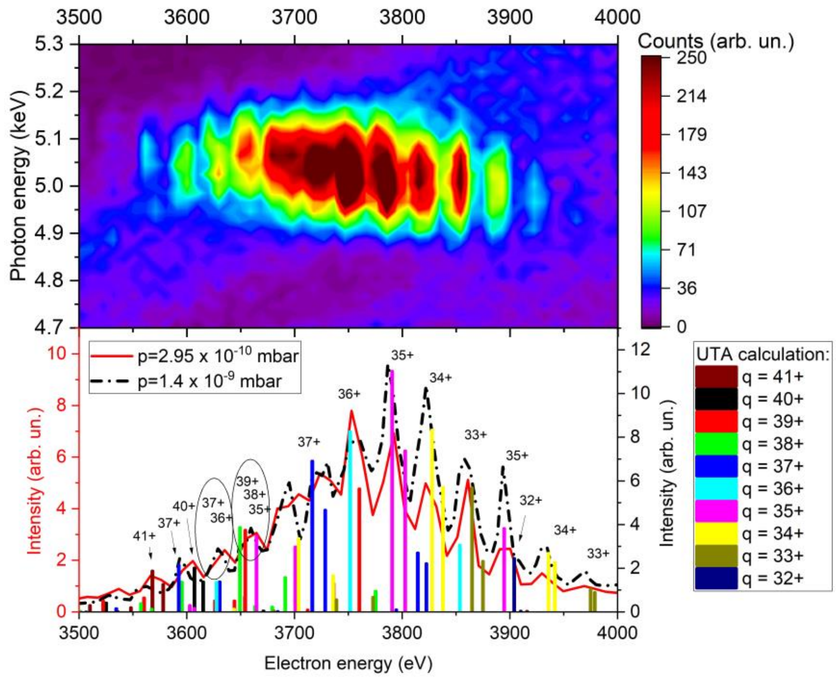

Figure 1: Top panel: selected part of the experimental data. Bottom panel: projection of the x-ray spectra on the electron energy axis. Bars shown in bottom panel present results of the UTA calculations for various cerium charge states.

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DELHI PENNING TRAP FOR THE STUDY OF RELATIVISTIC ELECTRON IMPACT IONIZATION

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Studying relativistic electron impact ionization cross-sections with MeV electrons in highly ionized atoms is fundamental for understanding the atomic interactions in high-energy environments. Accurately determining these cross-sections, particularly for highly charged ions, is essential for advancements in astrophysics, plasma physics, and radiation physics. In electron-beam ion trap experiments, some experimental data has been obtained for electron-impact ionization cross-sections for a few intermediate- and high-Z hydrogen-like ions [1, 2, 3].

A cryogenic Penning trap has been built to carry out these fundamental studies at Inter-University Accelerator Centre (IUAC), New Delhi, India. Electrons with energies ranging from 1 to 8 MeV, produced by the Free Electron Laser facility at IUAC, will be used to ionize the targeted ions at the trap's center. Both destructive and non-destructive detection methods measure the breeding time and the evolution of the charge state of stored ions and their relative ionization cross-section. The photo of the experimental setup of the Delhi Penning Trap (DPT) is shown in Figure 1(a).

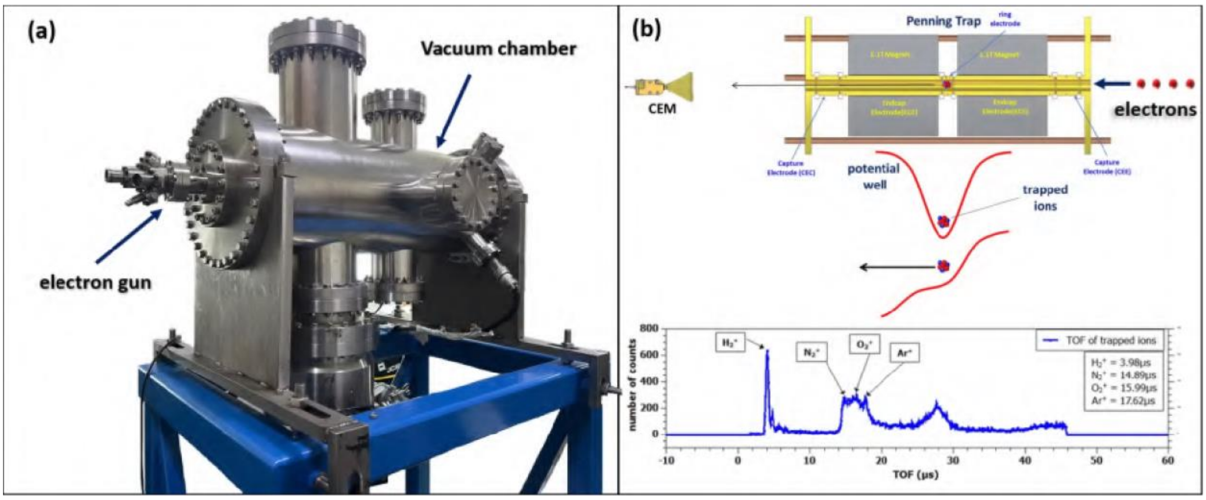

Figure 1: (a) TOF of trapped residual gaseous ions (b) Schematic overview of the Delhi Penning Trap.

