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HCI2026

Book of Abstracts

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Program

Date Time	6 Sept Sun	7 Sept Mon	8 Sept Tue	9 Sept Wed	10 Sept Thu	11 Sept Fri		
		Chair: Xinwen Ma	Chair: Ronnie Hoekstra	Chair: Thomas Stöhlker	Chair: Richard Wilhelm	Chair: Shaofeng Zhang		
9:00-9:45	Registration, 14:00-22:00	Opening Meng Wang	Yuri Ralchenko	Ronnie Hoekstra	Toshiyuki Azuma	Tom Kirchner		
9:45-10:15		José R. Crespo López-Urrutia	Shaolong Chen	Endre Takacs	Günter Weber	Tianyu Zheng Sergey Litvinov		
10:15-10:35		Conf. Photo	Chunyu Zhang	Tomoko KAWATE	Chintan SHAH	Alexander Voitkov		
10:35-11:05		Coffee Break						
		Chair: Marek Pajek	Chair: José R. Crespo López-Urrutia	Chair: Martino Trassinelli	Chair: Shenyue Xu	Chair: Toshiyuki Azuma		
11:05-11:35	Lunch	Atsushi Yamaguchi	Shiqian Ding	Shenyue Xu	Moto Togawa	Yury Litvinov		
11:35-11:55		Chunhai Lyu	Wu Wang	Antonin Bourgeteau	Enliang Wang	Xinliang Yan		
11:55-14:00		Closing						
			Chair: Yuri Ralchenko	Chair: Károly Tókési	Chair: Hajime Tanuma			
14:00-14:30	Registration, 14:00-22:00	Ling Zhang	Victoria Vojtech	Daniel Fischer	HIAF tour 13:00-17:00	Adjourn ----- Transport to IMP new campus for follow-up related meetings *.		
14:30-14:50		Naoki Kimura	Martino Trassinelli	Alexandre Gumberidze				
14:50-15:10		Guiyun Liang	Grzegorz Wesolowski	Zhongwen Wu				
15:10-15:30		Jieru Ren	Luc Assink	Nicholas Antonio				
15:30-16:00		Coffee Break						
		Chair: Ke Yao						
16:00-16:30		Stefanos Nanos	Poster Session-A	Poster Session-B				
16:30-16:50		Yijiao Wu						
16:50-17:10		Hajime Tanuma						
17:10-17:30		Guocheng Wei						
17:30-18:00		Károly Tókési	Social activity					
18:00-19:00	Reception	Dinner						
				Chair: Reinhold Schuch				
19:00-20:00				Public Lecture	Conference			
19:00-21:00				Di Li	Dinner			

*For those taking part in the scheduled FIPI - SPARC 2026 meeting

REVIEW REPORTS

Sensing old and, possibly, new physics with highly charged ions

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Our current theoretical description of the physical world is very successful in its predictive power, yet it leaves essential phenomena unexplained, including the nature of dark matter and dark energy and the observed matter–antimatter asymmetry. Searches for physics beyond the Standard Model therefore remain a major goal of fundamental physics. Precision experiments in atomic systems can provide sensitive probes of hypothetical new particles and fifth forces. Historically, increasingly precise studies of the discrete spectrum of hydrogen, including its fine and hyperfine structure, the Lamb shift, and proton-radius effects, have played a central role in testing and developing fundamental theory. Highly charged ions (HCI), particularly hydrogenlike systems, extend such tests into the strong-field regime, where relativistic, quantum-electrodynamic (QED) and nuclear-size effects are greatly enhanced. Few-electron ions provide similarly clean testing grounds for QED and *ab initio* treatments of electron correlation, and remarkable agreement between experiment and theory has been achieved (see, e. g., Refs. [1–3]). HCI are also promising systems for searches for physics beyond the Standard Model [4]. At the precision frontier, however, uncertainties associated with nuclear structure limit further progress. Nuclear charge radii, hyperfine anomalies such as the Bohr–Weisskopf effect, and nuclear polarization obscure the atomic-structure contributions of interest. Even the exceptional precision now available in isotope-shift measurements and King-plot analyses does not in general eliminate these nuclear-structure limitations [5–9].

Rather than merely constituting an obstacle, this situation offers an opportunity. The novel tools of frequency metrology can be used to investigate open problems in nuclear physics while simultaneously improving atomic-structure theory for increasingly complex electronic systems. The well-known advantages of systematic studies along HCI isoelectronic sequences are particularly valuable in this context. Their potential for resolving such “old-physics” questions must be fully exploited if searches for “new physics” are to become robust. Precision measurements of many-electron HCIs, isotope shifts, including those involving radioactive nuclei, and nuclear moments coupled to electronic structure can progressively disentangle the relevant atomic and nuclear contributions and may ultimately reveal signatures of physics beyond the Standard Model.

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From clusters of galaxies to tiny nuclei: the robust utility of EBIT spectroscopy

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Over the past four decades, electron beam ion traps (EBITs) have become among the most versatile and widely used sources of highly charged ions (HCIs). They have enabled studies of HCI interactions with solids, provided some of the most stringent tests of quantum electrodynamics (QED) in atomic structure and spectroscopy, supplied critical atomic data for astrophysics and fusion plasma diagnostics, and supported searches for physics beyond the Standard Model, among many other applications.

Since the mid-1990s, the EBIT facility at the National Institute of Standards and Technology (NIST) has been at the forefront of HCI research, producing landmark results in the spectroscopy and physics of medium- and high- Z ions from a wide range of elements. Although the NIST EBIT program was recently terminated, the research effort will continue following the relocation of the EBIT to NASA's Goddard Space Flight Center (GSFC).

In this talk, I will highlight the program's major achievements over the past several years. Topics will include the determination of charge radii of heavy nuclei [1]; measurements of electron-impact ionization cross sections in He-like Fe [2], which are important for modeling the spectroscopic signatures of shock waves generated during galaxy-cluster collisions; tests of relativistic atomic structure and bound-state QED in Co-like ions [3]; and investigations of the role of metastable states in ladder-type ionization processes in highly charged ions.

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Surprises in Electron Capture by low-energy Sn ions: Hop-skip-and-jump versus long-jump double electron capture from H₂

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The forefront of photolithography is defined by Extreme UltraViolet (EUV) photolithography at 13.5 nm is. Because loosely speaking, the shorter the wavelength the smaller and faster the features that one can pattern. A hot plasma of tin ions is used to generate the 13.5-nm light in so-called Laser-Produced tin Plasma (LPP) sources. The figure shows the operational schematics of such a source. A 50-kHz stream of liquid tin droplets is irradiated twice with infrared laser light. A first prepulse reshapes the droplet into a larger pizza-shaped disk. The prepulse is followed by a high-power main pulse to convert the liquid into a plasma of, of approximately 500,000 K. Line radiation by highly charged tin ions in the plasma is the actual source of the 13.5 nm EUV light.



Artistic atomic physicist's impression of the ion world inside an EUV photolithography machine.

In this talk we follow the "life" of tin ions from their creation inside the EUV generating plasma all the way to their mitigation in the H₂ buffer gas surrounding the plasma or their running into plasma facing materials. To start out I will briefly address why Sn ions in charge states of 10+ - 15+ all radiate at 13.5 nm and why so efficiently, and why does one not observe ions escaping from the plasma in charge states higher than roughly 8+?

After this scene setting part, I will focus on their interactions inside the buffer gas surrounding the laser-produced plasma. Since the charge transfer reaction from Sn²⁺ to Sn⁺ is forbidden (endothermic), why is the final charge state of the ions in the H₂ buffer gas not 2+, but 1+? And even more puzzling, why does a highly endothermic (energy forbidden) reaction as two-electron capture by Sn³⁺ occur at low energies? In particular, the answer to the latter question led to new insights in the physics of ion-molecule interactions [1]. The synchronous-sequential electron-capture explanation of the large two-electron capture cross sections at low collision energies (< 5 keV) requires an expansion of the internuclear distance of the transient H₂⁺ during the collision. This process that we coined the "Hop-Skip-Jump" mechanism implies that kinetic energy release KER) to the protons is much less than the Coulomb explosion value of almost 20 eV. To proof that the hop-skip-jump mechanism is indeed underlying the large two-electron capture cross sections we have measured KER values in Sn³⁺ - H₂ collisions. By measuring the KERs in other low-energy collision systems, we seek to verify the universal nature of the hop-skip-jump mechanism.

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QED Tests via Resonant Coherent Excitation in Thin Crystals and Muonic Atoms

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The experimental study of bound-state QED using highly charged ions (HCIs) has a long history and has been pursued by many groups. The standard approach relies on storing HCIs in ion storage rings or ion traps. Our group, however, has developed and pursued two distinctive approaches.

One is **resonant coherent excitation using a single thin silicon crystal**. By utilizing the periodic electric field of a crystal, we can excite HCIs of relativistic velocities in the x-ray energy regime for the transition. We have applied this technique to precision tests of bound-state QED of Li-like uranium ions provided at GSI. This project has been ongoing for more than a decade, during which we have overcome a variety of experimental challenges step by step [1]. We prepared a uranium ion beam with a narrow energy spread by introducing electron cooling at the ESR and determined its absolute energy with high precision by monitoring the voltage applied to the electron-cooler electrode. Recently, we have reached the stage where the absolute transition energy can be compared with theoretical predictions at a precision better than a few tenths of an eV. At this level of the absolute energy comparison, however, a new issue has emerged concerning the characterization of the thin crystal itself.

Our second approach uses **muonic atoms**. During the formation and cascade processes of muonic atoms, the bound electrons can be completely stripped off, leaving a simple two-body system consisting of a muon and a nucleus for muonic Ne or muonic Ar. The electric field experienced by the muon is comparable in strength to that experienced by a 1s electron in uranium [2]. Following successful proof-of-principle experiments on x-ray detection using a superconducting transition-edge sensor (TES) calorimeter for muonic Ne [3], we have recently completed measurements on muonic Ar. In the course of these studies, we also succeeded in observing highly charged exotic atoms consisting of a muon, electrons, and a nucleus [4], and, furthermore, the electron-refilling process of highly charged muonic atoms embedded in metallic solids [5]. The initial stage of muon capture into atoms is also understood in the light of the concept of *orbital collapse* [6].

In this talk, I will present the latest status of these two complementary approaches and discuss their respective advantages and limitations for precision tests of bound-state QED.

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PUBLIC LECTURE

Time Frontier: Extend Human's Cognizance of the Dynamic Universe

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Modern physics and astronomy both originated from Galileo. Since Galileo's pioneering use of telescopes, optical observations have been dominating astronomy. Hertz invented the first antenna and demonstrated the wave-particle duality of light. These developments give rise to radio astronomy and giant dishes.

The 20th century saw the advent of a scientific and technical wonder that is Arecibo. Since its inception in November of 1963 as a direct result of the cold war, the Arecibo telescope perched on the apex of human antenna for more than half a century, generating a series of landmark discoveries, including the double neutron star that won the Nobel prize in 1993.

First proposed in 1990s, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) started full operation in early 2020. Since then it has become a leading observatory in radio astronomy, facilitating 12 Nature/Science (main journal) publications in its first 5 years.

Most of the major discoveries so far from FAST came from its 19-beam system, which was built by the same group who has built the Parkes 13-beam system. Parkes became famous when it broadcasted the first Apollo landing. As a major upgrade to Parkes telescope, its multi-beam system transformed single-dish radio astronomy, delivering the largest haul of new pulsars, definitive HI galaxy catalogues, and the standard HI maps of the Southern sky. These landmark surveys had to be conducted separately, due to the conflicting observation requirements. We invented the high-cadence CAL technique, in which the calibration signal is injected at the sampling rate and facilitate, for the first time, truly commensal pulsar and spectral-line surveys. Implemented on FAST with drift-scan mode, the Commensal Radio Astronomy FAST Survey (CRAFTS) has multiplied the survey efficiency of FAST and discovered more than 260 pulsars as well as 10 Fast Radio Bursts (FRBs) and released over 5,000 square degrees of calibrated HI images. I will report a few science highlights from CRAFTS, in the context of surveying the dynamic radio sky.

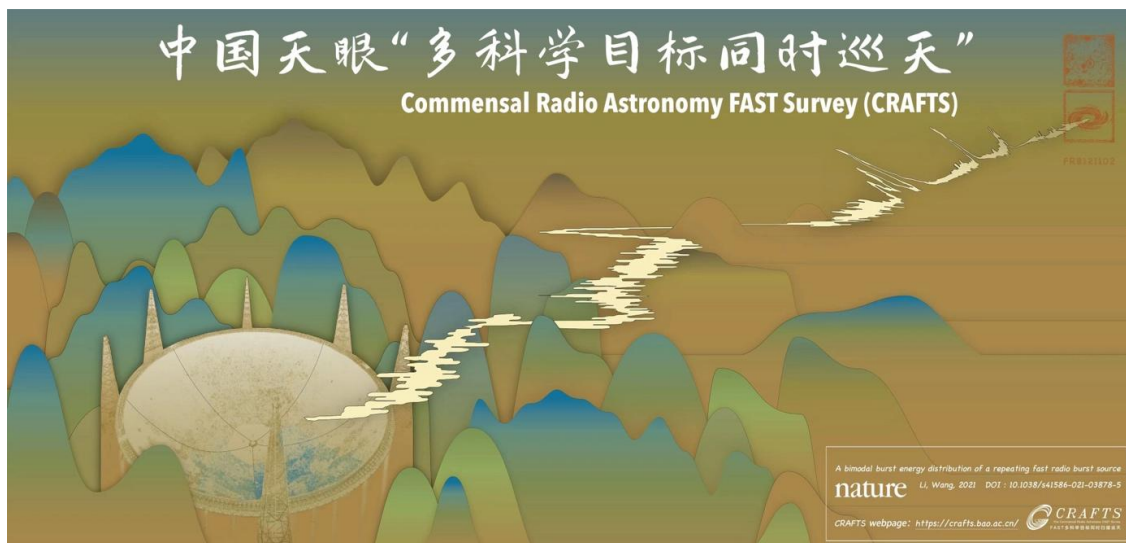


Fig. 1 Artist's impression of CRAFTS's detection FRBs.

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The experience of setting up high-cadence surveys also lead to a few recent discoveries, including the first radio pulsar from a Central Compact Object (CCO) with the MeerKAT array and the first long-period-transient (LPT) residing in a supernova remnant with the DART array. These recent discoveries from radio telescopes world-wide are filling in the missing puzzles of a richer and more complete picture of compact objects, which started by Landau's suggestion of a 'giant nucleus', elucidated by Baade & Zwicky's invention of the terms of supernova as well as neutron stars, make prominent by Bell's discovery of pulsars that won the Nobel prize in 1974.

CRAFTS' high cadence sampling of the radio sky also give rise to the concept of the "time frontier". I coined this term to represent the quantum foundation of the Universe that is to be revealed by exploring extreme transients. Hypothetical considerations will be given to possible lines of investigations.

PROGRESS REPORTS

Progress towards a trapped-ion nuclear clock

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The first excited nuclear state of thorium-229 (^{229}Th), known as the isomer, has attracted significant interest due to its remarkably low energy, which has been determined to be approximately 8.4 eV [1-3]. This specific nuclear transition between the ground and isomeric states of ^{229}Th provides an unprecedented platform for direct laser spectroscopy of an atomic nucleus. A primary application is a nuclear clock based on this nuclear transition frequency [4]. Because this nuclear transition frequency is exceptionally resilient against external environmental disturbances, a ^{229}Th -based nuclear clock is anticipated to surpass the performance of existing atomic clocks [5]. Furthermore, various proposals suggest employing this nuclear clock as a highly sensitive detector to search for novel physical phenomena, including dark matter and temporal variations in fundamental constants.

We are currently developing a trapped-ion nuclear clock. An ion trap serves as a suitable framework for achieving ultra-high accuracy, as it allows ^{229}Th ions to be isolated within an ultra-high vacuum environment. Our experimental setup is specifically engineered to confine triply charged thorium ions ($^{229}\text{Th}^{3+}$). Triply charged thorium ions feature closed cyclic electronic transitions, wherein an electron excited by a laser spontaneously relaxes back to its initial state. These cyclic transitions are an essential prerequisite for implementing laser cooling, laser-induced fluorescence detection, and electronic state preparation, all of which are critical operations for running a trapped-ion nuclear clock.

For our $^{229}\text{Th}^{3+}$ ion source, we utilize uranium-233 (^{233}U), which undergoes α -decay into ^{229}Th . The recoil ^{229}Th ions are subsequently thermalized and cooled using helium buffer gas. During this buffer-gas cooling phase, charge-exchange collisions simultaneously manipulate the charge state of the thorium ions to the $3+$ state. The ^{229}Th ions are then gathered via a radio-frequency carpet acting as an ion collector [6] and confined within a linear Paul trap. A distinct benefit of utilizing a ^{233}U source is that it yields ^{229}Th ions not only in their nuclear ground state but also in the isomeric state, with a branching ratio of roughly 2%. Leveraging this, we have developed a nuclear-state-selective laser spectroscopy method that permits the isolated detection of isomer ions. This spectroscopy technique allows us to identify and analyze the detailed characteristics of trapped, triply charged ^{229}Th isomers [7]. As a next step towards a nuclear clock, we are currently working on cooling of the trapped $^{229}\text{Th}^{3+}$ ions.

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Highly Charged Tungsten Ion Observation: Enabling Insights into Tungsten Transport Study in Magnetically Confined Fusion Plasma

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With tungsten being widely adopted as plasma-facing material in magnetically confined fusion devices, highly charged tungsten ions are prevalent in high-temperature plasmas. Consequently, the investigation and effective control of tungsten impurity transport have emerged as critical issues for achieving steady-state operation of fusion devices.

Recently, significant progress has been made on this topic at the EAST tokamak with a full-tungsten divertor. A high-performance spectroscopic diagnostic platform for tungsten impurities has been established [1], enabling the observation of the fast temporal behaviour of W^{4+} - W^{46+} ions and the spatiotemporal evolution of W^{24+} - W^{46+} ions [2]. The observation and quantitative diagnosis of highly charged tungsten ion distributions, combined with numerical simulations, have been successfully applied to the study of tungsten impurity transport [3-5]. Based on these achievements, effective control strategies for tungsten impurities have been developed.

This work provides important insights into the understanding of tungsten impurity behaviour in fusion plasmas and contributes to the development of impurity control techniques for future fusion reactors, making it highly relevant to the theme of this conference on Applications of the field of highly charged ions.

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Spin-statistics breaking in swift collisions of He-like metastable ions with atoms

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The process of single electron capture in fast ion–atom collisions provides a sensitive probe for studying correlated many-electron dynamics in highly excited atomic systems. Recent combined experimental and theoretical studies in collisions of He-like pre-excited carbon projectiles in the $1s2s\ ^3S$ state¹ with He gas targets, showed that the population of the final $1s2s2p$ configuration, resulting in the $1s2s2p\ ^4P$ and $^2P_{\pm}$ states, cannot be explained solely by spin statistics or by the frozen-core approximations, thereby resolving a long-standing puzzle in the field². The studies further indicated the presence of a “Pauli shielding” mechanism, in which exchange-driven electron correlations selectively suppress specific capture channels, resulting in strongly non-statistical final state populations. These findings provide new insight into the quantum dynamics governing multi-open-shell ion-atom collisions and highlight the limitations of simplified population models.

Building on these results, an ongoing systematic isoelectronic investigation extends the study to low- Z He-like ions, aiming to explore how electron-correlation effects evolve along the sequence³. In this talk, previous findings and ongoing studies will be discussed, together with prospects for future investigations.

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Recent Progress on Sympathetic Cooling of Ni Highly Charged Ions for Optical Clock Development

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Highly charged ions (HCIs) are promising candidates for next-generation optical clocks. Compared with neutral atoms or singly charged ions, HCIs feature compact electron clouds and reduced sensitivity to external perturbations, making them promising platforms for realizing optical clocks with uncertainties at the 10^{-19} level or even lower. In addition, HCIs exhibit enhanced sensitivity to variations in the fine-structure constant, enabling stringent tests of its possible temporal variation and searches for new physics beyond the Standard Model [1–3].

In recent years, our group has selected Ni^{12+} [4] as a candidate system for HCI optical clocks and has carried out a series of key technological developments toward its realization. In collaboration with Fudan University, we developed a Shanghai-Wuhan electron beam ion trap (SW-EBIT) and successfully produced Ni^{12+} ions. With fluorescence spectroscopy in the SW-EBIT, the wavelength measurement accuracy was improved to the sub-picometer level [5,6]. We further designed and constructed an ion deceleration and trapping system, enabling the preparation of pure, low-energy Ni HCIs [7]. Using Be^+ ions as coolant ions, we experimentally achieved sympathetic cooling and the formation of Coulomb crystals composed of Ni HCIs and Be^+ ions [8].