In the initial measurements, atomic and molecular ions were generated through electron impact ionization of residual gas molecules and argon atoms within the Penning trap. The stored ion species were then analyzed by extracting them and measuring their time-of-flight (TOF) to a Channeltron electron multiplier (CEM) detector. The different ions were distinctly identifiable in the TOF spectrum as shown in Figure 1(b). Future measurements will extend this approach to include heavy ions, utilizing electrons from a Free Electron Laser (FEL).

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Poster Session

ITRIP DESIGN AND THE PROOF OF PRINCIPLE TEST

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Intense Highly Charged Ion Beams (HCIB) are crucial for the development of heavy ion accelerators and particle physics research. To meet the increasing demands for HCIB in new and existing heavy ion accelerators, we propose the Ion TRap for high Intensity Pulse beam (ITRIP)[1]. ITRIP aims to convert a DC ion beam from an Electron Cyclotron Resonance Ion Source (ECRIS)[5,6] into a high-intensity, short-pulsed ion beam with suitable compression ratios.

The conceptual design of ITRIP, inspired by Electron Beam Ion Sources (EBIS)[2,3,4], features a simple trap consisting of an electron gun, a solenoid, and a set of drift tubes (DTS). Ions injected from an ECR ion source are trapped radially and axially within the ITRIP. By controlling the potential of the drift tubes, highly charged ions can be accumulated through multiple injections and extracted in pulses of tens of microseconds.

To verify the principle of ITRIP, a dedicated ITRIP prototyping platform has been developed. The key issues of ITRIP, including beam injection,beam accumulation and pulsed extraction properties, have been tested and analyzed. Preliminary results and conclusions have been obtained, demonstrating the feasibility and performance of ITRIP as a novel ion trap for generating pulsed high-intensity highly charged ion beams. In this paper, a general overview of the ITRIP concept, its design, and the experimental verification conducted with the platform will be presented.

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HIGH PERVEANCE ELECTRON GUN WITH CONTROLLABLE CURRENT DENSITY

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The possibility of controlling the electron current density in an EBIS without changing the actual beam current looks very attractive because it allows to maximize the ion intensity. Our previous publication [1] describes a non-adiabatic electron gun with variable current density that requires an adjustment of the electron energy before the non-adiabatic element, in this case an iron ring. The next step was to design an electron gun, which does not need such adjustment while still generating a laminar electron beam in a wide range of currents and densities, a so-called “broadband” electron gun. Furthermore, we aimed to double the perveance of the gun, to avoid beam retardation in the trapping region to attain the desired space charge capacity. To realize the broadband electron gun, we used an iron ring as a non-adiabatic element to create a modest local magnetic field modification. Even though this non-adiabatic magnetic field does reduce the beam oscillations perfectly, the result is sufficient for the electron beam to penetrate the magnetic mirror. Moreover, this non-adiabatic field configuration appears to reduce the amplitude of the cyclotron motion in a wide range of beam parameters (density, energy and current). In this paper we present the computer simulations of this broadband electron gun.

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EFFECT OF A NONADIABATIC MAGNETIC FIELD ON THE AMPLITUDE OF CYCLOTRON MOTION

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This analysis extends the previously published study of the effect of a nonadiabatic magnetic field on the electron beam [1] for different electron beam currents. Specifically, it presents 2-dimensional maps of relative amplitudes of radial beam oscillations in a space defined by non-adiabatic magnetic field strengths and electron beam currents. As before, the electron gun and the drift region are immersed in a uniform magnetic field to avoid distorting the cyclotron motion. Unlike in a previous paper, the cathode of the electron gun has a radius of 3 mm, which is more suitable for EBIS applications. These maps show the operating range of such an optical system with a non-adiabatic magnetic field and the options of optimizing the non-adiabatic coil strength and position for different electron beam currents.

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BENCHMARKING OF CST AND TRAK IN THE SIMULATION OF AN ELECTRON GUN FOR A FUTURE C6+ ION SOURCE

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This study benchmarks the CST Studio Suite and TRAK codes in simulating an electron gun for a future C6+ hadrontherapy installation. CST Studio Suite offers 3D simulation capabilities, allowing detailed modelling of complex geometries and electromagnetic fields. TRAK, on the other hand, offers efficient 2D simulations, which can significantly reduce computational time while still providing valuable results.

These studies are being conducted in the framework of a project dedicated to the design of the initial stage of a C6+ hadrontherapy linac. The electron gun studied is based on the MEDeGUN developed at CERN. This study provides an overview of the results obtained so far and outlines plans for future improvements and development.

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RECENT PROGRESS IN OFF-LINE TEST FACILITY EXPERIMENTS FOR THE RAON ISOL ION SOURCES

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At the Rare isotope Accelerator complex for ON-line experiments (RAON), the Isotope Separation On-Line (ISOL) facility utilizes three types of ion sources to produce Rare Isotope (RI) beams for various research purposes. The RAON ISOL RI beam commissioning was achieved by producing Na, Al, and Li beams with the Surface Ion Source. Beam tests using the Resonant Ionization Laser Ion Source (RILIS) were also successfully conducted. We are currently developing a new plasma ion source, the Forced Electron Beam Induced Arc Discharge (FEBIAD) Ion Source [1].

The existing FEBIAD ion source has thermal issues due to its high operating temperatures, leading to performance degradation and stability problems. The Raon ISOL Facility (RISFAC) developed a new structure for the FEBIAD ion source to fix these issues. The redesigned FEBIAD ion source incorporates effective thermal distribution and expansion mechanisms, enabling stable operation even at high temperatures. To test the new FEBIAD ion source, an ISOL Off-line test facility was re-installed. This Off-Line Test Facility (OLTF) consists of the target/ion source and front-end system, ion beam optics and beam diagnostic system, dipole magnet, vacuum system, and control system. The OLTF provides an environment for independent testing and optimization of the ion source. The data and experience gained from this testing process will be invaluable for improvements and optimization of the FABIAD ion source of RISFAC.

After conducting the FEBIAD ion source test using OLTF, the ISOL RI beam experiment will combine the uranium carbide (UCx) target from mid-2025. RISFAC will be able to supply users with various RI beams of neutron-rich by using a plasma ion source along with an existing surface ion source and laser ion source.

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DEVELOPMENT OF AN EBIT USING A CRYOGEN-FREE HIGHTEMPERATURE SUPERCONDUCTING SPLIT MAGNET

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We present the design of a new EBIT with a cryogen-free high-temperature superconducting magnet. The new device is currently being developed not only for spectroscopic studies but also for studying the interaction between highly charged ions and photons at advanced light source facilities. The cryogenfree feature has a great advantage in transporting and operating the EBIT to such facilities. A compact low-energy EBIT with a permanent magnet is one solution for that purpose, but the weak magnetic field limits the electron beam parameters and the available charge state. Thus, we designed a split-pair magnet wound with REBCO-based high-temperature superconducting tapes. A magnetic field of 5 T, which is useful for the operation with normal EBIT parameters, such as several tens of keV and several hundreds of mA, can be achieved by cooling the magnet at 20 K with a GM refrigerator. We plan to complete the construction and make the first operation in 2026.

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EBIS APPLICATIONS - FROM SUPERNOVAE TO NEXT GENERATION TRANSISTORS

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The Dresden EBIS-A is a table-top sized facility for ion production and acceleration with multiple application areas ranging from astrophysics to materials science and information technology. Every ion source built by DREEBIT, a Pfeiffer Vacuum company, is customized to meet the specific demands required by the individual application. In this presentation, we give an overview of recent Dresden EBIS-A installations at various institutions worldwide to demonstrate their capabilities and inspire future projects.

Using colinear laser spectroscopy like it is done at the COALA apparatus at TU Darmstadt, it is possible to determine transition frequencies and fine-structure splitting in He-like low-Z Atoms, which are highly charged (e.g. C4+-Atoms [1]). To reach the highest possible accuracy, the line shape of the fluorescence response function was studied for pulsed and continuous ion extraction modes, as the Dresden EBIS-A can provide both. Thus, the symmetry and linewidth could be optimized and a high accuracy could be reached.

Moreover, EBIS-A machines can be used to study the interior of stars and supernovae by means of x-ray and optical spectroscopy, measuring characteristic x-rays form highly charged metal ions. The challenge here is the production of highly charged ions from rare earth elements. The solution provided by Dreebit is the technique of Metal Ions from Volatile Compounds (MIVOC) [3] in combination with a Metal Alloy Ion Source with the possibility to inject ions produced by both methods into the EBIS-A.

For materials research in solid state physics, highly charged ions (HCI) can be used to obtain permanent modifications of surfaces and to obtain next generation transistors [4,5] Those modifications range from isolated point defects to phase transitions. Ion induced surface features are widely studied, but the theoretical understanding of the mechanisms is difficult. Since the EBIS allows for production of ions with different charge states and a tunable kinetic energy, contributions from potential and kinetic energy deposition can be studied independently, gaining a deeper understanding of the interaction details.

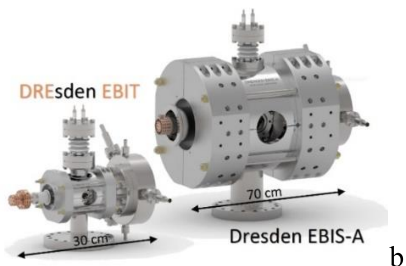

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Figure 1: Dresden EBIS and EBIS-A machines

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DECAY OF THE POSITRONIUM WITHIN A QFT FRAMEWORK

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In the framework of quantum field theoretical approach, we evaluate the two-photon decay of the positronium. This electron-positron bound state, besides its relevance in the fundamental physics, plays an important role in medical physics as well [1]. Within our approach we evaluate a triangle-shaped diagram with virtual electrons circulating in it. We concentrate on the importance of the positronium electron-positron vertex associated with the positronium wave function. We present the impact of possible choices of the vertex function on the $\gamma\gamma$ decay rates. Moreover, different decay channels, e.g. into four γ are studied. Outlook for different positronium states are briefly discussed.

Acknowledgments
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ION-TRAPPING PROPERTIES OF SCRIT: CHARGE STATE AND SPATIAL DISTRIBUTIONS OF ^{132}XE IONS

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A SCRIT (Self-Confining RI Ion Target) method is a target-forming technique in an electron storage ring for electron scattering experiments with unstable nuclei [1]. A target ion beam with a charge state of 1+ is injected into a SCRIT device. They are trapped transversely by periodic focusing forces from electron beam bunches (150 – 300 MeV) and longitudinally by the electrostatic well potential in the SCRIT device. After ion trapping in the SCRIT device, the target ions are extracted and transported to the ion analyzer consisting of movable 4-channel slits, an E×B velocity filter, and a 43-channeltron array. Most trapped ions are detected as a total trapped charge by the slits, with only a few ions passing through the slit aperture being analyzed for their charge-to-mass ratio (A/q). Previous studies demonstrated that an electron beam instability is one of the major sources causing the trapped ions to escape from the SCRIT [2]. The escaping rate affects the SCRIT target density, and of trapped ions with a small A/q was greater than that of the ions with a large A/q. The charge state distribution of trapped ions in the SCRIT is important in forming the optimal target for the electron scattering.