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A nuclear clock based on Th-229

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The Th-229 nucleus has an isomeric transition near 8.4 eV, which is the only known nuclear transition directly accessible to laser excitation and is a promising reference for a nuclear optical clock. In this talk, I will present our recent progress on continuous-wave laser spectroscopy and clock operation of the Th-229 nuclear transition.

We have developed a continuous-wave 148 nm vacuum-ultraviolet laser based on resonance-enhanced four-wave mixing in cadmium vapor. The source provides tunable, narrow-linewidth VUV radiation near the nuclear resonance with high output power. Using this laser together with home-grown Th-229-doped CaF₂ crystals, we perform fluorescence and absorption spectroscopy, resolve nuclear transitions in the solid-state environment, and close the feedback loop by stabilizing the laser to a selected nuclear transition. Our results establish continuous-wave optical interrogation and clock operation of the Th-229 nuclear transition, providing a platform for compact solid-state nuclear clocks and future precision tests of fundamental physics.

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Looking behind the surface to disentangle electron emission mechanisms in HCI-solid interactions

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The impact of a slow highly charged ion (HCI) on a surface is typically accompanied by the emission of numerous low-energy electrons (~ 100 per ion) [1]. Detection of these electrons provides an experimental way to study the electron dynamics responsible for neutralization and subsequent deexcitation of the ion. In fact, measurements of ion-induced electron yields have largely shaped the current understanding of HCI-surface interactions [2]. For conventional bulk targets, however, the observable electron yield is not a direct fingerprint of the ion neutralization and deexcitation processes, but is obscured by secondary processes in the bulk.

Here, we separate the total electron yield into its contributions from electrons originating in the primary HCI-surface interaction and from those generated by secondary processes in the bulk. We achieve this by using freestanding single-layer graphene (SLG) as a model system for the topmost surface layer of highly oriented pyrolytic graphite (HOPG). Because of its single-atom thickness, electron-electron scattering is strongly suppressed, and the emitted electrons originate mostly from the primary interaction between ion and surface. In addition, freestanding SLG facilitates experimental access to the electron yields emitted in backward and forward directions as well as to the transmitted ion and the number of electrons it has captured during the interaction. By performing coincidence spectroscopy of ion and electrons on SLG and comparing with electron yields from bulk HOPG, we estimate the relative contributions of surface and bulk processes to the total low-energy electron yield [3].

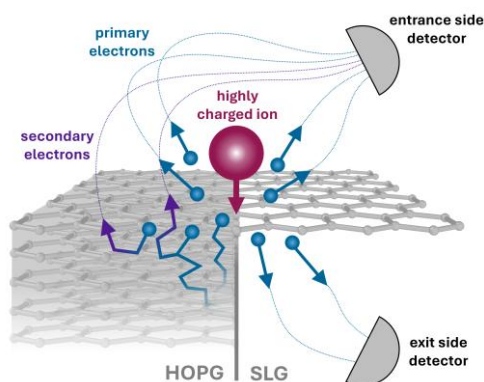


Figure 1. The contribution of primary electrons to the HCI-induced electron yield can be isolated experimentally by reducing the target thickness from HOPG (left) to a single layer of graphene (right).

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Highly Charged Ions as Emerging Probes of Nuclear Structure

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Precise knowledge of nuclear charge radii is essential not only for nuclear structure studies, but is also increasingly recognized as a key uncertainty in precision tests of fundamental physics [1]. In heavy atomic systems, uncertainties associated with the nuclear charge distribution can limit the interpretation of beyond-the-Standard-Model searches, including isotope-shift searches for new physics and searches for possible variation of the fine-structure constant.

In Na-like and Mg-like heavy ions, electronic wavefunctions contract toward the nucleus, enhancing nuclear-size sensitivity while retaining sufficiently simple atomic structure for precision theory. Our collaboration has established precision extreme-ultraviolet spectroscopy of these ions as a quantitative method for nuclear charge-radius studies. This approach is complementary to traditional techniques such as optical isotope-shift measurements, muonic-atom spectroscopy, and elastic electron scattering, while offering unique advantages for heavy and radioactive nuclei.

Using this method, we have performed recent measurements in the deformed rare-earth region, where the extracted charge radii reveal pronounced isotonic odd–even staggering and challenge current nuclear density-functional calculations [2]. Because this experimental approach requires only a small number of trapped ions and can be implemented at existing electron beam ion trap facilities, it is particularly promising for future studies of short-lived radioactive isotopes.

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Damaging intermolecular relaxation processes of hydrated biomolecules after heavy-ion irradiation

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Heavy-ion-irradiation can cause severe damage to cell and DNA. Acting on cancer cells, heavy ion therapy servers as an efficient radiotherapy technique due to the ability of carrying a large amount of energy and accurate delivering these energies to the tumor area by controlling the depth of the so-called Bragg Peak, and the high biological effectiveness of killing cancer cells. Despite its importance in both fundamental research and clinical applications, the mechanistic details of the heavy ion irradiation are unclear. Employing the reaction microscope built up in the Heavy Ion Research Facility in Lanzhou, we investigated the relaxation mechanisms of the hydrated pyrimidine clusters after heavy-ion irradiation [1].

The measurements were performed with the 25-MeV/u bare Fe^{26+} beam and the 112.5-keV/u C^{5+} beam. The carbon beam has been successfully applied in radiotherapy. It was found that inner-valence ionization of the clusters can initiate ICD and trigger proton transfer between water molecules, producing destructive low-energy electrons, $\text{HO}\cdot$ radicals, and hydrated protons. The efficiency of ICD was found to increase dramatically with the number of water molecules, making ICD the dominant decay mechanism after inner-valence ionization. Such processes can significantly contribute to the high biological effectiveness of heavy-ion irradiation.

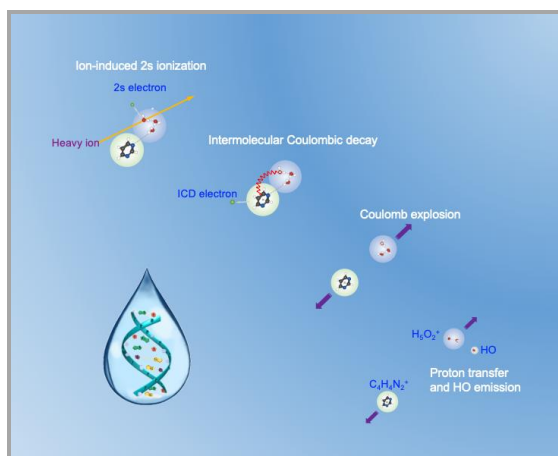


Figure 1. Schematic description of the observed relaxation mechanisms.

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Fully differential ion–atom collision experiments in storage rings: past, present and future

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Reaction microscopes (ReMi/COLTRIMS) provide kinematically complete information on atomic collision processes by measuring three-dimensional momenta of electrons and recoil ions in coincidence. In ion storage rings, they combine this capability with intense, well-defined projectile beams. This contribution reviews past and present storage-ring reaction-microscope experiments and discusses new opportunities with an in-ring COLTRIMS spectrometer at CRYRING.

Early experiments at the Test Storage Ring (TSR) of the Max Planck Institute for Nuclear Physics demonstrated the feasibility of operating reaction microscopes inside a storage ring. A magneto-optical trap combined with a reaction microscope provided a cold, state-selective lithium target [1]. Fully differential ionization measurements with stored highly charged ions revealed pronounced sensitivity of the electron emission pattern to the electronic structure and initial-state preparation.

More recently, an in-ring reaction microscope has been implemented at the Cryogenic Storage Ring (CSR) in Heidelberg [2]. Its cryogenic environment provides exceptionally cold stored ion beams with reduced translational and internal excitation, enabling state-selective, high-resolution collision studies under technically demanding conditions. Neutralized projectiles are also detected in coincidence after electron transfer. Recent measurements of He–Ar⁺ electron transfer reveal contributions from metastable projectile states, whose evolution with storage time allows their lifetimes to be extracted directly.

A new generation of storage-ring reaction-microscope experiments is now being prepared at CRYRING at GSI/FAIR [3]. A COLTRIMS spectrometer with a supersonic gas-jet target has been designed and constructed within the SPARC Reaction Microscope collaboration. Combined with highly charged ion beams at GSI, it will enable momentum-resolved multi-coincidence studies of charge transfer, ionization, and fragmentation. Of particular interest are correlated few- and many-electron dynamics driven by the strong, ultrashort electromagnetic fields generated in heavy-ion collisions.

The developments from TSR through CSR to CRYRING illustrate the evolution of storage-ring COLTRIMS from fully differential ionization measurements toward versatile multi-particle imaging experiments with increasingly complex and highly charged projectiles.

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Quantum Electrodynamics in Strong Electromagnetic Fields: Substate Resolved $K\alpha$ Transition Energies in Heliumlike Uranium

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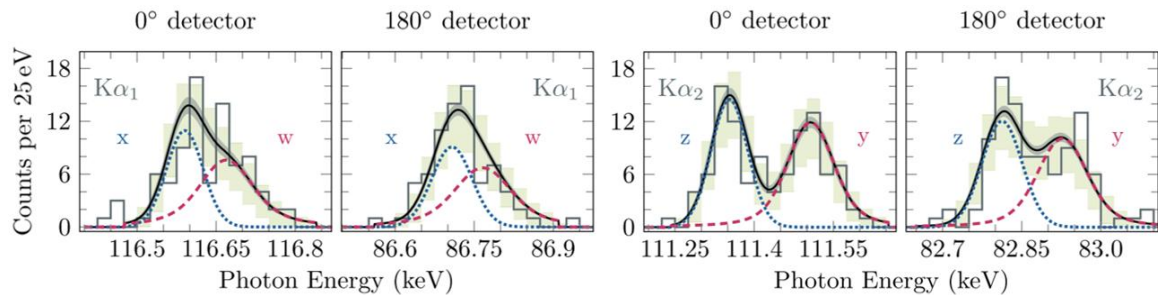
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Precision spectroscopy of radiative transitions in few-electron, high-Z systems is an indispensable tool for the study of relativistic effects and bound-state quantum electrodynamics (QED) in the presence of strong electromagnetic fields [1]. However, in the past spectroscopy of heavy ions in the hard x-ray regime was limited by the intrinsic resolution of semiconductor detectors (a few 100 eV FWHM at 100 keV photon energy). While crystal spectrometers can overcome this limitation, their applicability is usually limited to a narrow window of photon energies, combined with a high sensitivity to uncertainties in the geometry of the experimental setup [2].

To achieve a high spectral resolution over a broad range of x-ray energies, novel microcalorimeter detectors were developed within the SPARC collaboration, in particular the maXs detector design [3]. These are based on the metallic magnetic calorimeter (MMC) technology, where at operation temperatures below 30 mK the temperature increase of a small-volume absorber upon absorption of an incident x-ray is measured via the change in the magnetisation of a paramagnetic sensor. Nowadays, MMC detectors combine an excellent energy resolution (a few tens of eV FWHM at 100 keV) comparable to hard x-ray crystal spectrometers with the broad bandwidth acceptance of semiconductor detectors (from 0.1 to above 100 keV).



Spectral region of the $n = 2 \rightarrow n = 1$ transitions in U^{90+} , observed by MMC detectors at 0° and 180° with respect to the ion beam axis. The achieved resolution enabled for the first time to unambiguously determine the energies of all four transitions (x, y, w, and z, respectively) [5].

In this contribution, we report on a recent study performed at CRYRING@ESR, where two maXs-type detectors were employed to record the x-ray transitions in helium like uranium (U^{90+}) [4]. A spectral resolution of <90 eV FWHM over a wide energy range from a few keV to above 100 keV was achieved. This enabled for the first time to disentangle all four components of the K α radiation of U^{90+} , resulting in an accurate determination of their transition energies [5]. As a cross-check, we also obtained an accurate value of the U^{90+} groundstate ionization energy. Moreover, radiative transitions from the N and M shell to the L shell were also studied. details of the experimental setup as well as its scientific output will be presented, together with an overview on current developments.

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Ultrafast Highly Charged Ion Dynamics

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Highly charged ions (HCIs) allow for stringent tests of relativistic effects, quantum electrodynamics, and nuclear structure. Monochromatic X-rays are particularly well suited for probing their core-electron dynamics, yet most previous studies have been limited to states accessible through single-photon excitation. In this presentation, I will discuss how X-ray free-electron lasers (XFELs) and fourth-generation synchrotron sources, combined with electron-beam ion traps (EBITs), enable new approaches for investigating the atomic structure and ultrafast dynamics of HCIs.

First, I will present experiments in which HCIs confined in an EBIT are irradiated with ultraintense XFEL pulses, allowing controlled studies of multiply excited states. These measurements reveal novel nonlinear two-photon ionization pathways beyond the well-known resonance-enhanced X-ray multiphoton ionization (REXMI) mechanism. In particular, the interplay of relativistic and electron-correlation effects leads to near-cancellation of energy shifts for specific states, creating quasi-degenerate resonant conditions that strongly enhance nonlinear ionization processes.

Second, I will describe an all-X-ray pump-probe scheme realized using the two-color operation mode of the European XFEL. Pairs of femtosecond X-ray pulses were used to directly record the exponential decay of femtosecond atomic lifetimes in HCIs in the time domain. Unlike conventional linewidth-based approaches, which become challenging in this regime, this technique enables precision lifetime measurements with unprecedented sensitivity to atomic-structure effects.

Finally, I will present recent results obtained at the NanoTerasu fourth-generation synchrotron, where full angular distributions of resonantly scattered X-rays were measured while controlling the incident linear polarization. By exploiting the Hanle effect in this configuration, precise lifetime measurements in the previously inaccessible picosecond regime may become possible.

These precision laboratory studies provide critical benchmarks for state-of-the-art atomic theory and valuable reference data for current and future X-ray astronomy missions.

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Generalized independent-atom-model approach for net ionization of molecules by multiply-charged heavy-ion impact

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There has been considerable recent interest in collisions involving complex molecules, a major motivation being their relevance across a wide spectrum of areas ranging from astrochemistry to ion-beam cancer therapy. We demonstrated in previous work that the independent-atom-model pixel-counting method (PCM) is successful in describing net ionization in proton–molecule collisions and also for moderately-charged ion impact at relatively high (nonrelativistic) impact energies [1]. The method was introduced to amend the additivity rule (AR) in which ion–atom cross sections are simply added together, by taking into account geometric overlaps of atomic cross-sectional areas. PCM cross sections are smaller than or, in the case of negligible overlap, equal to AR cross sections and in many instances in better agreement with experimental data. For highly-charged projectiles we have found that the PCM appears to overcorrect AR predictions.

The work presented in this talk will focus on an extension of the PCM to incorporate the possibility of multiple scattering along the projectile trajectory [2]. The extension is based on estimated mean free paths for sequential ion–atom collisions within the target molecule. We find that the new model agrees well with the original PCM for proton and moderately-charged ion impact but provides cross sections that are in between PCM and AR results for highly-charged projectiles. If the target molecule has a large atomic number density for a given species as is the case for, e.g., the carbon atoms in anthracene ($C_{14}H_{10}$), the multiple-scattering effect can become very substantial. These predictions, to be detailed at the conference, call for experimental verification.

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Precision experiments at the intersection of Atomic, Nuclear and Astrophysics

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Radioactive decays of atomic nuclei are conventionally studied in neutral atoms. But this is a poor proxy for the conditions inside stars, where atoms are stripped of most or all of their electrons. In such highly charged ions (HCI), the interplay between the nuclear and atomic degrees of freedom can dramatically alter decay properties. Familiar decay channels can be blocked, while new ones, forbidden for neutral atoms, can open up. These effects make HCI decay studies relevant simultaneously to nuclear structure, atomic physics, and stellar nucleosynthesis [1].

To observe such processes experimentally, a radioactive species must be produced and held in a well-defined, high atomic charge state for a time comparable to or longer than its decay half-life. This is achievable today in a heavy-ion storage ring operated under ultra-high vacuum [2]. Coupled to the FRS fragment separator, the Experimental Storage Ring (ESR) at GSI, Darmstadt, has hosted the vast majority of such experiments to date. The methodology relies decisively on versatile beam manipulations, such as accumulation of weakly produced secondary beams and stochastic and/or electron cooling, together with sophisticated instrumentation. At the heart of these experiments lies the non-destructive Schottky diagnostics. In recent years, its performance was boosted, enabling half-life measurements in the millisecond range [3].

This contribution concentrates on two representative cases. The first is the bound-state β -decay of fully ionized $^{205}\text{Tl}^{81+}$, in which the emitted electron is created directly in the empty K-shell of the daughter ^{205}Pb ion — a decay channel that does not exist for neutral atoms. We stored $^{205}\text{Tl}^{81+}$ ions for up to 10 hours and obtained the first measurement of this decay. This removed the dominant nuclear-physics uncertainty in the ^{205}Pb – ^{205}Tl cosmo-chronometer, with direct consequences for dating the isolation of the Sun's parent molecular cloud [4]. Furthermore, our result constrained the possible application of Tl-bearing mineral lorandite as a long-term Solar pp-neutrino detector [5].

The second case is the nuclear two-photon (2γ) decay, a rare second-order process observable in bare ions when competing first-order channels (single-photon emission, internal conversion, pair creation) are kinematically or selection-rule suppressed. We report the measured 2γ decay of bare ^{72}Ge [6], together with the ongoing analysis of ^{98}Zr and ^{98}Mo .

We close with an outlook on future perspectives at existing and upcoming facilities, including FAIR in Germany and HIAF in China.

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SELECTED TALKS

Periodic table for ultra-accurate highly charged ion clocks

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Highly charged ions (HCIs) are less sensitive to external perturbations and are therefore attractive for the development of ultrastable clocks. However, only a few HCI candidates are known to provide optical clock transitions.

Through the theory of angular momentum coupling, we successfully constructed a periodic table suitable for HCIs [1], which simplifies our understanding of their complex energy structures. This enables us to identify clock transitions in open-shell HCIs across more than 70 elements, thereby expanding the number of ultra-accurate HCI clock transitions to over 700 in ions from 25 isoelectronic sequences. Their projected instabilities ($\sim 10^{-17}/\tau^{1/2}$) and accuracies ($< 10^{-20}$) surpass state-of-the-art optical clocks by several orders of magnitude [1-3]. This suggests that having a high-performance optical clock transition is not a property exclusive to particular elements, but rather a characteristic shared by most elements in the periodic table. The existence of multiple clock transitions in different charge states of a single element, as well as in a whole isoelectronic sequence, would significantly enrich the search for new physics and the test of nuclear theories via high-precision spectroscopy [4,5].

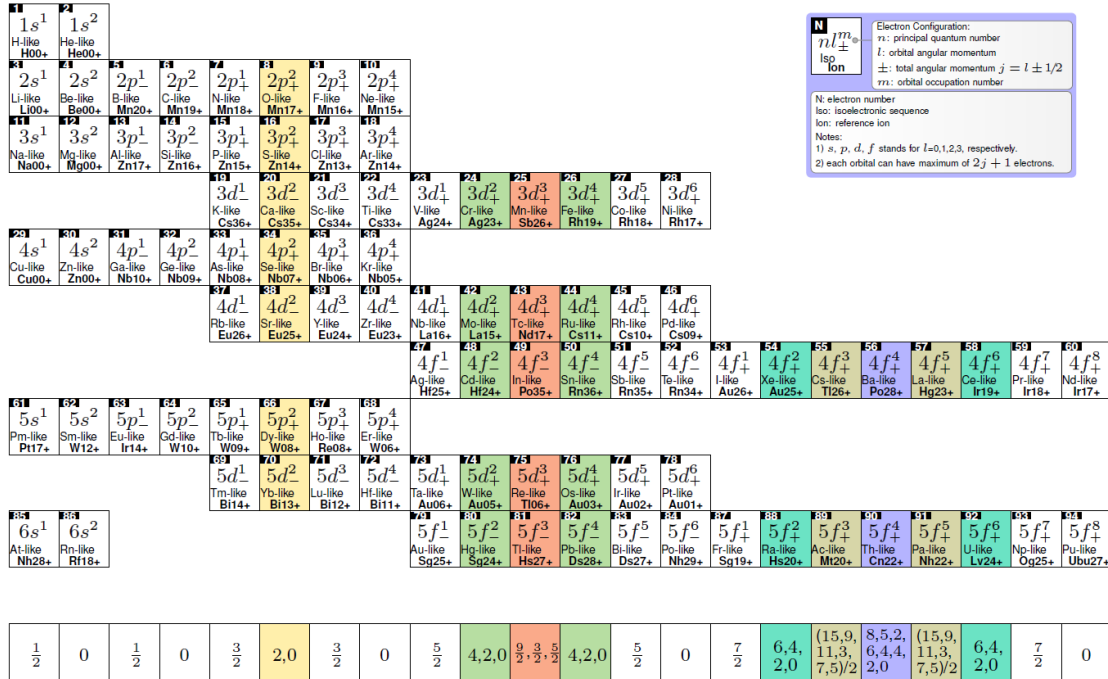


Figure 1. Periodic table for HCIs. The bottom row presents all allowed state ordered according to their increasing energies. Each colored cells contains dozens of high-accuracy clock ions.