In previous experiments with ^{138}Ba ions [3], we observed the time evolution of $^{138}Ba^{+}$ to $^{138}Ba^{8+}$ ions during trapping in the SCRIT, and did not observe ^{138}Ba ions with a charge state greater than 9+. This suggested that the highly charged ions were not passing through the slit aperture because ion spatial distributions in radial direction of the electron beam depends on their charge states. In this study, charge state distributions of ^{132}Xe ions were measured with varying the slit aperture position. The slit aperture was 0.2 mm × 0.2 mm. Electron beam energy was 150 MeV, and its current was 200 mA. In these results, we observed the time evolution of $^{132}Xe^{+}$ to $^{132}Xe^{16+}$ ions (Figure 1), and we found that the spatial distributions of highly charged ions are focused along the electron beam axis compared to ions with lower charged ions. This suggests that the dominant contribution to electron scattering comes from highly charged ions.

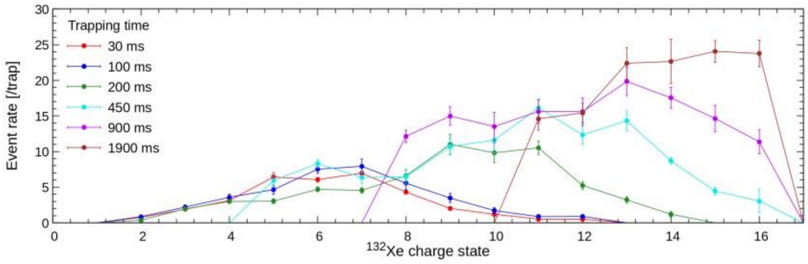

Figure 1: Time evolution of charge state distributions of ^{132}Xe ions.

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PHENYLALANINE IRRADIATION: DESTRUCTION CROSS SECTION DEPENDENCE WITH ENERGY AND TEMPERATURE

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Fragments´ analysis of Murchison meteorite revealed that they are made of Solar System (SS) primitive material, before the beginning of nowadays terrestrial life. In its interior, tiny quantities of 17 primary amino acid and 13 sugars were found. Furthermore, phenylalanine (Phe) has been identified in several carbonaceous meteorites [1]. Amino acids are the building blocks of proteins, which are fundamental in the composition of all organisms. Thus, the academic community suggests to the possibility of an evolution theory with exogen principles. But a major question appears: how this prebiotic material could survive billions of years in the interplanetary medium.

This research aims to determine in laboratory the Phe radioresistance, that is, its half-life under irradiation of solar wind analogues. Since α particles are one of the main components of solar wind especially with energies around 1 keV, the current work seeks to estimate the destruction cross section of the Phe due to α particles bombardment. Several irradiations were carried out, varying parameters of astrophysical interest such as the beam energy and sample temperature. Irradiation effects on the sample were analyzed *in situ* by infrared spectroscopy. Preliminary results show that, for energies on the order of keV phenylalanine destruction cross section increases with increasing sample temperature, unlike what happens with energies on the order of MeV. Fig. 1 illustrates how the destruction cross section dependence on temperature for some amino acids and ion beams, including Phe. Concerning the beam energy, the same trend was observed, however data analysis is in progress. Because of the nuclear stopping power regime, it was also possible to observe that sputtering is highly relevant in this process. Furthermore, results of Phe destruction cross section by keV electrons will be compared.

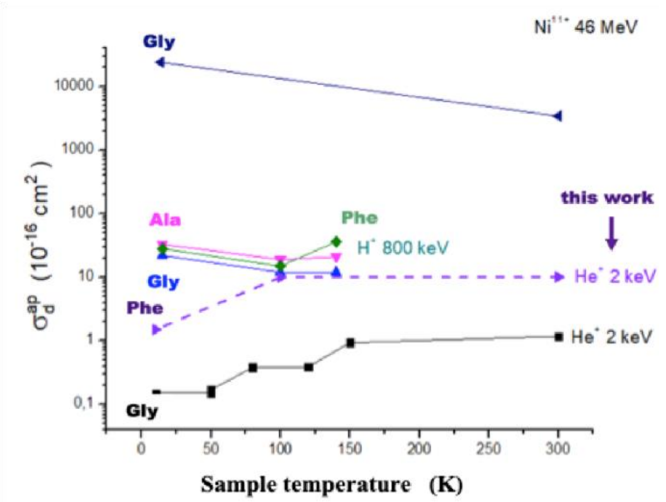

Figure 1: Temperature dependence of the destruction cross section for Phe, Gly and Ala irradiated by He^{+} at 2 keV, H^{+} at 800 keV and Ni^{11+} at 46 MeV [2]. Dashed purple line corresponds to this work.

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DEUTERED PROPANE (C_3D_8) FRAGMENTATION AT EBIS FACILITY IN KIELCE

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The electron beam ion source (EBIS) is a universal device for producing, trapping, and extracting of highly charged ions. The EBIS can also be used for production of low charged molecular ions by fragmentation of complex molecules in high-energy dense electron beam [1]. Study of fragmentation processes at high electron energies is interesting field of research both in the context of the description of the fragmentation phenomena as well as interactions of the fragmentation products with surfaces [2].