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Recent activities of the Japanese EBITs: Optical and EUV spectroscopy and instrument development

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An electron beam ion trap (EBIT) is a powerful tool for studying highly charged ions (HCI). Over the past three decades, several EBITs have been commissioned in Japan. In recent years, Tokyo-EBIT [1], CoBIT-I [2], CoBIT-II [3], and JAXA-EBIT [4] have been actively operated. In the oral presentation, we review the recent activities of the Japanese EBIT community. Regarding experiments using the existing EBITs, we focus on spectroscopic studies of Optical and extreme ultraviolet transitions in HCIs.

One of the important topics is the successful demonstration of time-resolved plasma-assisted laser spectroscopy using CoBIT-I. This technique enabled us to measure high-resolution laser-induced fluorescence (LIF) spectra [5, 6] and microsecond-order lifetimes [7, 8].

In the emission spectroscopy of CoBIT-II, we have systematically studied the electric-octupole emission of Ag-like ions under low-density plasma conditions [9, 10]. Recently, we have installed an electron-impact metal injection method [11] and expanded the scope of the systematic investigation. In addition, various optical forbidden transition lines of metallic HCIs have been measured [12].

Recently, we have conducted two projects for the development of new EBITs. In 2026, the third Japanese compact EBIT, CoBIT-III, was commissioned at Tokyo University of Science (TUS). In addition, we have started the development of a new EBIT, NIFS-EBIT, at National Institute for Fusion Science (NIFS) for synchrotron radiation spectroscopy of few-electron heavy HCIs, such as H-like, He-like, and Li-like ions, using a high-energy, high-density electron beam. In the oral presentation, we will report the recent status of these new developments.

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Charge-exchange emissions in astrophysical and laboratory simulated plasmas

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Since the discovery of X-rays in Hyakutake comet, X-rays have been detected in almost all solar system objects. Later, this kind of X-rays was confirmed to be the charge-exchange of highly charged particles in solar wind with water molecular in comet or H in planetary exosphere. Currently, charge-exchange emission is regarded as a widespread emission source in many dynamical objects, e.g. stellar winds, supernova remanants and star-bursting galaxies. The inclusion of charge-exchange emission in spectral models deeps our understanding to a specified object. However the solar wind charge-exchange (SWCX) emission is a significant contamination to the studies of celestial objects. So accurate constrains on the SWCX in Earth magnetosphere and heliosphere is a necessary and challenging work due to the inherient characteristic of dynamic variation in solar wind. In this work, we will demonstrate our recent progress in the SWCX [1]. We further carried out an exploration to explain lower accretion rates from X-rays than those from optical tracers in young stellar objects (YSOs) by using charge-exchange [2]. Moreover, such charge-exchange emission has been confirmed in our laboratory analog for the accretion in YSOs and outflow impacting on interstellar medium [3].

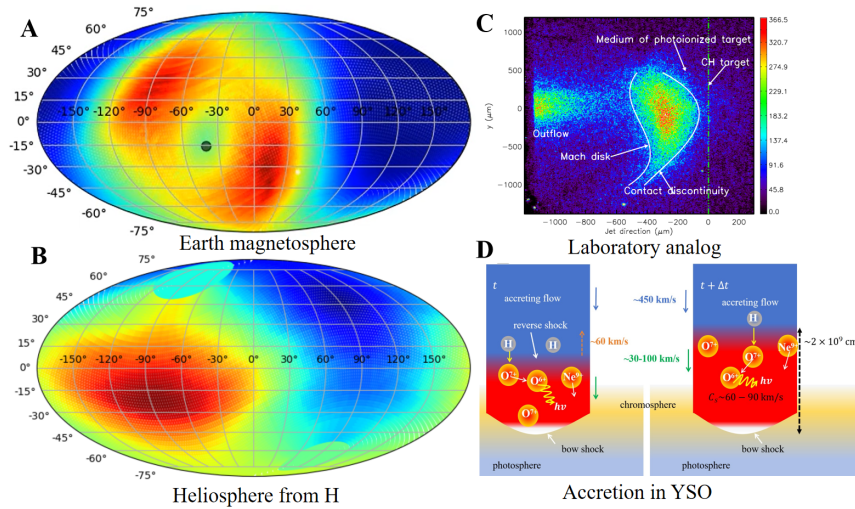


Figure 1. Soft X-ray sky map of solar wind charge-exchange emissions in Earth magnetosphere (A) and heliosphere (B) due to collision with neutral H. X-rays in laboratory simulated outflow interaction with interstellar medium (C), as well as a schematic diagram to illustrate the charge-exchange in YSOs (D).

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Atomic processes in dense plasma

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Dense plasma widely exists in our universe and is the important state of matter in inertial confinement fusion. During the past decades, various models are developed to describe the basic atomic processes in dense plasma. However, the experimental data are scarce for the model benchmark, because research into the matter under extreme conditions represents a frontier of experimental techniques, and requires infrastructure at the most technologically advanced level. In our work, a well-defined, uniform, large-scale~mm, long-living~20ns plasma sample ($n \sim 4 \times 10^{20}/\text{cc}$, $T \sim 17\text{eV}$) was generated through heating a Tri-Cellulose Acetate (TCA) foam with the high-power-laser-driven hohlraum radiation. Series of experiments regarding the plasma radiations as well as the laser-accelerated intense ion beam interaction with the plasma sample were performed. The main findings are as below.

1) The QED Effects, Breit Interaction, and Electron Correlation are demonstrated in Highly Charged Au Ions produced by high power lasers. White-dwarf-atmosphere-like plasma radiation property are obtained.

2) Target density effects, that are supposed to increase the effective charge state of ions in plasma, are for the first time proved in NCD plasma and porous foam.

3) Ion-plasma coupling effects are demonstrated to reduce the ion stopping power at unprecedented coupling parameter exceeding unity for the first time.

4) Collective electromagnetic effects are proved to lead to the non-linear stopping and transportation.

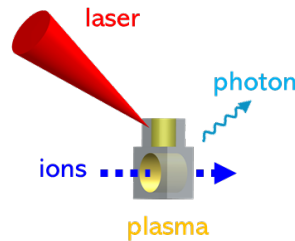


Figure 1. Ion-plasma interaction scheme based on laser facility.

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Cross Section Measurements and State-Selective Electron Capture in Ne^{7+} – H_2/He Collisions

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Single-electron capture (SEC) in collisions between highly charged ions and neutral targets plays an important role in fusion plasmas, astrophysics, and fundamental physics. Despite extensive investigations of charge-exchange processes involving highly charged ions [1-2], comprehensive measurements combining total, state-selective, and angular differential cross sections remain limited for the Ne^{7+} system, particularly over a broad collision-energy range.

Here, we report an experimental study of SEC cross section for Ne^{7+} colliding with He and H_2 at impact energies from 2.45 to 35 keV/u. Absolute total SEC cross sections were measured using the growth-rate method [3], while the state-selective cross section was determined by using the Cold Target Recoil-Ion Momentum Spectroscopy (COLTRIMS) apparatus at Fudan University [4]. By normalizing the relative state-selective cross sections to the absolute total values, absolute state-selective cross sections were obtained [4, 5]. For the Ne^{7+} –He system, Q-value spectra indicate that capture into the $n=4$ manifold dominates, with minor contributions from $n=3$ and transfer-projectile-excitation channels. For the Ne^{7+} – H_2 system, both $n=4$ and $n=5$ capture channels contribute significantly.

The state-selective cross sections exhibit pronounced energy-dependent population distributions, and higher- n capture channels become increasingly important with increasing projectile energy. The scattering-angle distributions are strongly forward peaked and become increasingly concentrated at smaller angles as the projectile energy increases. The present work provides benchmark state-selective and angular differential data for Ne^{7+} –He/ H_2 collisions, essential for testing charge exchange theories and modelling astrophysical X-ray emissions.

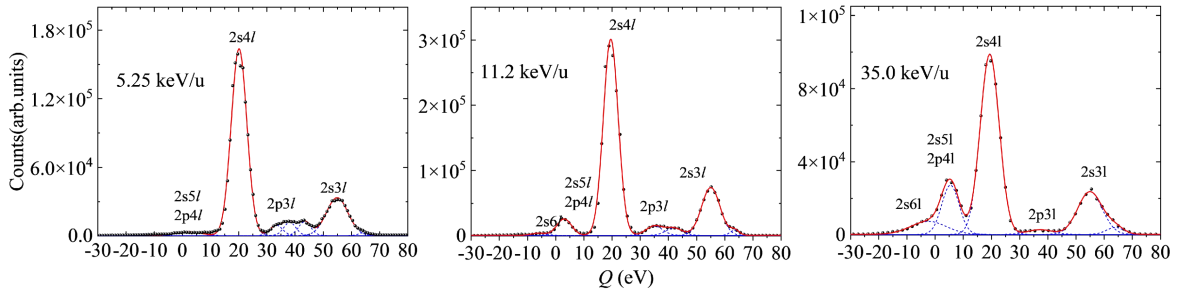


Figure 1. Measured Q-value spectra for SEC in Ne^{7+} –He collisions at three selected energies.

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Observation of highly excited fragment atomic ions from diatomic molecules in collisions with highly charged ions in EUV emission spectra

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The ion-molecule collision process, in which diatomic molecules dissociate into pairs of atomic ions in collision with highly charged ions, has been studied in detail by measuring the kinetic energy release of the fragment ions. Although some cases have considered the possibility that the fragment atomic ions may be in an excited state rather than the ground state, there is only one reported instance of them being in a very highly excited state. We observed emission spectra in the extreme ultraviolet region during collision experiments between highly charged Ta ions and N₂ and O₂ molecules, and detected emission in the 17–29 nm wavelength range from 3+ to 5+ atomic ions [1]. This corresponds to excitation energies of 42–73 eV, indicating that the fragment ions are excited to a considerably highly energetic state.

In this study, we observed emission from fragments using multiply charged Ar and Kr ions, as shown in Figure 1. Although most emission lines are common to both spectra because they are due to the same projectile ions, some are observed only in one, eg. 28.36 nm in N₂ and 27.22 nm in O₂. These are thought to originate from the target, and their wavelength-based identification revealed that they correspond to optical transitions in multiply charged atomic ions. We also estimated the emission cross-section using the experimentally determined detection efficiency. The cross-section values were approximately 10⁻¹⁶ cm², which are not particularly small; therefore, this process warrants further investigation as an important mechanism in the study of molecular dissociation by highly charged ions. In particular, we believe the excitation mechanism warrants theoretical discussion and therefore eagerly seek cooperation from theoretical researchers.

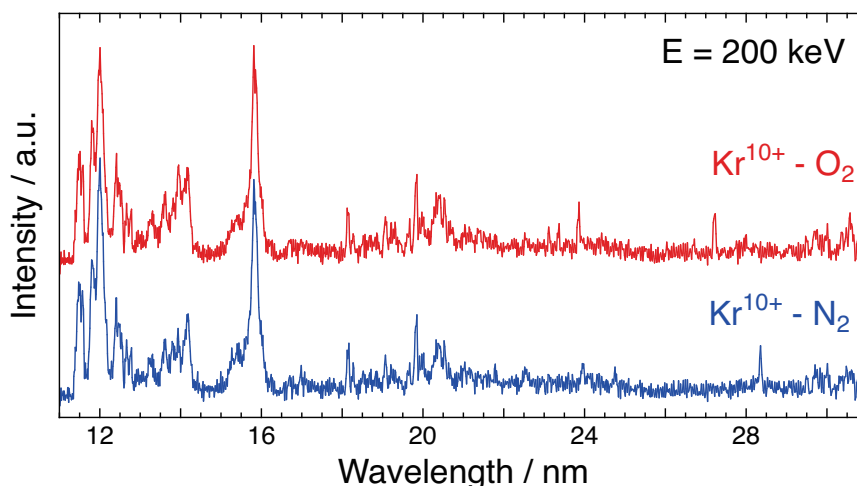


Figure 1: EUV emission spectra in collisions of Kr¹⁰⁺ with N₂ and O₂ at 200 keV.

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X-ray emission following charge exchange between Al^{13+} and He

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Charge exchange (CX) between highly charged ions and neutral atoms constitutes a fundamental atomic process and serves as a significant contributor to soft X-ray emission across a variety of astrophysical environments [1, 2]. CX X-ray spectra are essential for elucidating the underlying mechanisms and interpreting astrophysical observations. Here, we report a high-resolution measurement of X-ray emission resulting from CX between Al^{13+} and He at collision energies of 1.44–12.04 keV u⁻¹.

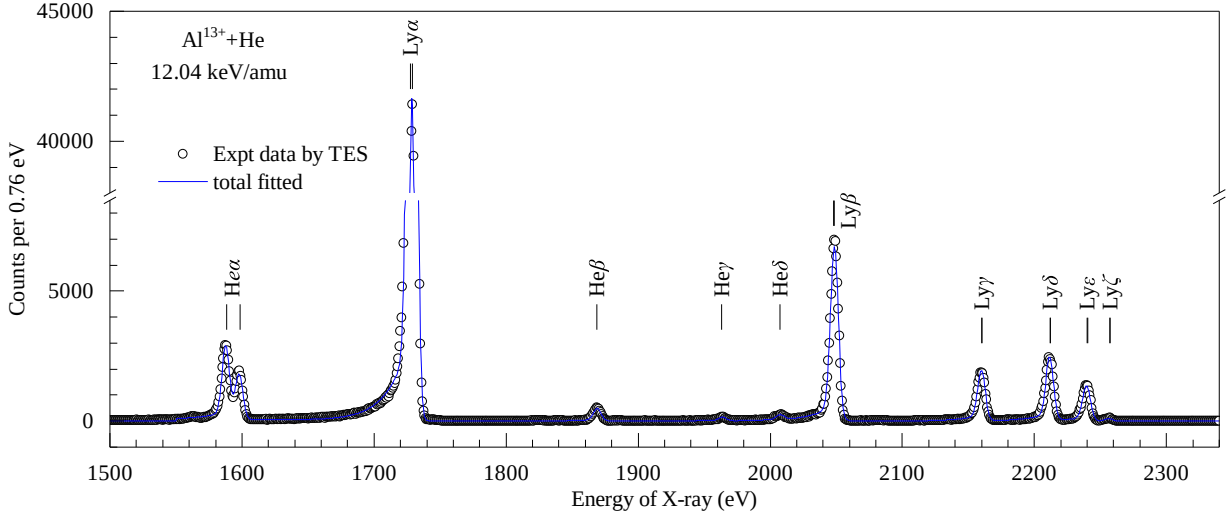


Figure 1: X-ray spectra from CX collisions between Al^{13+} ions and He at 12.04 keV u⁻¹.

The experiments were performed at the terminal of an electron cyclotron resonance (ECR) ion source facility. The emitted X-ray emission was recorded using a microcalorimeter. The typical X-ray spectra at a collision energy of 12.04 keV/u are shown in Figure 1. The spectra include well-resolved Lyman lines corresponding to $np \rightarrow 1s$ transitions for $n = 2-7$. Detailed analysis of the spectral features is currently underway. The experimental results are expected to provide critical benchmarks for both astrophysical plasma modeling and fundamental studies of ion–atom collision dynamics.

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Classical and Quasi-Classical Modeling of Cross Sections and Stopping Powers in He^{2+} –H/D/T(1s) Collisions

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Fusion energy is widely regarded as a promising long-term solution to the growing global demand for clean and sustainable power. Accurate cross-section data for collisions between He^{2+} ions and hydrogen isotopes are essential for modeling and optimizing fusion plasmas. The classical trajectory Monte Carlo (CTMC) method has long served as an effective framework for investigating atomic collision processes [1]. However, its purely classical nature limits its accuracy, particularly at low incident energies where quantum effects become significant. To address this limitation, we developed a three-body quasi-classical trajectory Monte Carlo (QCTMC) model that incorporates key quantum characteristics of the collision system. This approach introduces a Heisenberg correction term into the classical Hamiltonian, thereby emulating the effects of the Heisenberg uncertainty principle [2,4].

Using both CTMC and QCTMC models, we present total ionization and charge-exchange cross sections for He^{2+} collisions with hydrogen isotopes over an incident-energy range of 2.5–885.0 keV/u. The QCTMC model yields substantially improved agreement with available reference data, especially in the low-energy regime [5]. In addition, we investigate in detail state-selective charge-exchange cross sections, as well as angular and energy distributions of scattered projectiles and emitted electrons. Trajectory information obtained from the simulations is further employed to understand the details of the collision dynamics. The close agreement between QCTMC predictions and previously reported quantum-mechanical results demonstrates that the proposed method provides an accurate and computationally efficient alternative for studying collision dynamics and evaluating cross sections relevant to fusion applications.

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Application of Dielectronic Recombination in Strong-Field Physics and Kilonova Spectroscopy

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Dielectronic recombination (DR) is a fundamental atomic process that governs the ionization balance in plasmas relevant to strong-field physics and astrophysics. It plays a unique bridging role in two frontier fields: testing strong-field quantum electrodynamics (QED) and diagnosing non-local thermodynamic equilibrium (NLTE) kilonova spectra. In strong-field physics, the inner-shell electrons of highly charged heavy ions (e.g., H-like U^{91+} and Li-like U^{89+}) experience Coulomb fields as strong as $Z\alpha \sim 1$, where higher-order QED effects (two-loop self-energy and higher-order vacuum polarization) become significantly enhanced. In the recent collaboration with S. Schippers and colleagues from the University of Giessen [1], I provided critical theoretical support for the precision DR resonance spectroscopy of Be-like $Pb78+$ ion measured at the CRYRING facility. The study successfully revealed the contribution of second-order QED effects to the resonance energies, validating the reliability of theoretical methods under strong-field conditions and establishing a methodological foundation for strong-field QED tests at next-generation heavy-ion facilities, such as the High-Intensity Heavy-Ion Accelerator Facility (HIAF-SRing) in Huizhou. On the other hand, in NLTE kilonova spectroscopy, the DR processes of lanthanide elements directly regulate the ionization balance and level populations, thereby shaping the intensity and profiles of mid-infrared spectral lines. I am currently studying the DR processes for lanthanide ions (e.g. Nd II–IV and Sm II–IV), to fill critical gaps in the relevant atomic data. These efforts provide essential atomic physics support for extracting true lanthanide abundances from astronomical observations by JWST, XRISM, and future missions, ultimately contributing to unraveling the origin of heavy elements in the universe. This report will present recent advances in DR study, spanning from well-benchmarked highly-charged ions to complex lanthanide ions, and demonstrate how precise atomic data bridge the frontiers of strong-field physics and astrophysics.

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Nuclear Clock Meets Highly Charged Ions

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An important direction in modern precision timekeeping technology is the development of nuclear clocks, which employ nuclear transitions as frequency standards. Compared with conventional atomic clocks, nuclear clocks are more robust against external electromagnetic perturbations and more sensitive to variations in fundamental physical constants. In previous studies of atomic and nuclear clocks, electronic and nuclear transitions were generally treated as independent processes. However, in hyperfine electronic bridge transitions, the nucleus and the electron can undergo transitions simultaneously [1]. We find that, in highly charged ions of Th-229, hyperfine electronic bridge transitions can significantly enhance the sensitivity to variations in the fine-structure constant compared with bare nuclear transition [2].

Currently, research on nuclear clocks has been primarily focused on Th-229. A possible extension of nuclear clock systems is U-235, which possesses a nuclear isomeric state at 76.7 eV that can, in principle, be accessed by extreme-ultraviolet frequency combs. However, its radiative lifetime is as long as 10^{16} years, making it unsuitable as a clock transition. We find that, by exploiting hyperfine-induced nuclear transitions [3] in highly charged ions of U-235, the radiative lifetime can be reduced to the order of several decades. This enables the U-235 nuclear isomer to be manipulated by precision spectroscopic techniques while maintaining an extremely high quality factor, significantly exceeding that of Th-229 [4]. Our finding opens a new avenue for nuclear clock research.

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Detecting surface magnetism with highly charged ions

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We demonstrate that surface magnetism can be detected using highly charged ions as a probe, without the need for an external magnetic field. This is achieved through x-ray spectroscopy of the $n = 2 \rightarrow 1$ transitions of highly excited argon ions produced in grazing incidence collisions of a 170 keV Ar^{17+} ion beam with a monocrystalline Ni(110) sample at various temperatures. As the sample temperature increases, the unresolved $n = 2 \rightarrow 1$ x-ray transitions exhibit a shift toward lower energies, indicating an increased electron population in the $n = 2$ level and thus the effect of the electron screening on the energy transition. This behavior agrees with the expected reduction of the Pauli exclusion effect at the $n=2$ level as a result of a spin alignment loss of the captured electrons caused by the change of magnetic phase (from a ferromagnetic phase at low temperature to a paramagnetic one at higher temperature). The same effect was also observed in the $n = 3 \rightarrow 2$ transitions for Ar^{16+} ions colliding with the same sample. These results resolve a longstanding controversy arising from contradictory Auger spectroscopy studies on ion–magnetic surface interactions and open new perspectives for surface characterization. This study will be soon extended to other types of material. In particular, the surface magnetism of epitaxially grown iron will be studied in the presence or not of oxidation.

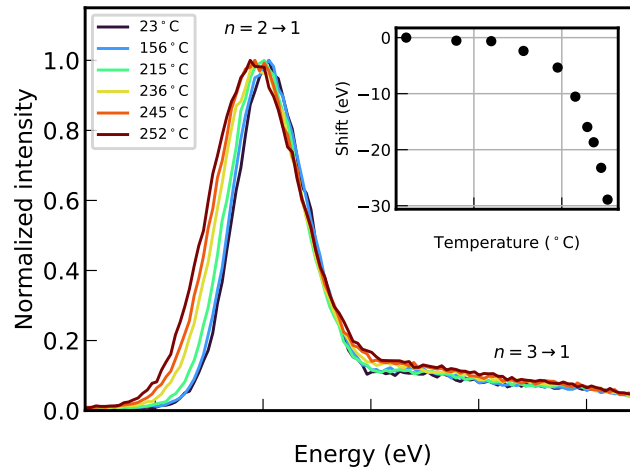


Figure 1: X-ray spectra for Ar^{17+} at 170 keV hitting the nickel sample for various temperatures. In the inset is reported the main line barycentre shift with respect to the room temperature spectrum.

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Highly charged ion-induced surface modifications studied by low-angle X-ray techniques

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The physicochemical properties of nanostructured materials can be intentionally tailored by irradiation with both swift heavy ions (SHIs) and slow highly charged ions (HCIs), offering a versatile route for controlled surface nanostructuring and tuning of functional properties [1,2]. Precise evaluation of the structural and chemical changes induced by such interactions requires highly surface-sensitive analytical techniques. In this work, we present a comprehensive multi-technique approach for the characterization of metallic nanolayers deposited on silicon substrates before and after irradiation with low-energy highly charged Xe^{q+} ions ($q \leq 40$), produced by the Kielce EBIS facility [3].

To investigate HCI-induced modifications in elemental composition, surface homogeneity, and electronic structure, we employed conventional X-ray Photoelectron Spectroscopy (XPS) together with Total Reflection XPS (TRXPS) and Grazing Incidence XPS (GIXPS) using a SPECS mono-XPS system [4]. Measurements performed at low grazing incidence angles significantly enhanced surface sensitivity while reducing the inelastic background contribution. In addition, synchrotron-based X-ray Reflectometry (XRR) and Grazing Incidence X-ray Fluorescence (GIXRF) measurements were carried out at the Elettra Sincrotrone Trieste facility to determine structural parameters of the nanolayers, including thickness, density, surface and interface roughness, and elemental depth profiles [5].

The combined use of XPS, TRXPS, GIXPS, GIXRF and XRR provides a robust analytical framework for the characterization of ion-induced surface modifications. This complementary methodology enables a detailed interpretation of the physicochemical changes and nanostructures formed during the interaction of highly charged Xe ions with solid surfaces.

Acknowledgements

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Electron emission induced by slow Sn^{1-5+} ions on metal surfaces

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Electron emission induced by slow Sn^{1-5+} ions impacting Sn, Cu, and stainless steel targets is investigated. Average absolute electron yields, as shown in Fig. 1, were obtained from electron statistics measurements and adjusted for zero-electron counting losses via Poisson-based correction. Deviations from Poisson statistics at higher electron numbers reveal a weak “background” source of electrons with an average electron yield of $\gamma^* \approx 2.5$. The final set of data is corrected for this background contribution. For Sn^{1+} and Sn^{2+} , the electron yield scales linearly with ion velocity, indicating that electron emission is dominated by kinetic emission (KE). The extracted KE thresholds ($\approx 3 \times 10^4$ m/s) are nearly an order of magnitude lower than theoretical predictions and are similar for all targets. In contrast, the absolute values of electron yields show a clear material dependence, with Cu yielding the highest yields. For Sn^{3-5+} , an additional velocity-independent contribution is observed and attributed to potential emission (PE). By separating KE and PE contributions, a clear increase of PE with charge state is found for Sn and stainless steel, while Cu exhibits significantly reduced PE yields. These results demonstrate that electron emission by Sn ions, in the range of 0.5 – 20 keV, is governed by an intrinsic interplay of KE and PE, depending on charge state and target material.

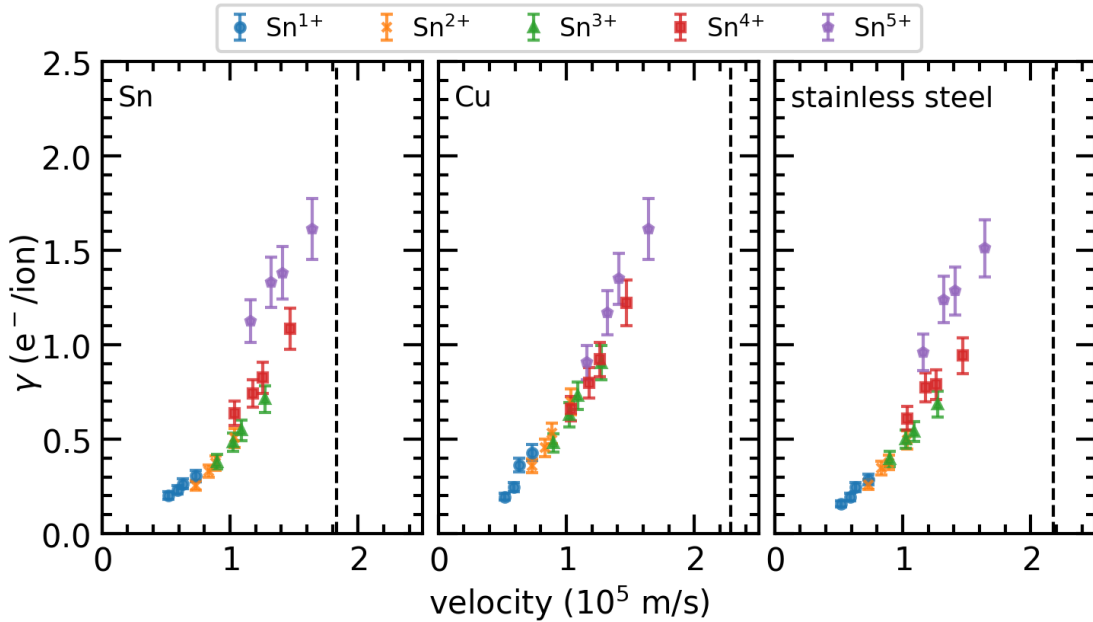


Figure 1. Average electron yield γ as a function of projectile velocity for Sn ions with charge states $q = 1 - 5+$ interacting with Sn, Cu, and stainless steel targets. Each panel corresponds to a different target material, as indicated. The dashed vertical line marks the characteristic threshold velocity v_{th} derived from the Fermi energy and work function of the respective material.

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Study of electron temperature anisotropy in high temperature plasmas via x-ray/EUV polarization spectroscopy

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The anisotropy of velocity/temperature in plasmas plays an important role in plasma equilibria and instabilities. To detect anisotropic electrons in plasmas, the polarization of emission lines from the X-ray to infrared wavelength ranges is often utilized in astrophysical and laboratory plasmas. In this work, we examine Ar XVI spectra measured by an X-ray crystal spectrometer to estimate electron temperature anisotropy in high-temperature electron-cyclotron-heated plasmas in the Large Helical Device (LHD).[1,2] We calculate the atomic structure and electron impact excitation cross sections between magnetic sublevels of Ar XVI. Assuming a bi-Maxwellian electron distribution function and taking into account the mount geometry of the X-ray spectrometer in LHD, we model the expected intensity ratio q/r as a function of $T_{e\perp B}$ and $T_{e\parallel B}$, where $\perp B$ and $\parallel B$ denote perpendicular and parallel components to the magnetic axis of the toroidal plasma, respectively.

The calculation results show that the intensity ratio of q and r , which are formed by inner-shell excitation from the ground state of Ar^{15+} , is sensitive to electron temperature anisotropy. We apply the calculation results to the LHD experiments, and find that the ratio of q/r changes with variations in electron density and collision frequency. In the core and low ν_e region, $T_{e\perp B}$ is predominant, whereas the electron temperature becomes isotropic above $\nu_e > 10^4$ Hz. By combining electron temperature measurements from Thomson scattering and radial profile of Ar^{15+} ions estimated using the extreme ultraviolet (EUV) spectrometer, local values of $T_{e\perp B}/T_{e\parallel B}$ are quantitatively estimated from the q/r ratio. The derived $T_{e\perp B}/T_{e\parallel B}$ values are compared with the electron collision frequency, radial electric field, and effective helical ripple, and the experimental results are explained qualitatively. In the presentation, we will present the results of the LHD experiments, as well as our recent work on the development of EUV spectropolarimeters and the calibration of optical components at the UVSOR synchrotron facilities.

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Measuring ion-induced biomolecular fragmentation using a Velocity Map Imaging spectrometer

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With the development of ion beams (protons or carbon) for the treatment of cancer in medicine, the study of ion collisions with biologically relevant molecules such as nucleobases, nucleosides, amino acids or peptides has received increasing interest in recent years. Indeed, these studies help understanding the fundamental mechanisms involved at the molecular level. The interactions between the energetic ions and the biomolecular target leads mostly to ionisation and excitation of the biomolecules which then can relax by molecular fragmentation. Thus, to better quantify the collision processes, it is important to identify not only the different fragmentation pathways but also to measure both the kinetic energy (KE) and emission angle of the emitted fragments. To do so, a Velocity Map Imaging (VMI) spectrometer initially designed to measure ion-induced electron emission from biologically relevant molecules [1] has been adapted to study fragmentation dynamics.

The pulsed projectile ion beam and the biomolecular target beam produced from an effusive cell cross perpendicularly in an interaction region. The fragments formed in this volume are velocity focused by a multi-electrode VMI spectrometer onto the 2D position sensitive detector mounted after a flight tube. The time-of-flight (ToF) arrival signals are used to distinguish the fragments according to their m/q ratio with m and q , the mass and the charge state of fragment respectively. An image of the fragment of interest is acquired by pulsing the detector voltage during a small time window corresponding to the ToF of this fragment. An inverse Abel transform of the image is then used to reconstruct the initial velocity vector and deduce both kinetic energy spectra and emission angle.

In this contribution, the different fragmentation pathways of Uracil upon collision with both 120keV-Ar⁸⁺ and 42keV-N³⁺ ion beams will be presented. Some of the most dominant fragmentation channels will be compared based on the measured kinetic energy and mass spectra. Moreover, a method to retrieve absolute cross section for n -fold ionization (with n from 1 to 4) will be presented.

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Absolute cross sections for excitation of helium-like uranium in relativistic collisions

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In this contribution, we present an experimental and theoretical study of K-L excitation for helium-like uranium ions occurring in relativistic collisions with hydrogen and argon gas-jet targets. The experiment was performed at the Experimental Storage Ring (ESR) of GSI in Darmstadt. The excitation process has been studied via observing the $K\alpha$ x-rays of He-like uranium following the decay of the excited L-shell states. In previous studies of this collision system, we looked at angular distributions and intensity ratios of the $K\alpha$ x-rays [1,2]. In this study, we concentrate in particular on extracting the absolute K-L excitation cross sections for the heaviest helium-like ion. For this, we use the x-rays associated with the L-shell radiative electron capture (L-REC) process occurring in the same collisions for normalization. Comparison with state-of-the-art fully relativistic theoretical predictions including both proton/nucleus-impact excitation as well as the electron-impact excitation processes will be presented.

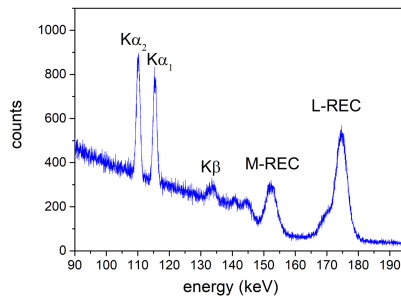


Figure 1. X-ray spectrum recorded for 218 MeV/u $U^{90+} \rightarrow H_2$ collisions with a Ge(i) detector at the observation angle of 60° with respect to the ion beam. The REC transitions into L, M, and higher shells are clearly visible together with the characteristic transitions into the K shell [1].

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Angular and spin-polarization properties of Auger electrons emitted from nonradiative decay of highly charged ions

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Electron-impact excitation (EIE) and photoionization (PI) of atoms and ions are fundamental atomic processes in astrophysical and laboratory plasmas. Nonradiative (Auger) decay of polarized atoms and ions excited by electron impact or photoionization may give rise to not only anisotropic but also spin-polarized Auger electrons. Angular and spin-polarization properties of Auger electrons emitted from highly charged ions (HCIs) can provide novel insights into electron-electron and electron-photon interactions in strong Coulomb fields.

As a crucial relativistic effect, the Breit interaction plays a very significant role in fundamental atomic processes of HCIs with free electrons involved. However, its effect on nonradiative decay properties of HCIs following EIE was rarely addressed. To address this, we investigated the effects of the Breit interaction on angular distribution [1, 2] and spin polarization [3] of Auger electrons emitted from the nonradiative decay $1s2s^22p_{1/2} J_d = 1 \rightarrow 1s^22s J_f = 1/2$ of Be-like ions excited by electron impact. Our results show that the Breit interaction dominates the Auger decay of heavy HCIs and also reveal a strong competition between its effects on both the excitation and the Auger decay.

To obtain strong spin polarization of Auger electrons, we further studied the identical nonradiative decay but following inner-shell $1s$ PI of B-like ions by circularly polarized light [4, 5]. The results show a quite strong circular polarization transfer of the ionizing light to the Auger electrons, which is analogous to the well-known polarization transfer in linear polarization of characteristic photons but is the first evidence in spin polarization of Auger electrons emitted from HCIs. Moreover, it is found that for heavy HCIs both the Breit interaction and the multipole mixing significantly affect the spin polarization, with the effects exhibiting a pronounced dependence on the nuclear charge.

The presently observed angular distribution and spin polarization of Auger electrons as well as the contributions of both the Breit interaction and the multipole mixing are sizable, which are therefore expected to be measured in the near future by combining electron spectrometers or Mott polarimeters with ion storage rings or electron-beam ion traps. Such measurements could provide novel insights into excitation and nonradiative decay dynamics of HCIs in strong Coulomb fields.

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State-resolved target-excitation and electron-loss cross sections in ion collisions with high charge states of Ne and Ar

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Accurate cross-section data for ion collisions with multi-electron impurity ions are needed for predictive modelling of magnetically confined fusion plasmas. Two species of particular interest are neon and argon, which are among the important candidate impurities for radiative power exhaust in ITER and DEMO. Although introduced as neutral gases, these impurities are rapidly ionised in the edge and core plasma, producing a wide range of charge states, including few-electron and open-shell ions. Reliable data are therefore required for collision processes involving these ions. To address this need, we model collisions of protons with various charge states of Ne and Ar ions to calculate state-resolved target excitation and electron-loss cross sections in a wide energy range relevant to fusion. This is done by applying the multi-electron Coulomb-Sturmian convergent close-coupling (CS-CCC) method [1, 2]. In this approach, the total scattering wavefunction of the collision system is expanded in terms of a set of target pseudostates which are obtained using a new general atomic structure code developed for this purpose. The code is based on the configuration-interaction method, in which each target pseudostate is expanded in terms of a set of configuration state functions (CSFs). The CSFs themselves are constructed using the method of coefficients of fractional parentage with a hybrid basis consisting of Hartree-Fock [3] and Coulomb-Sturmian spin-orbitals. These collision systems represent a new dynamical regime for the CS-CCC method, since the target electrons in the initial state are much more tightly bound than in the systems previously studied, including B, C⁺ and C targets [1, 2]. As an example of the results obtained, we present in Fig. 1 the CS-CCC cross sections for target excitation and electron loss in $p + \text{Ne}^{6+}$ (left) and $p + \text{Ne}^{8+}$ (right) collisions.

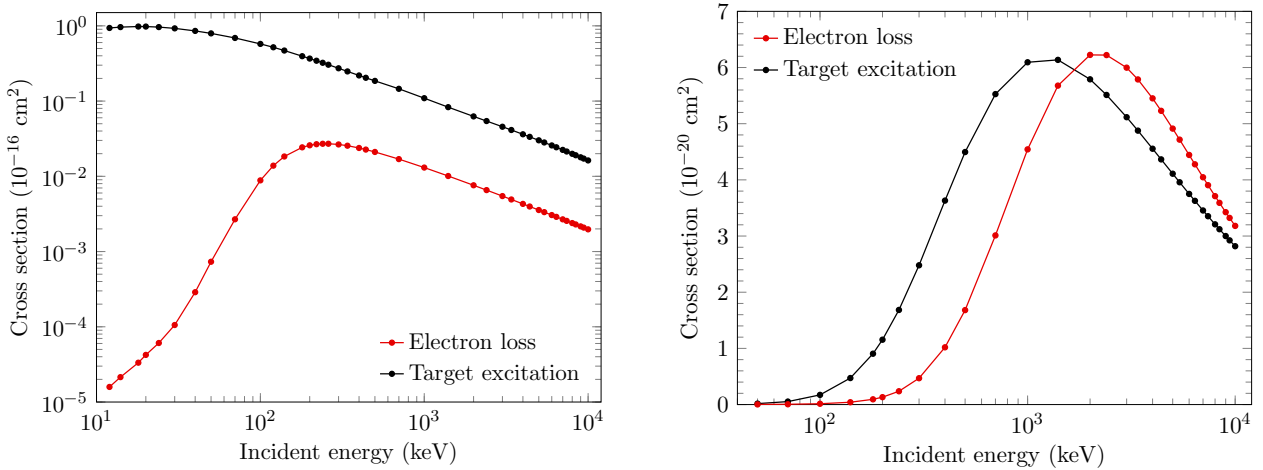


Figure 1: Cross sections for target excitation and electron loss in $p + \text{Ne}^{6+}$ (left) and $p + \text{Ne}^{8+}$ (right) collisions.

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From laboratory EBITs to space observatories: precision atomic data for X-ray plasma diagnostics

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Large X-ray observatories, such as Chandra, XMM-Newton, and XRISM, deliver high-resolution soft X-ray spectra ranging from 0.3 to 12 keV. These spectra reveal rich emission and absorption features from the multiple charge states of elements that are abundant in astrophysical environments. Accurately interpreting these spectra requires precise atomic data for key plasma diagnostics, such as electron temperature and density, ionization balance, turbulent velocities, and opacity. However, most astrophysical and plasma spectral models primarily rely on theoretical calculations. If these uncertainties are not accounted for, they introduce significant systematic errors. Laboratory measurements play a central role in providing the high-precision atomic data needed to validate and improve these models.

Here, we present recent measurements performed using electron beam ion traps (EBITs), both standalone and in combination with external light sources, such as synchrotrons and free-electron lasers. We report new measurements of K- and L-shell electron-impact excitation and dielectronic recombination cross sections with the lowest experimental uncertainties to date. These measurements directly support line ratio diagnostics used in astrophysical and laboratory plasma modeling. Additionally, we demonstrate how portable EBITs coupled with external photon sources can determine transition wavelengths, oscillator strengths, and branching ratios with high precision. These results provide stringent benchmarks for state-of-the-art atomic structure theories and are essential for current and future space missions, as well as for the broader community of atomic data users.