In this work the EBIS source was used to study the molecular fragmentation of the deuterated propane molecule. The experiments were performed in the EBIS-A facility at Jan Kochanowski University (Kielce, Poland) [3]. During the measurements the EBIS was operating in so-called leaky mode, which guaranteed a wide spectrum of fragmentation ions with a constant value of the beam current. The measurements were carried out at a fixed electron beam energy of E_e=15 keV for different gas flows in the range from p=3x10^{-9} mbar to 1.5x10^{-8} mbar. The molecular fragments produced in the source were charge separated using a dipole magnet and detected with Faraday cup connected to a high-sensitive electrometer. In the measured mass spectrum variety of possible molecular fragments were registered, including: CD_n, (n=0-3), C_2D_n, (n=0-5), and C_3D_n, (n=0-8). In the mass spectrum some molecular ions of hydrocarbons - C_nH_m, (n = 1-3, m = 1-5) were also identified, as well as multiply ionized carbon atoms and molecular fragmentation remnants. Systematic tests were performed to illustrate the effect of working gas pressure and intensity of the electron beam on the intensity of individual fragmentary ions.

This work was co-financed by the Minister of Science (Poland) under the "Regional Excellence Initiative" program (project no.: RID/SP/0015/2024/01).

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X-RAY PHOTOELECTRON SPECTROSCOPY IN ANALYSIS OF Ti, Pd AND Au NANOLAYERS

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Nanolayers belong to a group of nanomaterials that are designed, manufactured or controlled at the nanometer scale. Nanolayer physics is one of the dynamically developing fields of physics over the last several decades, dealing primarily with the physical properties of organic and inorganic structures deposited on appropriate substrates, and the study of physical processes occurring during their preparation and in applications. Modification of nanolayers to achieve new desirable properties can be performed in process of their irradiation with low-energy highly charged ions (HCI) [1].
In characterization of morphology and physicochemical properties of nanolayers X-ray spectroscopy techniques, as for example X-ray photoelectron spectroscopy (XPS) [2], can be applied. In XPS method, a low-energy X-ray beam (e.g., Al-Kα) is directed at the studied sample, leading to the emission of photoelectrons. The registration and analysis of photoelectron spectra provide information about surface properties such as qualitative and quantitative elemental composition, surface homogeneity, and the chemical state of elements. The sensitivity of XPS can be enhanced by applying total reflection of the primary X-ray beam, achieved by directing the excitation beam at the analyzed sample at an angle smaller than the critical angle. This geometric modification of the XPS technique is known as total reflection X-ray photoelectron spectroscopy (TRXPS) [3, 4].
In presented study, XPS and TRXPS methods were applied in analysis of Ti (75 nm), Pd (100 nm) and Au (10 nm, 50 nm, 100 nm) nanolayers deposited on Si substrate. The measurements were conducted using the SPECS mono-XPS system [5] at the Institute of Physics at the Jan Kochanowski University (Kielce, Poland). In the TRXPS and XPS measurements both survey and detailed spectra were investigated. Analysis of the TRXPS/XPS spectra concentrated on examination of the nanolayer elemental composition and surface homogeneity, structure of the photoelectron peaks and, consequently, on determination of the binding energy of electrons, the intensity and FWHM of photoelectron peaks and the background level. Finally, the detection limits for XPS and TRXPS measurements were estimated for studied nanolayers. The Au nanolayer with thickness of 10 nm was analyzed before and after Xe ion irradiation. The nanolayers were irradiated at the Kielce EBIS facility. The aim of the research was to determine the changes in the structure of photoelectron peaks induced by ion irradiation. This knowledge of the nanolayer surface properties will be applied in interpretation of the results of the studies carried out at the Institute of Physics of Jan Kochanowski University, related to the formation of nanostructures in the interaction of highly charged xenon ions with nanolayers [1].
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PRODUCTION OF SURFACE NANOSTRUCTURES IN COLLISIONS OF HIGHLY CHARGED XENON IONS WITH GOLD SINGLE CRYSTAL

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Fundamental understanding how materials respond to deposition of highly charged ion (HCI) energy is important for defect engineering, ion beam processing, ion beam analysis and modification, tokamak plasma-wall interaction, and many other applications. It is now well known that the interaction of slow HCl with solids transfers its kinetic and potential energy to the electrons and atoms of the solid and can lead to the formation of various surface nanostructures [1]. However, the understanding of the processes of deposition/dissipation of internally coupled energy in electronic and atomic subsystems, in particular for materials with high density of free electrons (e.g., metals), is still incomplete [2].

Recently, using micro-staircase model, based on the quantum two-state vector model of the ionic Rydberg states population, we showed how the process of energy deposition occurs during the impact of highly charged xenon ions with gold nanolayers [3,4]. According to the model, the formation of the nanostructures in such interactions, is governed by the processes of the ionic neutralization in front of the surface and the kinetic energy loss inside the solid. The interplay of these two types of processes in the surface structure creation is described by the critical velocity.

In this work, we studied the process of nanostructure formation during the interaction of xenon ions with the surface of Au (111) crystal. The experiment was performed on the high purity single crystal, with the face centered cubic (FCC) structure produced by Czochralski method. The sample was irradiated by highly charged Xe^{q+} ions (q=35) at the Kielce EBIS facility (Jan Kochanowski University, Kielce, Poland). The surfaces were imaged using scanning tunneling microscope SPM Aarhus 150 (SPECS & University of Aarhus). Various modifications on the irradiated surface resulting from the interaction of a single xenon ion were observed, mostly in the form of craters surrounded by different adatoms structures, including hillocks made of amorphous gold, a consequence of the high cooling rate of the ion metal interaction zone. The results are presently interpreted based on micro-staircase model [5].