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Imaging the variation of electron density of the covalent bond in photolysis reaction of CH₃I

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Real-time orbital-resolved detection of valence electron density rearrangement during bond dissociation is critical for atomic and molecular collision research. We utilize time-resolved electron momentum spectroscopy (TR-EMS) based on the coincidence (e,2e) reaction to trace electron density variations in CH₃I after 261 nm UV photolysis. The pump laser excites molecules to dissociative states and triggers C–I bond cleavage into CH₃ radicals and iodine atoms. By comparing binding energy spectra and momentum-space electron density distributions of intact parent molecules and dissociation fragments, we directly observe the complete disappearance of electron density originating from the bonding 3a₁ and anti-bonding 2a₁ orbitals that sustain the C–I covalent bond after fragmentation. This work establishes TR-EMS as a unique tool for visualizing chemical dynamics in momentum space, offering a physically distinct and complementary perspective to energy-domain spectroscopy.

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High precision experimental benchmarks for helium double-to-single ionization by fast highly charged ions

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Double ionization of helium by charged particle impact is the simplest process for probing electron-electron correlation in ion-atom collisions. For highly charged projectiles, particular attention has been paid to the ratio R of the total double-to-single ionization cross sections. However, apparent deviations of experimental values of R from reduced-velocity scaling have been reported in previous studies [1-3], and whether these deviations constitute robust experimental evidence for higher-order effects has remained an open question for decades.

In the present work, we employed a state-of-the-art COLTRIMS setup [4], together with rigorous electron detection efficiency correction, to determine the ratio R of helium double-to-single ionization with uncertainties below 1% for 25, 120 and 225 MeV/u Fe^{26+} and 5 MeV/u O^{7+} . The experimental results were compared with calculations based on the semiclassical approximation and the independent electron model [5].

The present results lie within the perturbative two-step regime and fit well with the semi-empirical reduced-velocity scaling. A reappraisal of the historical data further indicates that the previously reported deviations do not provide a consistent experimental basis for a breakdown of reduced-velocity scaling. The present work therefore resolves a long-standing discrepancy in high-energy ion-atom collision physics, establishes reliable experimental benchmarks, and deepens the fundamental understanding of ionization dynamics triggered by highly charged projectiles.

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Co-Moving Heavy-Ion Beam Collisions in the ESR near the Coulomb Barrier

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A novel experimental scheme for co-moving heavy-ion collisions in the Experimental Storage Ring (ESR) is presented. The concept is based on the simultaneous storage of two ion beams with different velocities but identical magnetic rigidity, enabling repeated low-energy collisions near the Coulomb barrier in the ESR. As a proof of principle, first experiments with uranium and gold ion beams have demonstrated the feasibility of simultaneous co-storage of two heavy-ion beams with different velocities circulating on the same orbit in the ESR. However, the achieved collision energies were significantly below the Coulomb barrier. To approach collision energies slightly above the Coulomb barrier, charge states with a larger number of bound electrons are considered in order to reduce the effective Coulomb barrier of the system. The long-term goal of the proposed scheme is the study of U–U collisions in the regime of supercritical quasi-molecular fields and possible spontaneous positron emission. Details of the experimental concept and first feasibility considerations will be presented at the conference.

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Ionization by dense electron beams versus ionization by beams of highly charged ions

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Normally the densities of beams of high-energy projectiles (electrons, ions) are relatively low such that in collisions the beam acts as a set of individual particles whose contributions to target cross sections add incoherently. However, highly relativistic electron beams of unprecedented density and with up to ≈ 10 GeV electron energy (the corresponding Lorentz factor up to $\approx 2 \times 10^4$) are nowadays generated by laser or plasma wakefield accelerators (see e.g. [1]). In collisions of such beams many beam electrons can simultaneously interact with a target, representing a qualitatively new physical situation. It was recently predicted [2] that a very efficient ionization mechanism arises in collisions with dense and compact beams of extreme relativistic electrons. In the present work we compare different aspects of ionization in collisions with such electron beams with the ionization by equivelocity beams of highly charged ions, assuming that the total number of projectiles is the same in both beams.

Figure 1 shows the total cross sections for the single ionization of helium atoms by beams of electrons and ions. The total number of projectiles in each beam is $N_t = 10^7$. For the electron beam we assume the beam duration of $T = 100$ as (the beam length $l_0 = 0.03 \mu\text{m}$) and the beam radius $a_0 = 20 \mu\text{m}$. The ionic beam has a "normal" (= relatively low) density and its length and radius do not affect the total ionization. The cross sections are given **per beam** as a function of the impact energy.

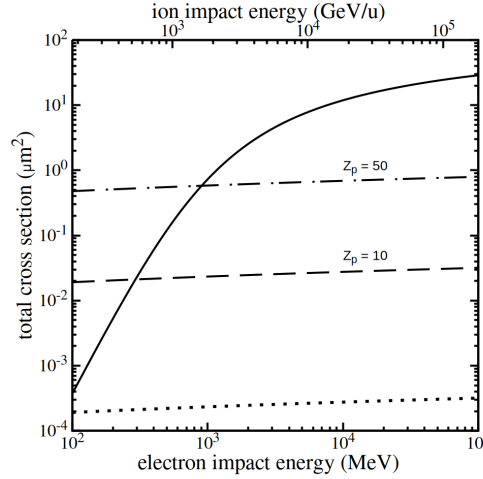


Figure 1. Single ionization of He ($1s^2$) atoms by the impact of electrons and ions. Solid and dotted curves: ionization by coherent and incoherent, respectively, action of 10^7 electrons. Dashed and dash-dotted curves: (incoherent) ionization by 10^7 ions with the charge $Z_p = 10$ and $Z_p = 50$, respectively.

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Mass and decay lifetime measurements of highly-charged Ions at the HIAF-SRing facility

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The HIAF-SRing at the High Intensity heavy-ion Accelerator Facility (HIAF) in Huizhou is a dedicated spectrometer ring designed for high-precision measurements of highly-charged ions [1, 2]. Following the facility's first beam extraction in October 2025, the SRing—equipped with Schottky detectors and an electron cooler—enables non-destructive, long-term measurements of ion revolution frequencies and radioactive decay. In 2026, initial online beam tests were conducted using ²⁰⁹Bi and ⁸⁶Kr beams. Building on the proven mass spectrometry techniques from the existing HIRFL-CSR facility [3, 4], the HIAF-SRing will benefit from beam intensities three orders of magnitude higher, allowing for the measurement of unknown masses and exotic decay modes of heavy neutron-rich nuclei. This report will present the first decay and mass results from the SRing, alongside performance evaluations of the electron cooling system.

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POSTERS A

Numerical investigations of the afterglow effect in Electron Cyclotron Resonance Ion Sources

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Electron Cyclotron Resonance Ion Sources can be tuned such that after terminating the microwave heating of the source plasma, large transient pulses are generated in the extracted ion currents. This so-called afterglow effect is usually explained as a sequence of abrupt losses of cold electrons out of the plasma followed by the ion expulsion toward the extraction by the plasma potential variations. We apply our NAM-ECRIS group of codes to study the ECRIS plasma dynamics in the afterglow transient stage. The group consists of the separate ion and electron particle-in-cell modules that iteratively follow the dynamics of the corresponding plasma components, while the microwave field distribution in the source is calculated by the RF-module of COMSOL Multiphysics solver.

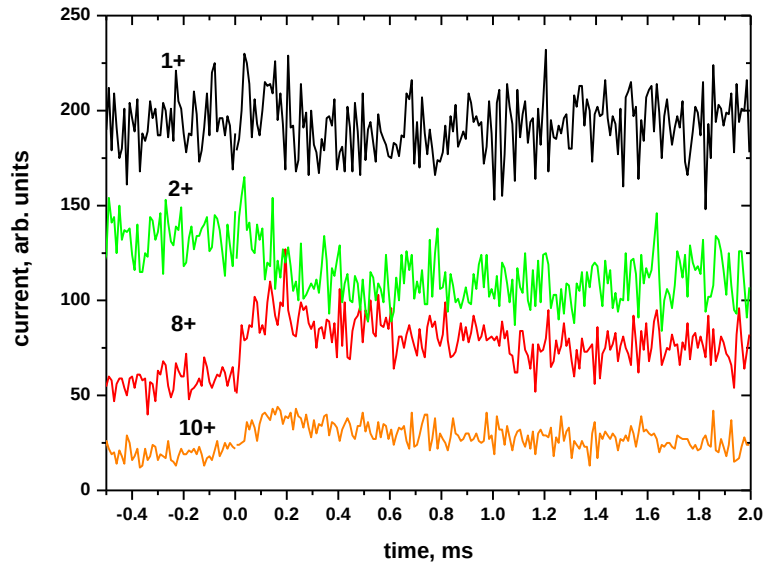


Figure 1. Calculated afterglow peaks in the extracted currents of argon ions.

Afterglow peak generation is reproduced in our calculations, with the proper pulse shapes and ratios between the peak and the preceding quasi-continuous levels of the extracted argon ion currents. The sequence that defines the afterglow parameters is a rather complicated interplay of different processes. First, losses of the energetic electrons out of the plasma are immediately reduced in the afterglow, being mostly defined by the RF-induced diffusion of electrons in the velocity space. The reduced flux of electrons to the source walls causes a drop in the flux of the secondary electrons into the plasma and in a content of electrons with intermediate energies in the range from 250 eV to 5 keV. The plasma potential builds up to balance the electron density variations and the cold electrons are accumulated in the plasma preferentially on the source axis, being electrostatically trapped by the plasma potential and the biased electrode voltage. The result is the increased plasma density on the source axis and subsequent increase in the extracted ion currents, followed by their relatively slow decay.

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State-resolved charge exchange in slow C^{2+} – He collisions

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In slow ion–atom collisions, one or more electrons can be captured from a neutral target into the ground or excited states of the projectile. The study of these charge exchange processes provides valuable insight into atomic structure, electron–electron correlations, and the dynamics of few-body interactions. Moreover, charge-exchange collisions play a crucial role in a wide range of fields, including astrophysics and fusion plasma physics.

Here, we report a kinematically complete study of state-resolved *single electron capture* (SEC) processes with C^{2+} projectile ions, and neutral He target using Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) technique. A projectile beam of 12 keV C^{2+} ions (in both ground state and an unknown fraction in metastable 1st excited state) extracted from an ECR ion source was collided perpendicularly with a supersonically cooled He gas jet. The recoil ions (He^+) and charge-changed projectiles (C^+) were detected in coincidence using a combination of the COLTRIMS setup and a projectile charge-state analyzer located downstream [1].

Q-value spectrum for the 1 keV/u $C^{2+} + He$ SEC processes is shown in Figure 1. SEC by metastable $C^{2+}(1s^2 2s 2p, ^3P^o)$ state predominantly occurs via an exothermic channel with center of the Q-value at 6.29 eV. Here, the e^- is captured into the half-filled 2s orbital (inner subshell), leaving the 2p orbital (outer subshell) unaltered, resulting in formation of the ground state of $C^+(1s^2 2s^2 2p, ^2P^o)$. Corresponding differential scattering angle distribution along with theoretical calculation will be presented in the poster.

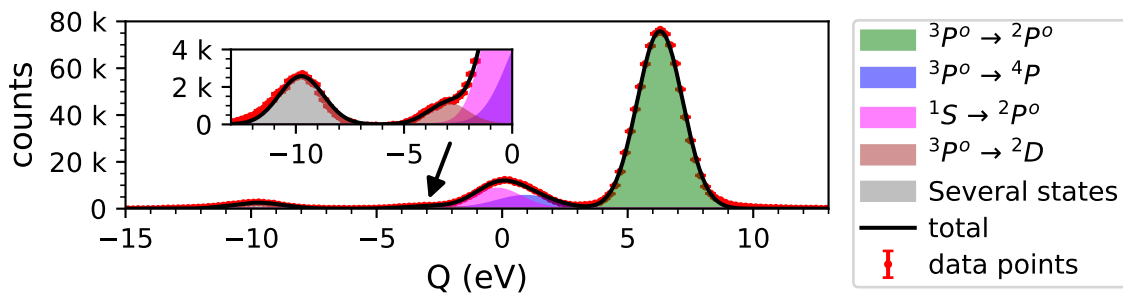


Figure 1. Q-value spectrum for 1 keV/u $C^{2+} + He$ SEC processes

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Electron capture induced dissociation of trifluoromethane trication in slow ion collisions

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The fragmentation of molecules induced by charge-transfer processes in collisions with highly charged ions serve as an effective probe of the coupling between electronic excitation and nuclear motion in highly excited molecular systems [1]. In the regime of slow ion-molecule collisions, electron capture constitutes the dominant interaction mechanism. It occurs primarily within the Franck-Condon region such that the nuclear configuration of the target molecule remains effectively frozen during the ionization process due to the extremely short interaction time, typically of the order of a few hundred attoseconds. The ensuing redistribution of the charge generates strong intramolecular Coulomb repulsion, driving the system to dissociate along pathways governed by the molecular structure and bonding. These dynamics can be investigated using Coulomb-explosion imaging [2], which enables the reconstruction of fragment momenta and the study of correlations involving kinetic energy release, angular emission patterns, and breakup geometry. Cold-target recoil-ion momentum spectroscopy (COLTRIMS) is one of the established experimental techniques for implementing this approach, and has been extensively employed in studies of ion-induced molecular fragmentation.

In the present work, COLTRIMS [3] is employed to investigate the dissociation dynamics of CHF_3^{3+} produced via electron capture in slow collisions with Ar^{4+} ions [4]. CHF_3 is a fluorinated methane derivative with a near-tetrahedral geometry and a pronounced asymmetry between the C-H and C-F bonds, making it a suitable system for investigating charge-driven fragmentation in polyatomic molecules. Analysis of time-of-flight coincidence maps reveals several complete and incomplete fragmentation pathways. In particular, the three-body dissociation channels exhibit clear signatures of sequential fragmentation dynamics, with the complete three-body channel proceeding predominantly via a double-sequential mechanism. In addition, some of the incomplete four-body channels also display characteristics of sequential dissociation. The relative electron-capture contributions for all observed channels are further examined and interpreted within the framework of the classical over-the-barrier model.

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Two-, Three-, and Four-Body Dissociation Dynamics of CHF_3 Cations

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Trifluoromethane (CHF_3) is widely employed in plasma etching, yet the correlated breakup dynamics of its multiply charged cations remain scarcely studied. Here we report a complete-momentum imaging study of strong-field ionized CHF_3 , aimed at separating prompt bond cleavage, rearrangement during dissociation, and sequential multibody fragmentation. A cold molecular beam was irradiated by 35 fs, 800 nm strong-field laser pulses at an intensity of approximately 10^{15} W/cm², and the fragment ion were detected in coincidence. Two-, three- and four- channels were resolved where C-H and C-F bond cleavage dominating the two-body fragmentations. For three-body channels, both concerted and sequential fragmentation mechanisms were identified. The heavy-fragment channels $\text{F}^+ + \text{F}^+ + \text{CHF}^+$ and $\text{F}^+ + \text{HF}^+ + \text{CF}^+$ form compact image in Dalitz plots and localized Newton islands, characteristic of concerted Coulomb explosion. In contrast, channels involving H^+ formation exhibits stripe-like structures in Dalitz plot and arc-like features in Newton diagram indicating sequential proton-first breakup through rotating intermediates [1,2]. One four-body channel, $\text{H}^+ + \text{F}^+ + \text{F}^+ + \text{CF}^+$, was observed, and the corresponding Newton diagram were constructed to present the three-dimensional momentum correlations [3]. Theoretically, a semi-classical Coulomb explosion model was adopted and the predicted Newton diagram describes the experiment well.

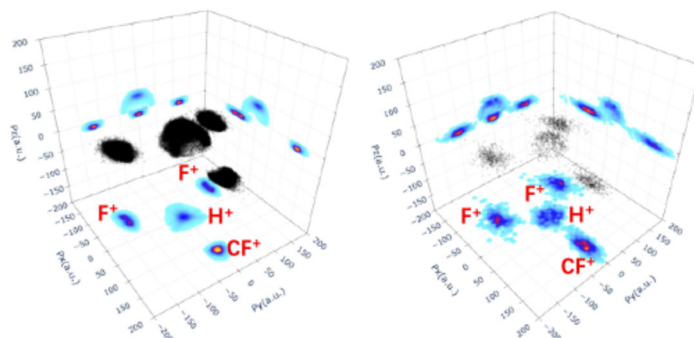


Fig 1. Simulated (left panel) and experimental (right panel) Newton diagrams of the four-body fragmentation channel.

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Single and double electron capture in low energy Au^{q+} collisions with H_2

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For EUV sources operating at photon wavelengths below 13.5nm, heavy atoms with open 4d or 4f shells are considered as atomic sources. Possible candidates are shown in the figure. Moving towards high-Z ions is required to generate photons of shorter wavelengths. This implies higher charge states of the emitting ions, and an increase in potential energy, as compared to the Sn ion plasma used for 13.5-nm EUV sources. We focus on the interaction of heavy ions with molecules, in a regime where potential energy dominates over kinetic energy. Our research provides the first experimental data on single and double electron capture in low-energy Au^{q+} collisions with H_2 molecules. We found that the double electron capture cross sections for Au^{3+} are unexpectedly large and show a distinct energy dependence. In previous research on $\text{Sn}^{3+} - \text{H}_2$ collisions we explained this behaviour with the "Hop-Skip-Jump" mechanism [1]. By measuring the kinetic energy release of H^+ collision fragments, we seek to verify the universal nature of this mechanism in gold. Additionally, gold's high mass provides a unique opportunity to study extremely slow collisions, allowing us to explore the transition into the Langevin regime.

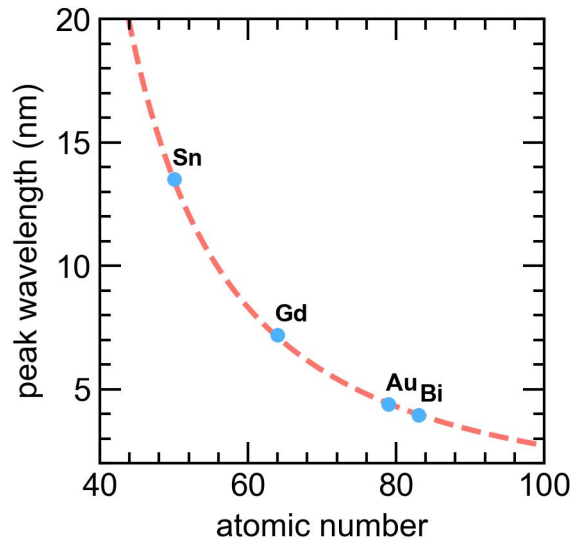


Figure 1. Atomic number dependence of peak emission wavelengths of $4d^{10}4f^n - 4d^94f^{n+1}$ and $4p^64d^n - 4p^54d^{n+1} + 4d^{n-1}4f$ transition arrays for high Z elements. Red dashed line is an approximated curve for ps-LPP emission based on a power law scaling [2].

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Nuclear charge radii determination for magic nuclei via muonic atoms

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Comprehensive evaluations of the root-mean-square nuclear charge radii are presented for ^{90}Zr , ^{120}Sn , and ^{208}Pb , using the historic muonic spectroscopy data. By integrating rigorous theoretical quantum electrodynamics calculations, state-of-the-art numerical methods, and a systematic reanalysis of the uncertainties, we significantly reduced the long-standing discrepancy between theoretical and experimental results. A 2-parameter Fermi nuclear charge distribution is assumed as the theoretical model, and the two model parameters are fitted with respect to the experimental data. In the analysis, some theoretical energy corrections are reevaluated and significantly improved, including nuclear polarization, which plays a key role for heavy nuclei, e.g., ^{208}Pb , and relativistic recoil, showing more importance for lighter nuclei. This work sets a benchmark for nuclear radius determination and paves a path for further model-dependent analysis.

Double to tenfold M-shell photoionization of singly charged lanthanum ions

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A “kilonova” is the optical “afterglow” of a neutron-star merger. A kilonova is powered by the radioactive decay of the neutron-rich material ejected in the merger. The kilonova light-curve potentially reveals the abundances of the heavy chemical elements that are produced in the preceding violent neutron-star merger event [1]. In order to be able to reliably infer elemental abundances from the astronomical observations, absolute cross sections are required for the basic atomic processes that occur in the afterglow. Generally, these cannot be easily calculated (if at all) to a sufficient precision for the heavy many-electron ions of interest. We used the photon-ion merged-beams setup PIPE, a permanently installed end-station of the PETRA III photon beamline P04 for measuring cross sections for photoabsorption (Fig. 1) and for multiple photoionization of La^+ ions [2], where La^{q+} product ions have been detected with ion charge states $3 \leq q \leq 11$. With these experimental data we have benchmarked new large-scale quantum calculations using the JAC atomic code [3]. Detailed comparisons between the experimental and theoretical results will be presented at the conference.

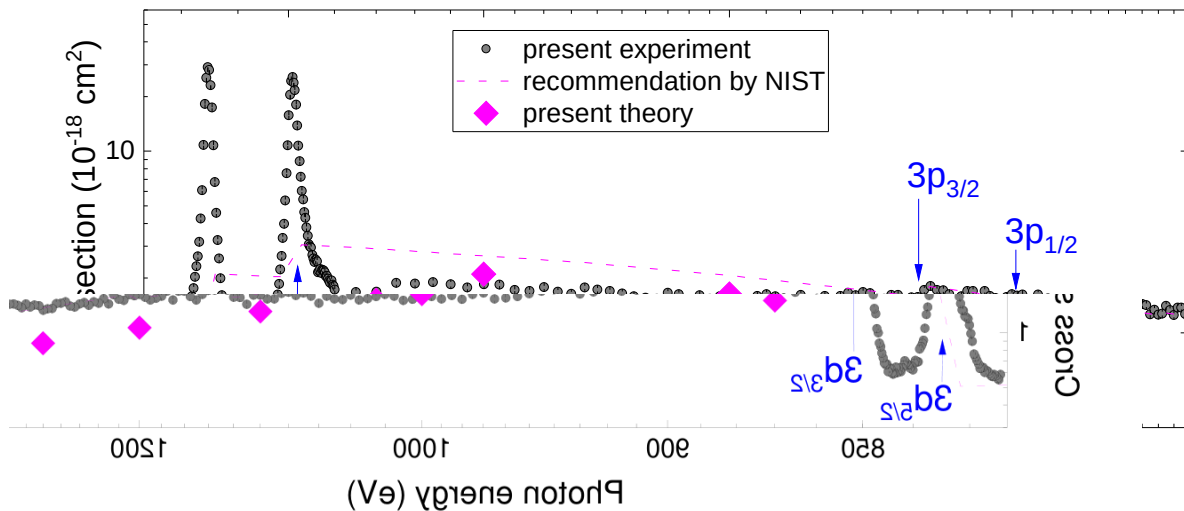


Figure 1: Experimental and theoretical cross section for photoabsorption of La^+ .

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State-selective single- and double-electron capture in slow N^{4+} -He collisions

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State-selective single- and double-electron capture in collisions of N^{4+} ions with He atoms have been studied at projectile energies in the range of 20 to 80 keV[1]. The state-selective single- and double-electron capture cross sections and projectile scattering angle distributions were obtained using a cold-target recoil-ion momentum spectroscopy[2].

For single-electron capture, the experimentally obtained state-selective cross sections show the obvious discrepancy with the calculated results by Molecular Orbital Close Coupling methods[3] and are in good agreement at a projectile energy of 20 keV with other experiment. The angular distributions compare with calculations from Multi-channel Landau-Zener model[4].

For double-electron capture, electrons captured into $2l2l'$ states of N^{4+} projectile is dominant. The angular distributions are explained by a two-step model combining the classical deflection function.

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New identification of forbidden M1 lines of Ga-like heavy ions using laboratory plasmas

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The intensities of forbidden lines due to magnetic dipole (M1) transitions of highly charged heavy ions can sometimes be comparable to those of permitted lines due to electric dipole (E1) transitions. These M1 lines are useful for plasma diagnostics as they typically appear as isolated lines in the longer wavelength range. In gallium-like (Ga-like) ions with the ground configuration $[\text{Ar}]3d^{10}4s^24p$, the M1 line resulting from the transition between the fine structure of the ground state doublet $(4p_-)_{1/2}-(4p_+)_{3/2}$ is expected to stand out prominently. For example, the M1 line of Ga-like tungsten ($Z=74$) ion has been readily identified as an isolated line in the extreme ultraviolet region at 12.63 nm in magnetically confined plasmas for fusion research [1, 2]. In contrast, no experimental identifications of the M1 lines of Ga-like ions had been reported for the lanthanide elements ($Z=57-71$), except for ytterbium ($Z=70$) [3].

At the National Institute for Fusion Science, high-temperature plasmas produced in the Large Helical Device (LHD) had been utilized for spectroscopic studies on various heavy elements of interest in plasma applications and basic atomic physics. As a result of a comprehensive Z -dependence analysis and a comparison with theoretical calculations using the GRASP code [4], the M1 lines of Ga-like ions of a large number of heavy elements have been experimentally assigned for the first time in the LHD. Although the assignments within the Z range of $Z=63-71$ have been previously reported [5], the present study extends the Z range to $Z=57-77$. Furthermore, new experiments carried out in the Tokyo electron beam ion trap at the University of Electro-Communications have confirmed that the assigned lines for $Z=63$ and 65 in the LHD are certainly emitted from Ga-like ions.

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Exotic-Boson-Mediated Interelectronic Interaction: Spectral Sensitivity of Few-Electron Atomic Systems

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In many scenarios of physics beyond the Standard Model, exotic light bosons arise naturally and are capable of inducing additional interactions between particles [1]. The substantial progress achieved in recent years in both the theory and experiment of precision atomic physics makes atomic spectroscopy a sensitive tool for testing the Standard Model and searching for effects of New Physics. Of particular interest in this context are highly charged ions, in which the contribution of the corresponding effects can be significantly enhanced.

Three problems are considered in the report. The first part is devoted to hydrogen-like ions and the isotope shifts of the bound-electron g factor; it is shown [2] that the sensitivity of such systems is substantially limited by nuclear effects, which determine the theoretical uncertainty. The second part deals with lithium-like ions, for which a relativistic formalism of boson-mediated interelectronic interaction has been developed and new constraints on the parameters of axion-like particles have been obtained [3]. The helium atom is also considered, in which the observed discrepancy between the theoretical and experimental values of the transition energies admits an interpretation within the framework of new physics associated with scalar interelectronic interaction [4].

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Study on Plasma Electron Temperature Diagnostic Technique Using Highly Charged Tungsten Ion Spectra for EAST Tokamak

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Electron temperature (T_e) is a critical parameter for evaluating plasma performance and sustaining the high-confinement mode (H-mode) in the fusion plasmas. Tungsten (W, $Z=74$) material is the top candidate for plasma-facing components (PFC) in next-generation fusion devices such as BEST and ITER due to its excellent properties. During the operation of the EAST equipped with full tungsten divertor, the W-UTA spectrum (W^{24+} – W^{45+} ions) in the 45–70 Å band measured by EUV spectroscopy [1-3] is commonly observed once tungsten impurity enters the plasma. Additionally, relevant studies have demonstrated that the relative abundances and spatial distribution of these charge states are determined by the electron temperature profile [4, 5]. Nevertheless, the correlation between tungsten spectrum and electron temperature is difficult to analyze by traditional physical models. To address the challenge, a random forest (RF) model was developed for predicting central electron temperature. This model was trained on a dataset derived from W-UTA spectrum, which was screened using physics-based analysis and feature importance analysis. Figure 1 shows the time evolution of the electron temperature predicted by the model and that measured by the electron cyclotron emission (ECE) diagnostic system during plasma discharge. Moreover, the absolute prediction error of the model is below 0.1 keV in 1.0-6.0 keV. Using this model, an central electron temperature profile diagnostic technique based on tungsten spectroscopy has been successfully developed. This technique not only enhances the robustness of electron temperature diagnostics for fusion devices, but also provides new insights for electron temperature diagnosis in future fusion devices such as ITER.

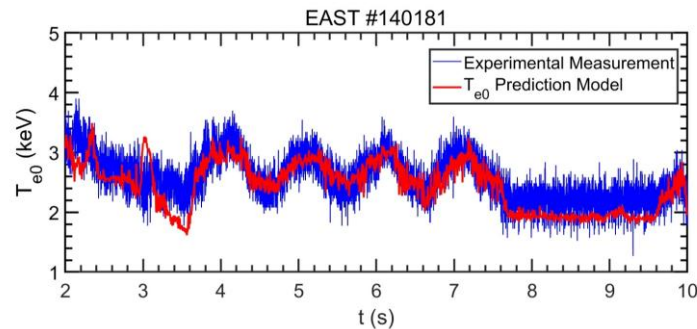


Figure 1. Time evolution of the central electron temperature, T_{e0} , predicted by the model (red solid line) and measured by the ECE diagnostic system (blue solid line)

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Line Difference Search: Line-Difference Identification and Atomic-Data Attribution

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The field of X-ray astronomy has entered a new era of high-resolution spectroscopy enabled by next-generation X-ray spectrometers. Accurate atomic data are critical for interpreting X-ray spectra from hot astrophysical plasmas, yet significant discrepancies remain among widely used atomic databases. SPEX and AtomDB/APEC are broadly consistent for hot X-ray plasmas, while CHIANTI is more tailored to solar/stellar optically thin plasmas [1, 2]. Their differing atomic data can still cause systematic shifts in inferred abundances and line properties.

The Line Difference Search (LDS) approach is developed as a new framework for identifying and attributing atomic-data discrepancies in spectral line formation [3]. LDS employs an abstraction-layer architecture for flexible atomic-data switching and replacement, enabling comprehensive evaluations across broad temperature and density ranges through a dynamic iterative search and discrepancy-driven optimization framework.

In this work, the LDS approach is applied to compare transition probabilities and effective collision strengths for hydrogen-like and helium-like ions with nuclear charge $Z = 6-30$, using AtomDB-3.1.3 and CHIANTI-11.0.2 as benchmarks. The resulting relative differences in line emissivities are reduced to approximately 20%, and the dominant sources of the discrepancies are systematically identified and analyzed.

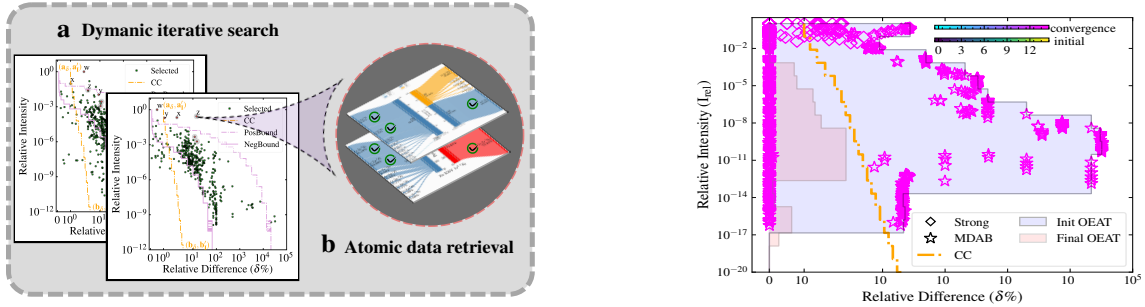


Figure 1. Left: LDS dynamic iterative search and atomic-data retrieval scheme. Right: evolution of discrepancy features for Fe XXV. The step-like curve (CC) marks the convergence boundary. The initial outermost edge (Init OEAT), traced by the maximum boundary discrepancies (MDAB; color indicates temperature), contracts into the shaded final outermost edge (Final OEAT). Diamonds denote the strong lines (w, x, y, and z).

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High-Resolution Measurement of Lyman-series X-Ray following Charge Exchange Between O^{8+} with He

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Charge exchange (CX) between highly charged ions (HCIs) and neutral particles is a fundamental atomic process dominating the low-energy collision regime. The characteristic X-ray spectra emitted during this process provide a powerful diagnostic tool for solar wind charge exchange (SWCX) processes. To ensure the reliability of these diagnostics, high-precision laboratory data of key collision systems are essential. In this work, we present high-resolution measurements of X-ray spectra resulting from CX collisions of O^{8+} with He over the collision energy range of 0.5 – 12.5 keV u^{-1} .

The experiments were performed utilizing ion beams extracted from the HECRAL facility [1]. X-ray spectra were measured using a Transition-Edge Sensor (TES) microcalorimeter [2]. Figure 1 shows a typical X-ray spectrum obtained at 10 keV u^{-1} . Distinctly, the Lyman- α , - β , - γ , and - δ lines of the singly-excited O^{7+} ions are well resolved, revealing electron capture up to $n = 5$. The transition contributions, extracted via an exponentially modified Gaussian (EMG) fit of the spectrum, will enable reliable subsequent line-ratio analysis. These results are expected to serve as crucial benchmark data for atomic databases and SWCX spectral modeling.

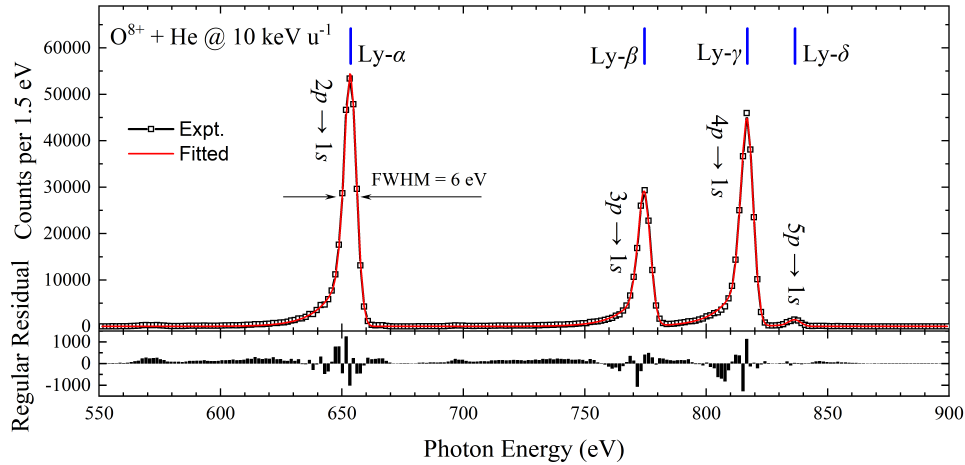


Figure 1: X-ray spectrum from CX in $O^{8+} + He$ collisions at 10 keV u^{-1} .

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Exploring a Data-Driven Inverse Optimization Approach for Atomic Modelling of Open-Shell Highly Charged Heavy Ions

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Highly charged ions of heavy elements are important atomic systems for fusion-plasma impurity diagnostics, extreme-ultraviolet and soft-X-ray light-source development, and precision spectroscopy. However, the complex open-shell structures of heavy ions make accurate atomic modelling difficult.

Figure 1 compares water-window soft-X-ray spectra of highly charged bismuth (Bi, $Z=83$)[1] and lead (Pb, $Z=82$)[2] ions measured with a compact electron beam ion trap (EBIT)[3] with collisional radiative model (CRM) spectra calculated using HULLAC[4] atomic data. These studies showed that the calculated spectra can reproduce the main experimental features but also revealed that the results strongly depend on the selected configuration set and atomic potential parameters.

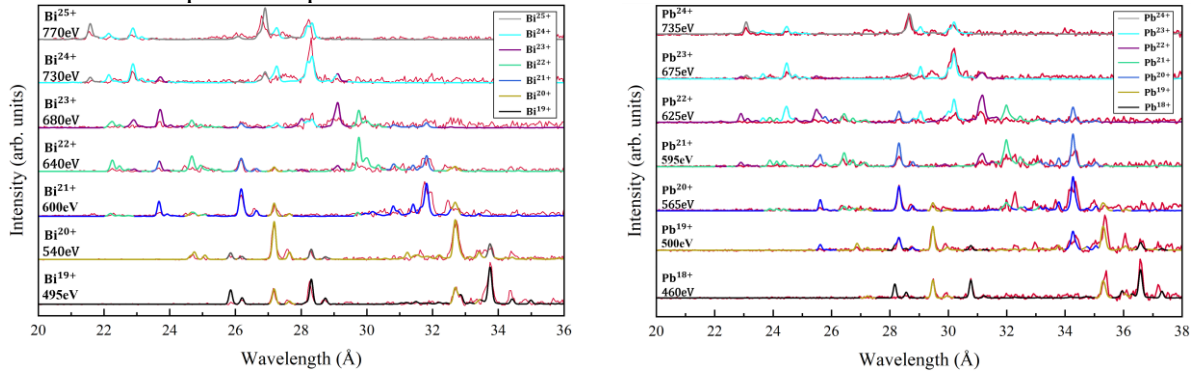


Figure 1. Water-window soft X-ray emission spectra of highly charged Bi and Pb ions.

Therefore, based on our previous studies, we investigate whether atomic-model construction can be guided by experimental spectra rather than relying solely on researcher experience and repeated trial-and-error calculations. To address this challenge, we propose to reformulate the construction of atomic models as an inverse optimization problem. In this framework, ODAT-SE[5], an open-source platform for data-analysis-driven black-box optimization, is coupled with FAC[6] or HULLAC-based CRM calculations to systematically search for suitable configuration sets and potential optimization parameters. Candidate models will be evaluated by comparing their predicted spectra with the overall spectral characteristics observed in EBIT measurements. This data-driven approach aims to reduce the dependence on empirical choices and provide a more systematic framework for constructing atomic models of highly charged heavy ions.

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State-resolved single- and double-electron capture in slow He^{2+} -Ne collisions

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Using cold-target recoil-ion momentum spectroscopy, we have experimentally investigated single- and double-electron capture processes in He^{2+} -Ne collisions at energies ranging from 1 to 30 keV/u. Relative state-resolved cross sections and angular differential cross sections have been obtained for both processes.

For the single-electron capture channel, capture is dominated by the Ne 2s orbital at low energies, consistent with earlier work [1, 2], while the 2p contribution increases with collision energy. The measured reaction windows are in good agreement with predictions from the molecular Coulomb barrier model (MCBM) [3]. The dominance of this inner-shell capture at low energies is an unusual phenomenon, and it appears to be an exception rather than a general rule in ion-atom collision systems.

For the double-electron capture channel, capture of two 2p electrons from Ne dominates at low energies, whereas contributions from 2s-orbital capture grow in importance with increasing collision energy. Simplified non-adiabatic potential energy curves [4], which include both Coulomb and polarization interactions, qualitatively reproduce the observed quantum-state populations following single- and double-electron capture.

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State-selective Single-electron Capture in Collisions of Ne^{6+} on He

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State-selective single electron capture in slow collisions of multiply charged ions with atoms and molecules plays an important role in various environments. In this work, we measured the full differential cross sections for single electron capture in collisions of Ne^{6+} ions with He atoms, at impact energies ranging from 60 keV to 1200 keV. The experiments were carried out using the COLTRIMS setup at IMP [1,2].

For single electron capture, the dominant reaction channel at low energies involves electron capture into the $3l$ states. As the projectile energy increases, the contribution from capture into nl ($n \geq 4$) states grows monotonically and becomes dominant at 1200 keV. The relative cross sections as a function of projectile energy were obtained. Figure 1 shows the state-resolved populations for single electron capture into $\text{Ne}^{5+}(nl)$ states from He atoms at 60 keV. In this meeting, we will present our most recent experimental results.

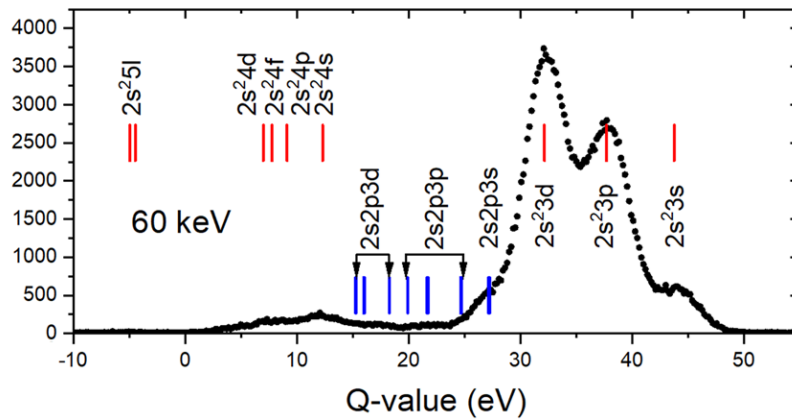


Fig. 1 The state-population for single electron capture channel $\text{Ne}^{6+}(1s) + \text{He}(1s^2) \rightarrow \text{Ne}^{5+}(nl) + \text{He}^+(1s)$ at impact energy of 60 keV.

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Angular momentum degrees of freedom in atomic scattering

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In experiments on atomic scattering at storage rings, the set of input experimental parameters is limited. Angular momentum can provide us with additional degrees of freedom. For example, the use of vortex beams of highly-charged ions, which carry a non-zero projection of the orbital angular momentum (OAM) onto their propagation direction, gives us access to new selection rules and modified angular distributions and polarization of reaction products. Spin-polarized heavy ion beams are also of great importance for ongoing research on spin, relativistic and quantum electrodynamics (QED) effects in the high-Z domain, as well as for testing the Standard Model, and for the search for new physics beyond it [1,2]. The current challenge in storage ring physics is the production and diagnostics of spin-polarized as well as vortex ion beams. The aim of the present talk is to review recent advances in these two important areas. In particular, we will discuss and assess various theoretical proposals in the context of (planned) studies at the GSI and FAIR facilities in Darmstadt.