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ANALYSIS OF Ti AND TiO_2 NANOLAYERS IRRADIATED WITH HIGHLY CHARGED Xe^{q+} IONS USING XRR AND GIXRF METHODS

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The application of irradiation with low-energy highly charged ions (HCI) has gained significant interest due to their unique interaction mechanisms with matter. HCIs enable the study of fundamental processes in materials science, such as phase transitions and defect dynamics, by providing a tool for controlled energy deposition at the nanoscale. The kinetic and additional potential energy of highly charged ions is deposited on the surface and in the first nanometers below the surface of the material, forming various surface nanostructures (e.g. hillocks and craters). The size and volume of these nanostructures strongly depend on the energy deposited by the ions during the interaction. Detailed research on the structure and properties of nanolayers modified with HCI allows an understanding of the physical and chemical processes that occur on the sample surface [1- 4].

The main aim of this work was to analyze titanium (Ti) and dioxide titanium (TiO_2) nanolayers deposited on Si substrate non-modified and irradiated with low-energy (hundreds of keV) highly charged Xe^{q+} (q = 25, 30, 35), and to determine the influence of this process on the morphology of irradiated surfaces. The nanolayers were irradiated at the Kielce EBIS facility (Jan Kochanowski University, Kielce, Poland) [5].

The analysis of non-modified and irradiated nanolayers was performed using X-ray reflectometry (XRR) and low-angle X-ray fluorescence (GIXRF) with synchrotron radiation excitation at Elettra Synchrotron XRF beamline, with a synchrotron X-ray beam energy equal to 6.0 keV. X-ray reflectometry (XRR) allows the determination of layer properties such as density, thickness, and roughness, Grazing Incidence X-ray Fluorescence (GIXRF) shows the depth distribution of a given element in the material [6].

The theoretical and experimental results obtained with both techniques XRR and GIXRF for TiO_2 and Ti nanolayers irradiated with Xe^{q+} ions will be presented and discussed. The differences in the samples' morphology depending on the charge state of the ions were observed. The roughness parameter of the TiO_2 and Ti nanolayers, unmodified and irradiated with HCI, shows that irradiation changes the roughness of the outermost surface layer and the change depends on the ion charge states.

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FORMATION OF NANOSTRUCTURES ON METAL SURFACES BY THE IMPACT OF SLOW HIGHLY CHARGED IONS

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In recent years, many experiments have been carried out to study nanostructures such as hillocks, craters, pores, and rings, formed by the interaction of highly charged ions (HCl) with the solid surface [1]. When HCI collides with a surface, its energy (in the form of the kinetic energy E_{kin} and the potential energy E_{pot}, which is related to the charge state of the ion) is deposited into the solid, which can lead to permanent surface modifications. Recently, a theoretical model was developed to study the creation of these nanostructures on metal surfaces at slow ionic velocities [2, 3, 4].

This work presents experimental research aimed at understanding the mechanism of formation of nanostructures on the surfaces of metal (Ti, Au) nanolayers as a result of their irradiation with highly charged Xe^{q+} ions (where q is an ion charge) [5, 6]. The nanolayers were irradiated at the Kielce EBIS facility of the Jan Kochanowski University (Kielce, Poland), under high vacuum conditions. The irradiations were performed for constant kinetic energy 280 keV and different ions charge states (Xe^{q+}, q = 25, 30, 35, 36 and 40). Before and after irradiation, the surfaces of the nanolayers were examined using an atomic probe microscope. As a result, surface modifications of the nanolayers in the form of craters and hillocks were observed. The experimental results were compared with cohesive energy model (CEM) [4], which consists of two stages. In the first stage of CEM I [2, 3, 4], the deposition of neutralization energy and E_{kin} in a solid was considered. Neutralization at the surface was analyzed using a two-state quantum vector model (TVM) of the Rydberg state population and a microstep model of cascade neutralization. Below the surface, elastic collisions between the projectile and target atoms have led to a loss of kinetic energy, which is calculated using a charge-dependent ion-atom interaction potential model. In CEM I, it was predicted whether the resulting nanostructures were hills or craters. The analysis was based on the calculation of the critical ion velocity v_c, defined as a measure of the interaction of these two energies. In CEM II, the diameters of the nanostructures were determined, assuming that the total deposited energy is responsible for the change of the target cohesive energy, resulting in surface modification. CEM results showed that the diameters of surface nanostructures depend on ionic charges and ion velocities, which is consistent with the latest experimental data (interaction of Xe^{q+} ions with gold and titanium nanolayers) [5, 6].