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Electron transfer and ionisation in Ar^{3+} ion collisions with atomic hydrogen

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Partially stripped Ar^{3+} ions are expected to be present in the edge and divertor regions of fusion plasmas as a result of impurity seeding in tokamaks. Studying collisions of these impurity ions with the neutral hydrogen beam injected into the reactor is therefore important for modelling plasma radiation and for plasma diagnostics using the CXRS technique. Despite its importance, this 16-electron system has never been considered before due to the significant challenges it poses for theoretical modelling. We employ the wave-packet convergent close-coupling (WP-CCC) method [1] and two independent implementations of the classical-trajectory Monte Carlo approach (Z-CTMC [2] and H-CTMC [3]) to study collisions between dressed Ar^{3+} ions and atomic hydrogen. We present a comparative analysis of state-selective charge transfer and ionisation at collision energies from 1 keV/u to 1 MeV/u, relevant to the ITER project [4]. The results show a good level of agreement between the methods, indicating that they are suitable for applications in fusion-plasma modelling and diagnostics. As an example, in Fig. 1 we show the total charge-transfer cross sections obtained using the three methods.

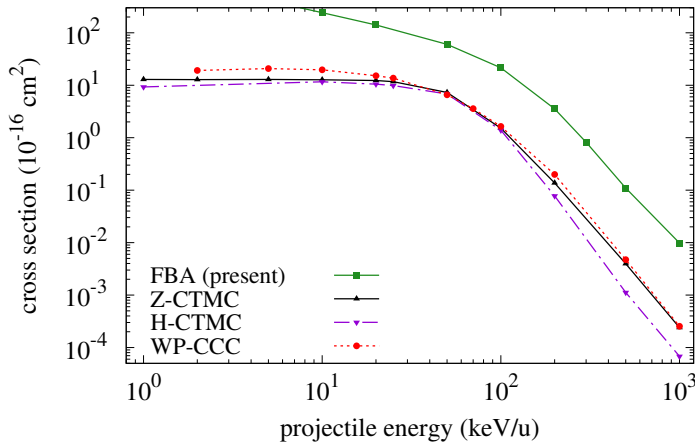


Figure 1: The total cross section for electron capture in $\text{Ar}^{3+} + \text{H}(1s)$ collisions as a function of the projectile energy. The results obtained using the first-order Born approximation (FBA), Z-CTMC, H-CTMC and WP-CCC methods are shown. The FBA results have been obtained using the WP-CCC code by decoupling the reaction channels.

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Precision X-ray absorption spectroscopy of metallic iron using Li-like fluorine ions for photon energy calibration

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Iron (Fe) is primarily injected as a gas into the interstellar medium (ISM) by supernovae, where it swiftly condenses into unknown solid compounds. Bright galactic X-ray binaries can be used as backlighters to study absorption by the intervening ISM, where Fe-bearing dust grains imprint Fe *L*-shell photoabsorption features at ~ 700 eV. Recent observational studies have shown that the published Fe *L*-shell photoabsorption cross section data for Fe-bearing compounds need to be blue shifted by $\sim 1 - 2$ eV to match the observations [1], possibly due to previously unrecognized systematic uncertainty in the laboratory energy-scale calibrations. But this energy difference is also similar to the spectral shift between metallic Fe, Fe oxides, and Fe silicates.

We have performed an experiment focusing on precision X-ray absorption spectroscopy of metallic Fe at the synchrotron light source PETRA III. We measured absolute cross sections for Fe *L*-shell photoabsorption of Au-coated, thin metallic Fe films. The samples were mounted in the Argus dynamic X-ray photoelectron spectroscopy setup, and the X-ray transmission vs. photon energy was measured using an intensity-calibrated photodiode. Au *4f* photoelectron spectroscopy was used to monitor the photon energy. The photon energy was calibrated via resonant photoionization of F^{6+} ions measured in the simultaneously operated Photon-Ion merged-beams end station at PETRA III (PIPE). The transition energies for the $1s^2 2s \rightarrow 1s 2s 2p$ excitations in F^{6+} are known theoretically [2] and experimentally [3] to a precision of ~ 3 meV. Taking into account these and other uncertainties, we have achieved an overall precision of 8 meV for the *L*-shell absorption feature of metallic Fe. In combination with our previous data for gas-phase Fe^+ [4], we have incorporated our results into astrophysical models and compared them to astronomical observations with the Chandra X-ray observatory. Our experimental results enable a deeper understanding for the composition of Fe-bearing interstellar dust.

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Orientation-Dependent Quantum Interference and Molecular-Frame Electron Dynamics in $\text{H}_2^+ + \text{He}$ Collisions

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Quantum interference in ion–molecule collisions sensitively probes few-body dynamics. We investigate target ionization with projectile excitation-dissociation in 50 keV/u $\text{H}_2^+ + \text{He}$ collisions using a Reaction Microscope. Reconstructing molecular geometries reveals strong orientation-dependent interference in emitted-electron energy spectra. Spectral ratios exhibit clear oscillations for near-parallel alignments ($\theta_M \sim 15^\circ\text{--}35^\circ$) that vanish for perpendicular orientations ($\theta_M \sim 80^\circ\text{--}90^\circ$). These patterns agree with theory at low electron energies, but deviations at higher energies suggest higher-order collision mechanisms. Furthermore, molecular-frame angular distributions for Projectile Excitation with Simultaneous Target Ionization (PE-TI) and Transfer-Excitation Autoionization (TEA) channels show suppressed electron emission along the internuclear axis. In the PE-TI channel, this suppression weakens at higher energies due to constructive interference and reduced Coulomb distortion. These highly differential results provide stringent benchmarks for modeling correlated collisions.

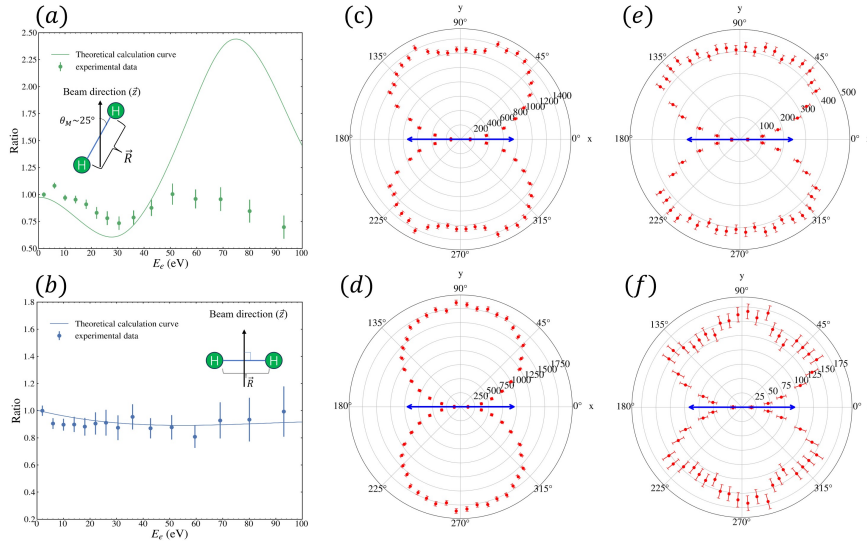


Figure 1: Ratio of electron emission cross sections ($\text{Ratio} = \frac{\sigma_{2.2 < R < 2.6 \text{ a.u.}}^{\text{norm}}}{\sigma_{R < 1.8 \text{ a.u.}}^{\text{norm}}}$) and molecular-frame angular distributions of emitted electrons in the TEA (c) and PE-TI (d–f) channels. (a) Nearly parallel alignment, (b) Perpendicular alignment. (d)–(f) Angular distributions of emitted electrons in the PE-TI channel for electron energies of 2–5 eV, 50–70 eV, and 70–100 eV, respectively.

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A21

Experimental investigation of x-ray emission by impact of 15-30 keV electrons in high Z thick targets.

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Abstract:

The collision of electrons with solid targets leads to different processes in atom and molecule, i.e., inner shell ionization, bremsstrahlung (continuous) radiation, backscattering of electrons, characteristic K- and L shells x-ray production, and secondary electron emissions etc. [1,2]. Electron induced x ray emission estimate the internal structure of the atoms or molecules which might be applied in different fields of science and technology.

In the present study, we have measured the x-ray production cross-section of L-subshells of Pb (Z=82) by 15-30 keV electron impact and bremsstrahlung yield of Pt (Z=78) by 10-25 keV using thick-target method [3]. Interaction of a mono-energetic electron beam with solid target (thickness=0.1 mm) generates both continuous and characteristic x-rays. These x-rays are detected using a Si-PIN diode x-ray detector [4]. MCA software is used for data acquisition and analysis of x-rays. Our experimental results have been compared with PENELOPE simulations and with works of other researchers. To the best of our knowledge, the total cross-section of L_I of Pb element by electron impact has been reported for the first time. Our results show good agreement with the simulation calculations.

Keywords: Thick target method, electron impact, PENELOPE simulation.

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Electron correlation in highly charged ion-atom collisions

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Charge exchange (electron capture) in collisions between highly charged ions and neutral targets has been the subject of extensive investigation for several decades. The interpretation and description of the underlying mechanisms at a fundamental level is highly challenging, particularly when several electrons actively participate in the collision process and electron–electron interactions play a significant role in the dynamics. Such arises in multiple-electron processes and, even in single-electron capture, when multi-open-shell atomic systems are involved in the initial and/or final channels. The situation becomes even more intricate in the intermediate-energy regime, where the projectile velocity is comparable to that of the active electrons. This presentation will provide an overview of these challenges and discuss recent advances in both experimental and theoretical studies.

Three-body fragmentation dynamics of triply charged 1,3-butadiene induced by 1 MeV/u C^{4+} ions: Channels involving H_2^+ formation

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Hydrocarbon molecules are ubiquitous in the universe and play important roles in industry. Due to the low mass of hydrogen, hydrogen atoms can rapidly respond to electronic perturbations and migrate along the carbon skeleton. While the fragmentation of hydrocarbons has been widely studied, channels involving H_2^+ formation remain poorly understood. Such channels are associated with ultrafast hydrogen migration and may involve complex dynamical processes. In this work, we experimentally investigate the dissociative ionization of 1,3-butadiene (C_4H_6) induced by 1 MeV/u C^{4+} ions using a COLTRIMS setup [1, 2, 3, 4], with a particular focus on three-body fragmentation channels involving H_2^+ formation. As shown in Fig. 1(a), the channels (I) $H_2^+ + CH_2^+ + C_3H_2^+$ and (II) $H_2^+ + CH_3^+ + C_3H^+$ are directly identified, whereas the channels (III) $H_2^+ + C_2H^+ + C_2H_3^+$ and (IV) $H_2^+ + C_2H_2^+ + C_2H_2^+$ are not well separated. We successfully disentangle the two channels by analyzing the correlation between the kinetic energy release and the dissociation angle, as shown in Fig. 1(b)-1(e). Sequential dissociation pathways with H_2^+ emitted first are identified for all four channels. In addition, the $H_2^+ + CH_2^+ + C_3H_2^+$ channel exhibits another sequential pathway in which CH_2^+ is emitted first, while the $H_2^+ + C_2H^+ + C_2H_3^+$ channel also proceeds via a concerted mechanism. These results provide new insight into the mechanisms and dynamics of H_2^+ formation in the three-body fragmentation of hydrocarbon molecules.

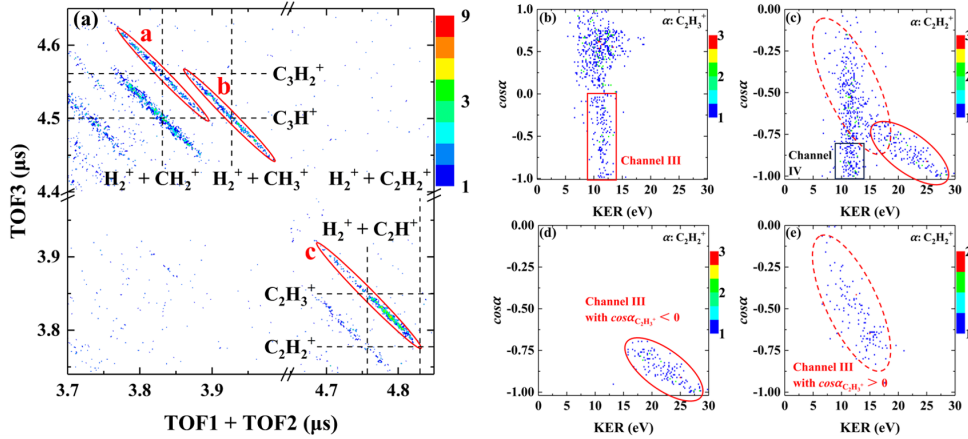


Figure 1: (a) Triplet-ion TOF correlation map of $C_4H_6^{3+}$ following 1 MeV/u C^{4+} impact. (b,c) KER- $\cos\alpha$ correlation maps obtained by assigning island-c events to the (III) $H_2^+ + C_2H^+ + C_2H_3^+$ and (IV) $H_2^+ + C_2H_2^+ + C_2H_2^+$ channels, respectively. (d) KER- $\cos\alpha$ map for events within the red rectangle in (b). (e) Corresponding map for the inferred momentum-inverted events.

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Extreme ultraviolet (EUV) spectrum and radial emissivity profile from W^{41+} to W^{46+} under EAST plasma conditions

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Many fusion devices, such as ITER, EAST, use tungsten (W) as plasma-facing components (PFCs) and operate with full W divertor. However, as a high-Z impurity, W induces plasma disruption when enter core plasma and its concentration reaches 10^{-5} . Consequently, investigation of the W flux distribution is imperative to achieve improved control over W impurity influx.

In this work, the charge state radial distributions of W^{41+} and W^{46+} was investigated by using high-precision atomic rate coefficients, which were calculated by employing Level-to-Level Distorted-Wave method in Flexible Atomic Code (FAC). We compare our results with those from FLYCHK and reported by Syrocki *et al.* for the W7-X stellarator, highlighting the significant influence of rate coefficients, such as electron impact ionization (EII), radiative recombination (RR) and dielectronic recombination (DR), as well as atomic processes, such as electron impact multiple ionization (EIMI) and charge exchange (CX) on the charge state profiles [1, 2, 3]. Studies have found that while EIMI has no effect on steady state W ion charge state distributions (CSDs), its impact on non equilibrium states can be as high as 40%. The effect of CX on highly charged ions can even exceed 100%. Furthermore, under the condition of #150425 EAST discharge, the extreme ultraviolet (EUV) spectra of W^{41+} through W^{46+} are calculated at electron temperature T_e and density n_e corresponding to the maximum W ions abundance. With respect to strong transition spectral lines, the corresponding photon emissivity coefficients (PECs) and the emissivity radius profiles are computed [2].

In addition, the plasma quenching event induces the generation of a substantial population of suprathermal electrons [4]. Accordingly, we systematically investigate the effects of suprathermal electrons on the CSDs, EUV spectral characteristics, PECs, and emissivity profiles of W ions. On the one hand, this investigation emphasizes the critical importance of accurate atomic data and atomic process for W impurity ion distributions. On the other hand, it provides reliable references for W impurity diagnostics and line identification in fusion devices.

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Absolute measurement of state-resolved charge-exchange cross sections for C^{4+} colliding with H_2

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Solar wind interaction with planetary atmosphere and cometary coma is a fundamental process for space weather studies [1]. Observations of extremely ultraviolet and soft X-ray emissions are generally attributed to charge exchange between highly charged ions and neutral atoms. To understand the emission spectra, reliable cross sections are required, particularly those resolved with respect to the principal quantum number n and orbital angular momentum quantum number l of the captured electron [2].

This work aims to measure absolute nl -resolved charge-exchange (CX) cross sections for C^{4+} colliding with H_2 at solar wind velocities, providing experimental benchmarks for theoretical calculations and accurate atomic data to support astrophysical EUV spectral simulations of solar wind CX emission. The experiments were conducted based on the 150 kV highly charged ion platform at Fudan University [3]. The total and state-selective cross sections were measured using beam-gas collisions in conjunction with cold-target recoil-ion momentum spectroscopy.

We present absolute total cross sections for single electron capture (SEC) and double electron capture (DEC), as well as nl -resolved cross sections for SEC in $C^{4+}+H_2$. The collision energy ranges from 2.3 to 33.3 keV/u, corresponding to velocities of 671- 2535 km/s. The cross sections are determined with uncertainties of 9% for SEC and 10% for DEC, respectively. The experiments extend CX cross section data to higher collision energies and reveal contributions from electron capture into high- n states. These results are not predicted by the existing theories [4].

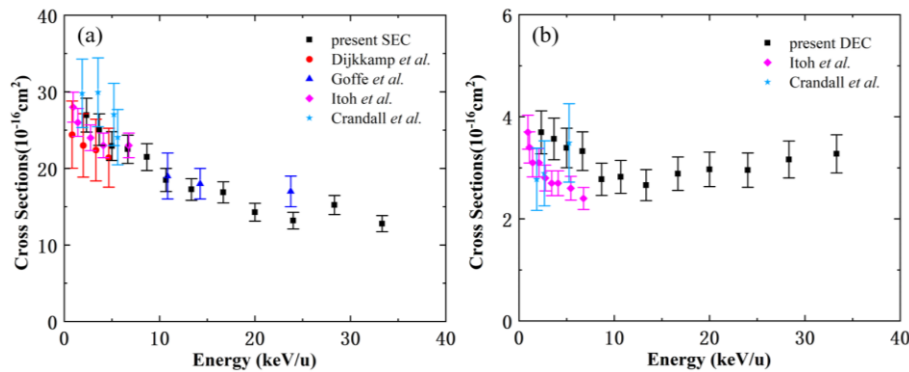


Figure 1. Measured absolute SEC (a) and DEC (b) cross sections for $C^{4+}+H_2$ collisions.

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Formation of H_n^+ ($n = 1,2,3$) from fluoroethane dications induced by ion collision

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Intramolecular hydrogen migration is a ubiquitous process that plays a pivotal role across numerous fields of physics, chemistry, and biology. When the target molecule contains multiple hydrogen atoms, Proton migration typically occurs as a means of charge transfer [1-2], such as in the hydrogen elimination reactions of methane and acetylene. Due to the unique electronic properties of halogen elements, the collision-induced dissociation process between fluoroethane and highly charged ions is regarded as a crucial reference for understanding the dissociation kinetics of polyatomic molecules [3].

In this article we report an experimental and theoretical study on H_n^+ ($n=1,2,3$) formation dynamics from Halogenated hydrocarbon compounds (C_2H_5F) in collisions with multi-charged ions of 3 keV/u Ar^{8+} . The experiment were performed with the Cold Target Recoil-Ion Momentum Spectroscopy (COLTRIMS) at Fudan University [4], thereby determining the KER distribution; Quantum chemical calculations were performed using the DFT method to identify the transition states and reaction pathways, and interpret the KER measured peak.

The formation of isomers via hydrogen migration, followed by the direct cleavage of the C-H bond, constitutes a critical step in the decomposition process of C_2H_5F . Comparative experiments using transition-state calculated reverse activation energies revealed that H^+ and H_3^+ are activated from electronic singlet (S_0), whereas H_2^+ is activated from electronic triplet (T_0). This elucidates the formation mechanism of H_n^+ ions in molecular systems and provides new insights into hydrogen migration and molecular cleavage kinetics.

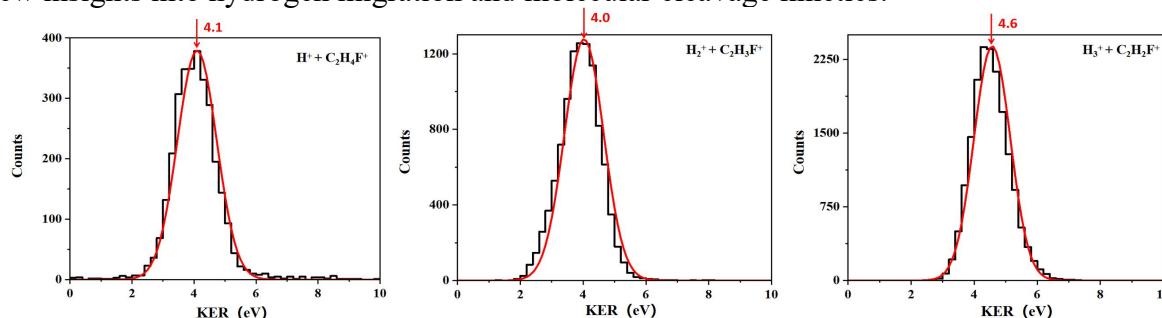


Figure 1. Experimental kinetic energy release distributions for H_n^+ channel.