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X-RAY STUDIES OF ATOMIC PROCESSES IN THE EBIT PLASMA

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The successive electron impact ionization of ions in the EBIT trap [1] leads to production of highly charged (q >> 1) ions (HCI) having rather wide charge state distribution and various electronic configurations. The atomic processes involved in formation of EBIT plasma include the electron impact ionization/excitation, radiative (RR) and dielectronic recombination (DR), charge exchange (CX) and radiative and Auger deexcitation.
The x-rays emitted from Xe plasma trapped in the EBIT, which was generated by electron beam of energy 3-9 keV, were measured by a silicon drift detector (SDD) separated from the EBIT plasma by 50 µm Be window. The electron beam current was in the range 30-70 mA and pressure was about 10^{-9} mbar. The EBIT trap was operated in the "leaky" mode allowing extraction of Xe^{q+} from the trap to be further charge state analyzed in the dipole magnet of the EBIS facility [2]. In this way the charge state distribution of ions extracted from the observed x-rays was confronted with the charge states measured directly by analyzing magnet.
In the measured spectra of x-rays emitted from EBIT the fluorescence x-ray transitions Xe ($nl \rightarrow n'l'$) and RR lines for $n \geq 3$ states for various highly charged Xe^{q+} ions ($q \leq 40$) are identified as well as the electron bremsstrahlung edges and K-x-ray fluorescence lines of Cr and Fe excited by electrons scattered on the trap walls. Generally, the intensities of various Xe x-rays depend on population of nl-states in the plasma which can be described by radiative-collisional (CR) models [3].
In the present work the charge state distribution of Xe^{q+} ions in the EBIT plasma was studied to interpret the observed RR lines, mainly for photorecombination into n = 3 states of Xe. The results are discussed in terms of the CR models developed for a low density and temperature non-Maxwellian plasma.

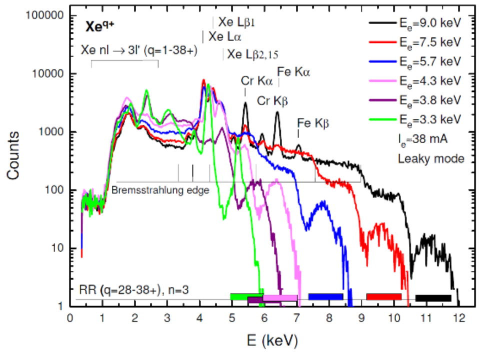

Figure 1: X-ray spectra of xenon ions at the EBIT plasma for electron impact energies 3.3–9.0 keV.

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INVESTIGATION OF DIELECTRONIC RECOMBINATION IN NEON IONS USING EBIT

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The Electron Beam Ion Trap (Dresden EBIT [1, 2], DREEBIT CO.) is a recent apparatus in the Department of Physics at the Jagiellonian University. This compact EBIT is available for students and researchers and allows the production and trapping of highly charged ions (HCIs) [2]. Equipped with an X-ray detector (Bruker XFlash 5030), the facility enables comprehensive investigations into radiative processes associated with the trapped ions. One such process is dielectronic recombination (DR).
The DR is a process in ion-electron collisions where a free electron is captured to an ion bound state with a simultaneous excitation of a core electron to a higher atomic shell. The DR process is completed by the radiative de-excitation. Previously, we reported experimental results on DR investigations for argon and cerium ions [3, 4, 5]. In this work, we present our findings on studies conducted with neon ions.

State	K_α [keV]	K_β [keV]	K ionization threshold [keV]
Ne^{9+}	1.022	1.211	1.362
Ne^{8+}	0.915	1.072	1.196
Ne^{7+}	0.896	1.041	1.334
Ne^{1+}	0.849	0.858	0.870

Table 1: Characteristic K radiation and ionization threshold for selected charge states of neon ions. [6].

The study of neon ions presents challenges due to their low atomic number, which results in the recorded characteristic radiation (values presented in Table 1) being at the detection efficiency limit of the X-ray detector used. The detector is separated from the trap by two 25 μm beryllium windows, and even after correction for absorption in these windows, the recorded count rate remains very low and is subject to high measurement uncertainty. Nevertheless, we observed an enhancement of K_β radiation at the intersection of the radiative recombination to L shell and K_β lines. The resonant nature of this enhancement and its location allowed for the identification of this structure as corresponding to K-LM and K-LN resonances for neon.

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OBSERVATION OF TWO-ELECTRON ONE-PHOTON X-RAY TRANSITIONS IN THE RELAXATION OF HOLLOW ATOMS

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Slow highly charged ions (HCI) colliding with metal surface are rapidly neutralized forming highly excited Rydberg states, so called, “hollow” atoms which subsequently relax in a series of rapid processes including Interatomic Coulombic Decay (ICD) [1] followed by X-ray and/or Auger electron emission cascade. It was also evidenced that the Internal Dielectronic Excitation (IDE) [2] contributes to relaxation of “hollow” atoms.

We report here on the first observation of the Two-Electron One-Photon (TEOP) X-ray transitions, which were measured in interaction of slow Xe^{35+} ions with metallic beryllium surface. We show that TEOP process, which was predicted by Heisenberg in 1925 [3] and observed by Wölfli *et al.* [4] in 1975, contributes to the relaxation of “hollow” atoms formed in collisions of HCI with surfaces. In the present experiment the X-rays were emitted from 282 keV Xe^{35+} ions neutralized at metallic Be foil by capturing resonantly the electrons into Rydberg states with $n \approx 30$. The ion beam was produced by the Dreebit EBIS-A facility [5]. The observed M-X-rays were measured with XFlash silicon drift detector (SDD) having energy resolution of about 80 eV for 2 keV photons. The measured M-x-ray spectrum was reasonably well interpreted in terms of the MCDF calculations as dominated by One-Electron One-Photon (OEOP) electric-dipole transitions (nf-3d), including their satellites and hypersatellites.

We have found that the high energy part of x-ray spectrum, extending roughly twice the energy range of the OEOP transitions, cannot be explained in terms of this process and can only be explained as TEOP transitions. This is the first observation of such transitions in the relaxation process of hollow atoms created by the interaction of highly charged ions with metal surfaces. Branching ratio for this process was determined in two dedicated experiments as $BR=3.8 \cdot 10^{-4} \pm 9.6 \cdot 10^{-5}$.

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A HIGH-RESOLUTION ASYMMETRIC VON HAMOS SPECTROMETER FOR X-RAY SPECTROSCOPY OF HCI

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The research program and project of built the high-resolution wavelength-dispersive asymmetric von Hamos (AvH) spectrometer dedicated to study the QED effects in Highly Charged Ions is presented. The spectrometer will allow to measure, with a high resolution down to 100 meV, the low-energy X-rays (5-10 keV) from radiative recombination (RR) few-electron mid-Z ions. For these ions the calculated one-loop Lamb shift is about 2-5 eV, being much larger than the nuclear size effect contributing about 15-120 meV [1]. Performed Monte-Carlo X-ray-tracing simulations [2] show that this spectrometer will allow to determine with sub-meV precision, the low-energy X-rays emitted from few-electron heavy ions. This experimental precision will enable accurate studies of the quantum electrodynamics (QED) effects in mid-Z ions.
In a standard von Hamos spectrometer the photons emitted from a point-like X-ray source are diffracted at the Bragg angle θ_B on the crystal, which is flat in the dispersive plane and cylindrically bent to the radius R_C in the focusing plane, and are measured at the focal point by a position-sensitive X-ray detector. In this geometry the distances source-to-crystal and crystal-to-detector are the same, equal $R_C/\sin\theta_B$ and both the X-ray source and the detector, are located on the axis of cylindrical crystal. In the proposed asymmetric von Hamos (AvH) spectrometer the source-to-crystal distance is four times larger than crystal-to-detector distance, which is still equal $R_C/\sin\theta_B$. Both the diffraction crystal and the X-ray detector will be mounted on the 4-axis motorized goniometers to secure the adjustment of their position for various bending radii of the crystal. The stepping precision of the linear and rotational movements will be 1 μm and 0.001°, respectively, which enables the necessary fine tuning of the positions and angles of the crystal and X-ray detector. The spectrometer will be equipped with a Si(111) cylindrically bent crystals. The diffracted X-rays will be measured by the position-sensitive Timepix3 detector that is sensitive to the hitting position (256 × 256 pixels with size of 55 × 55 μm^2) and time (1.6 ns resolution) of the registered photon. The AvH spectrometer will be able to work also in standard von Hamos geometry mode, which allow for off-line calibration of the spectrometer and checking the influence of crystal quality on the instrumental energy resolution. The off-line configuration will use a 30 keV electron gun delivering intense electron beam of a diameter down to 150 micrometers to excite the characteristic Kα X-rays from Fe target.
The X-ray-tracing Monte-Carlo simulations show that the QED effects in mid-Z (Z = 20–30) highly charged ions can be studied with an accuracy of sub-meV for photon about 5 keV enabling sensitivity to two-loop QED contributions.

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NA-LIKE D TRANSITION MEASUREMENTS WITH THE NIST AND SAO EBITS

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Quantum electrodynamics (QED) is currently one of the most precise theories governing fundamental interactions. Therefore, conducting stringent experimental tests of QED remains crucial. Highly charged quasi-hydrogenic Na-like ions are simple systems for testing QED and probing relativistic effects in atomic systems [1]. The fine structure splitting of the $3p_{1/2}$-$3p_{3/2}$ transition in Na-like ions is a relativistic effect, and the separation grows with Z to about 450 eV for heavy Na-like Ir^{66+} ions. We used the National Institute of Standards and Technology (NIST) electron beam ion trap (EBIT) to create and trap Ir ions and measured the emitted photons using a superconducting transition-edge sensor array (TES) [2] in the x-ray and a grazing incidence grating spectrometer [3] in the extreme ultraviolet (EUV) spectral ranges.

Fine-structure splitting of the $3p_{1/2}$-$3p_{3/2}$ levels was determined and compared with relativistic many-body perturbation theory (RMBPT) [1] and multiconfiguration Dirac-Fock calculations [4]. With a projected uncertainty of 70 meV, our measurements provide one of the most precise fine structure separation measurements of Na-like ions in the high-Z atomic number region. We plan to continue exploring these systems at the Smithsonian Astrophysical Observatory (SAO) EBIT. We are working on the detailed characterization of the spatial and density properties of the electron beam to support spectroscopic investigations both in the x-ray and EUV ranges.

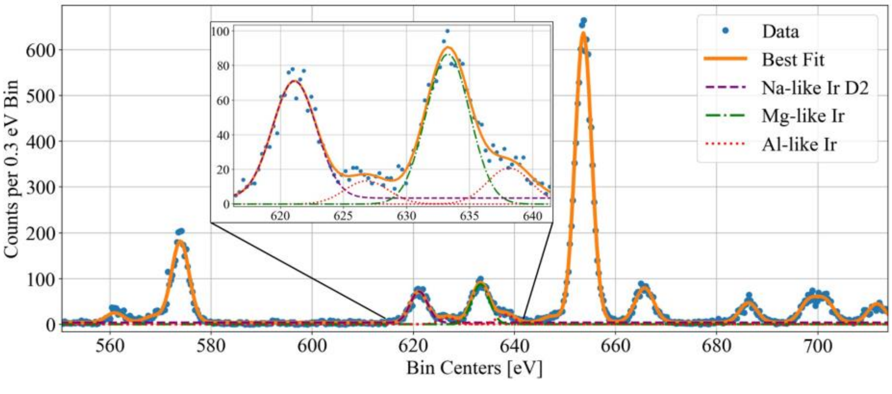

Figure 1: X-ray spectra of Na-like Ir at a 15 keV electron beam energy recorded by the NIST TES microcalorimeter array

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