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Relativistic high-precision calculations of energy levels and properties of HCI ions

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Highly charged ions (HCIs) possess rich energy level structures and long-lived excited states, with optical transitions between these states holding significant application value in areas such as astrophysical spectral identification, plasma parameter diagnostics, optical clocks, and tests of fundamental constants. We have carried out a series of relativistic high-precision calculations on HCIs. This presentation will introduce our accurate calculations of the energy levels and properties of Ni^{12+} , Ir^{17+} , and Yb^+ using the selected configuration interaction method. We will demonstrate how the treatment of electron correlation approaching the full-CI level improves the accuracy of theoretical predictions, and discuss the application of these data in the experimental development of optical clocks based on highly charged ions.

Hyper-EBIT@ALPHATRAP: Towards strong-field QED tests with very highly charged ions

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Quantum electrodynamics (QED) is considered to be the most successful quantum field theory within the Standard Model. Its most stringent test is provided by comparing high-precision QED calculations with measurements of the free-electron g -factor. However, these tests probe QED only in the regime of relatively weak electromagnetic fields. To investigate QED under much stronger field conditions, highly charged ions (HCIs) can be employed. In such ions, only the innermost electron(s) remain bound to the nucleus and are exposed to extremely strong electric fields of up to $10^{16} \frac{V}{cm}$ due to the vicinity of the electrons and the nucleus.

An experiment that enables such precision studies is ALPHATRAP [1], a cryogenic Penning-trap setup dedicated to measuring the bound electron magnetic moments of HCIs with high precision.

The measurement of the bound-electron g -factor of $^{118}\text{Sn}^{49+}$ [2] and $^{118}\text{Sn}^{47+}$ [3] at ALPHATRAP is the most stringent test of strong-field QED to date. To extend these tests to even heavier HCIs, such as $g_j(^{208}\text{Pb}^{81+})$, an electron beam ion trap (EBIT), the Hyper-EBIT [4], is being upgraded at MPIK. This EBIT is designed to produce and confine heavy HCIs by providing electron-beam energies of up to 300 keV and beam currents of up to 500 mA. This contribution reports on the recent experiments at ALPHATRAP and particularly the status of the Hyper-EBIT project.

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Systematic investigation of optical and extreme ultraviolet emission spectra of Ag-like and Cd-like ions with a compact electron beam ion trap

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Ag-like and Cd-like ions have the ground-state electron configurations $4f$ and $4f^2$, respectively, for atomic numbers $Z > 63$. These simple atomic systems with few valence electrons serve as useful benchmarks for atomic structure calculations involving $4f$ electrons. Furthermore, the simple energy level structures can give rise to interesting processes in plasmas, e.g. the anomalously strong electric-octupole (E3) emissions [1] and the anomalous ionization equilibrium caused by long-lived metastable states [2].

Here, we report systematic investigations of optical and extreme ultraviolet (EUV) emission lines of Ag-like and Cd-like ions with a compact electron beam ion trap, CoBIT-II [3], at National Institute for Fusion Science (NIFS). An electron-impact metal injection method, which we recently demonstrated [4], enabled us to observe spectra of Ta, Hf, and Pt, which were previously difficult to measure, completing the systematic measurements in the atomic number range of $Z=67-79$.

In this poster, we present the observed optical and EUV emission spectra and discuss the atomic number dependence of the EUV E3 transitions and the optical magnetic-dipole (M1) transitions.

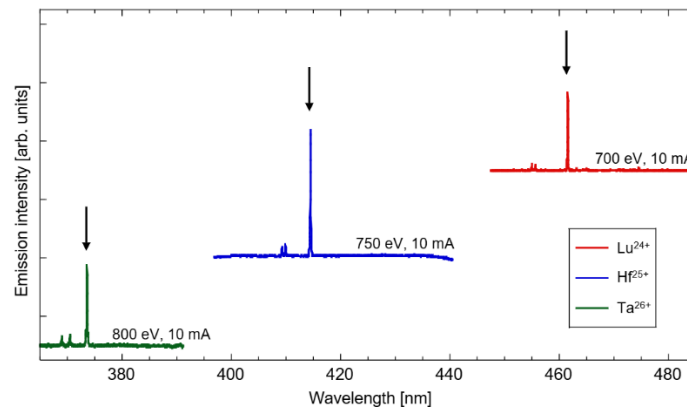


Figure 1. Typical spectra of Ag-like Ta^{26+} , Hf^{25+} , and Lu^{24+} .

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Measurements of Total and State-Selective Cross Sections for Single Electron Capture in O^{5+} -He Collisions

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Absolute cross sections for charge exchange (CX) processes in collisions of highly charged ions (HCIs) with neutral targets are of great significance for diagnosing fusion plasmas and modeling astrophysical X-ray emissions. Despite being studied for decades, considerable gaps across various collision systems and impact energy ranges exist in the measurements of CX cross sections.

As one of the most abundant HCIs on the surfaces of divertors in tokamaks and due to its unique spectral characteristics in the solar wind, O^{5+} ions are important research subjects. In the present work, the total and n , l -resolved cross sections for single electron capture (SEC) in O^{5+} -He collisions are measured in the energy range from 1.6 to 31.3 keV/u based on the HCIs Collision Platform at Fudan University [1]. The total cross section is determined using the growth-rate method [2, 3]. The state-selective ones are obtained via the cold-target recoil-ion momentum spectroscopy.

For the O^{5+} -He collision system, the electron captured into the $3l$ state of O^{4+} is the dominant channel in the present energy range. Higher- n channels like $2s4l$ and $2s5l$ gradually become significant with increasing collision energy. Transfer excitation (TE) channels are also observed in the SEC process including the transfer projectile excitation (e.g., $O^{4+}(1s^22p3l) + He^+(1s)$) and transfer target excitation (e.g., $O^{4+}(1s^22s2p) + He^+(n=2)$). It follows that the $2s$ bound electron of the O^{5+} ions and the two ground-state electrons of the He atoms participate in the CX processes, demonstrating the importance of considering the interactions among three active electrons in precise theoretical calculations for O^{5+} -He collisions.

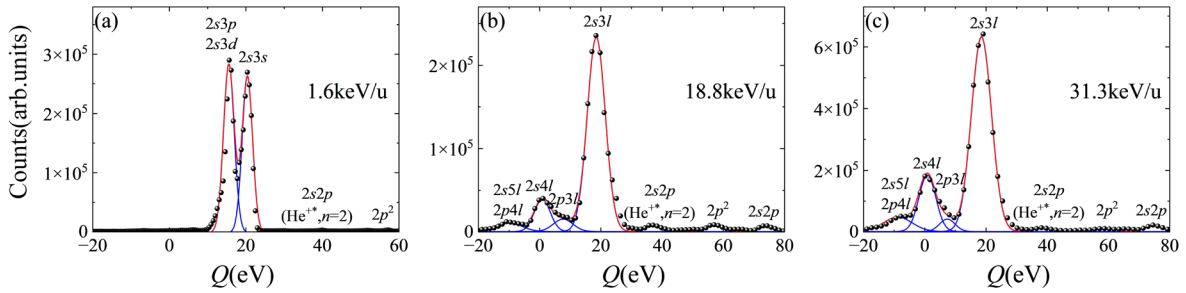


Figure 1. The Q -value diagram for SEC in O^{5+} -He collisions at the three energy points

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Transfer ionization dynamics in highly charged ions collisions with helium

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Two-electron processes have been widely explored over the past three decades to gain complementary insight into the role of electron-electron correlation when a target atom is inelastically affected by either charged particle or photon impact. In particular, double ionization (DI) and transfer ionization (TI) for He targets have been analyzed across different collisional regimes using various experimental techniques and theoretical formalisms.

In this work, we present our results for the TI process of He following the impact of a highly charged ion. Our study employs the classical trajectory Monte Carlo method in its energy-bounded (EB-CTMC) [1] and sequential (n-CTMC) [2] formalisms. The former includes electron-electron interaction at all times by considering energy constraints to avoid the collapse of the classical two-electron atom, while the latter neglects electron-electron interaction throughout the simulation. In both cases, a proper amount of 79 eV must be transferred by the projectile to achieve double electron removal from the target. The prototype projectile considered for our study is Ne^{10+} , and the impact energy range is 100-500 keV/u.

From our analysis of single differential cross sections, expressed in terms of the recoil ion momentum component parallel to the projectile incidence direction and the emitted electron energy, we identify structures that could serve as potential indicators of whether electron capture or ionization occurred first. From this classical analysis, we estimate the time-framing of these sequential processes and their dynamics as the impact energy is varied.

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Fragmentation dynamics of the Formamide Dication $\text{NH}_2\text{CHO}^{2+}$

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In this work, the fragmentation of $\text{NH}_2\text{CHO}^{2+}$ is ionized by strong-laser-field and investigated by means of cold target recoil ion momentum spectroscopy (COLTRIMS), in conjunction with *ab initio* reaction path calculations at the $\omega\text{B97XD/aug-cc-pVTZ}$ level of theory. Three two-body dissociation channels are resolved: $\text{NH}_2\text{CHO}^{2+} \rightarrow \text{H}^+ + \text{CH}_2\text{NO}^+$, $\text{NH}_2^+ + \text{CHO}^+$, and $\text{NH}_3^+ + \text{CO}^+$. For the $\text{H}^+ + \text{CH}_2\text{NO}^+$ channel, a measured KER of 4.12 eV is observed. The $\text{NH}_2^+ + \text{CHO}^+$ channel (KER = 5.41 eV) is attributed to direct C–N bond cleavage, with the triplet-state reaction path yielding the closest theoretical agreement (5.86 eV). For the $\text{NH}_3^+ + \text{CO}^+$ channel, the measured prompt KER of 4.22 eV is in agreement with the singlet hydrogen-transfer pathway (4.23 eV). The delayed dissociation of $\text{NH}_3^+ + \text{CO}^+$ channel is observed which yields a KER of 3.97 eV and the lifetime is determined to be $\tau = 576 \pm 87$ ns.

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Prompt and Delayed Dissociation Dynamics of C_5H_5N Dication induced by Intense laser

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Abstract: Multiply ionized aromatic molecules are crucial intermediates in astrophysical plasmas and model systems for radiation damage in biological matter [1]. Their fragmentation dynamics, particularly the interplay between prompt coulomb explosion and delayed dissociation from metastable states, encode detailed information about dication potential energy surfaces [2, 3]. While such processes have been extensively characterized in small molecules, quantitative coincidence studies of specific two-body channels in complex aromatic dications under intense femtosecond laser fields remain limited. In this work, we used Cold Target Recoil-Ion Momentum Spectroscopy (COLTRIMS) to study the two-body dissociation of doubly ionized pyridine ($C_5H_5N^{2+}$) produced by intense (10^{15} W/cm²) femtosecond laser pulses. We identify the $CH_2N^+ + C_4H_3^+$ channel and clearly separate prompt and delayed dissociations in the TOF coincidence spectrum (Figure 1). The prompt channel exhibits an averaged kinetic energy release (KER) of 2.2 eV, while the delayed channel shows a lower KER of 1.77 eV. The metastable lifetime of $C_5H_5N^{2+}$ is determined to be 136 ns.

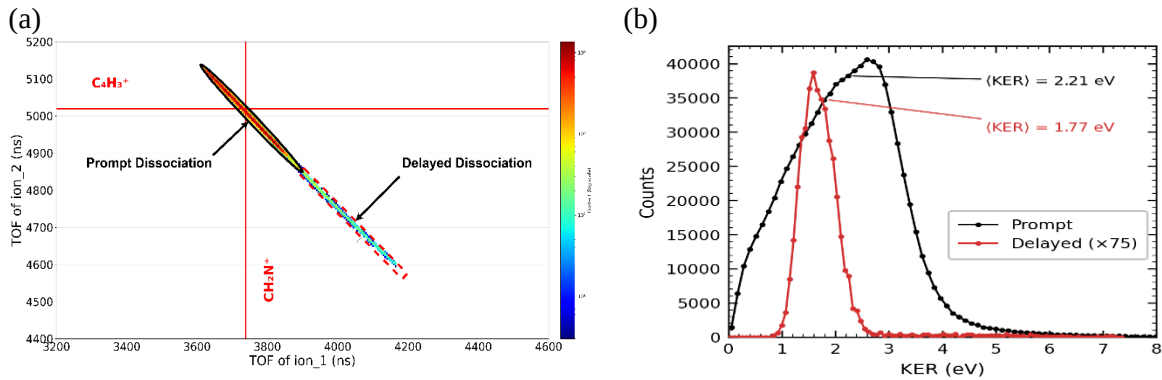


Figure 1. (a) TOF coincidence spectrum of the prompt and delayed $CH_2N^+ + C_4H_3^+$ channel. (b) KER distribution.

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Evaluation of MMC Detector Data from CRYRING@ESR 2025: Temperature Corrections and First Results

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Spectroscopy with Magnetic Metallic Calorimeters (MMCs) can overcome limitations of traditional X-ray spectroscopy methods. Their operating principle allows measurements with the flexibility of semiconductor detectors while achieving a resolution approaching that of crystal spectrometers. A new MMC detector system was deployed to study strong-field QED effects during the GSI beamtime 2025 using heavy, highly charged ions.

This experiment is a rerun of a successful previous study [1], aiming to increase the efficiency of the setup and thereby improve the statistics. The GSI facility provides a unique environment for the production and study of highly charged ions, enabling investigations into fundamental physics. For our studies, a high-intensity beam of hydrogen-like uranium ions was produced, decelerated to 11.5 MeV/u, and stored in the storage ring CRYRING@ESR. Using the electron cooler as a free-electron target, we observed the characteristic radiation subsequent to radiative recombination of cooler electrons with the stored uranium ions. The emitted X-rays were detected with the maXs MMC detector system, which was developed and built within the SPARC collaboration at the Kirchhoff Institute for Physics in Heidelberg [2].

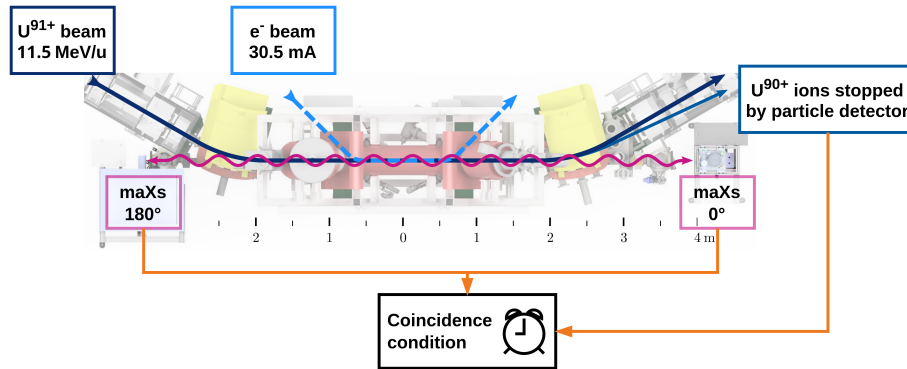


Figure 1: Schematic of the experimental setup at CRYRING@ESR. The MMC detector system consists of two arrays of 64 pixels each, mounted at the 0° and 180° ports of the electron cooler.

This contribution presents the evaluation of the experimental data, including the first analysis of the X-ray spectra obtained from the MMC detectors. Insights into the correction of energy information for detector temperature fluctuations are provided.

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RMBPT Energy Level Calculations for $4f^m6s$ Ground Configurations in Singly Ionized Lanthanides: Pr II–Eu II and Tb II–Tm II

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Heavy elements are produced via the rapid neutron capture process (r-process) of nucleosynthesis in violent astrophysical phenomena, such as kilonovae from neutron star (NS) mergers. Lanthanides are the dominant contributor of opacities in such processes due to their dense low-lying energy levels and abundant bound-bound transitions. Accurate atomic data of lanthanides is necessary for understanding this process [1].

The experimental and theoretical investigations focused on singly ionized lanthanides are hampered by the numerous energy levels and crowded spectral lines. On the experimental side, the crowded nature of the spectral lines calls for high-resolution spectrometers. On the computational side, the strong correlation effects arising from the complex open-4f subshell make ab initio calculations extremely challenging. For the ground-configuration levels, the state-of-the-art calculations conducted by Flörs et al. [2] using relativistic configuration interaction (RCI) still result in average deviations below $\sim 21\%$ compared with the NIST database [3]. The multi-configuration Dirac–Hartree–Fock (MCDHF) calculations implemented by Gaigalas et al. [4–6] have achieved the highest accuracy to date, yet still give deviations of 3% to 12% from the NIST data.

In this work [7], we performed calculations of ground-configuration energy levels for Pr II–Eu II and Tb II–Tm II using relativistic many-body perturbation theory (RMBPT) implemented in the Flexible Atomic Code (FAC). In contrast to MCDHF calculations [4–6], comparable or even higher computational accuracy is achieved for Eu II and Tb II–Tm II (e.g., average deviations for Tb II: 4.98% vs. 4.07%; Er II: 10.43% vs. 4.96%), extending the RMBPT method to ionic systems with an open-4f subshell plus a single 6s electron.

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The isotope ratio analysis in plasma by pulsed tunable laser with ultra-narrow width

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The radioactive elements and their isotope ratio analysis are of great significance for nuclear energy, nuclear forensics, and nuclear waste disposal^[1]. In this work, we propose a laser ablation absorption spectroscopy method resonant excited by two nanosecond pulse tunable laser with collinear transmission (as shown in fig.1). To meet the high resolution for isotopic analysis, a compact Ti:sapphire laser combination Littman configure with short cavity pumped with a self-developed portable nanosecond laser with 532 nm wavelength was designed. The linewidth of the Ti:sapphire laser can be as narrowed as several hundred MHz, which is far narrower than the isotope shift for many nuclear fuel elements. More importantly, the laser wavelength can be tunable more than 30 nm after frequency doubling and the linewidth can be changed from several hundred MHz to tens GHz, which could be used for absorption spectroscopy without isotope discrimination by well matching the energy split of different isotopes. Using the laser, the pulsed-LAAS have been demonstrated in a aluminum target successfully and the absorption ratio could be improved significantly by change the linewidth of laser matching with broadening of the Al line in plasma. Due to the nonuniform of laser plasma in spatiotemporal, the detection position and the delay time is very important for LAAS. To optimize the detection parameters, a 4D spectroscopic diagnostic method for laser-induced plasma using femtosecond filamentation was proposed^[2]. It could give the distribution of elements in inner of plasma at different delay time. In summary, the pulsed-LAAS with a narrowed linewidth laser developed by ourselves is proposed, which provides a new method and instrument for isotopic analysis.

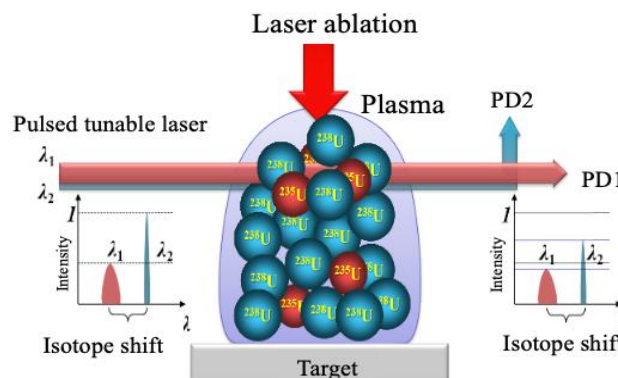


Figure 1. The pulsed-LAAS method for isotope analysis without isotope discrimination

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Charge exchange in collisions of fully stripped and hydrogen-like oxygen ions with H and He

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The study of collisions involving highly charged ions and atoms has important applications in astrophysics and fusion plasma modelling. Such collision processes play a key role in the interpretation of emission spectra from astrophysical plasmas and in understanding energy transport and radiation losses in laboratory and fusion plasmas [1]. Recently, we employed the two-centre wave-packet convergent close-coupling method to model ionisation and electron-capture processes occurring in O^{7+} and $O^{8+}+H$ collisions [2]. For the hydrogen-like oxygen ion, we used a model potential approach to reduce the corresponding scattering problem to an effective three-body one. We utilised a new straightforward method to obtain the model potential parameters. This method provides accurate orbital energies for the outgoing He-like ion formed by electron capture. The cross sections are in good agreement with the experimental measurements and other theoretical calculations, where available.

We extend the model potential approach to partially stripped ion collisions with He and perform calculations of charge transfer by O^{7+} projectiles. For comparison, we also perform calculations for $O^{8+}+He$ collisions. The calculations are done using both an effective one-electron (E1E) and a more robust two-electron (2E) treatment of the He target [3]. Both the E1E and 2E results for the total electron-capture cross section appear to overestimate the measurements [4,5]. For the O^{8+} projectile, we use the obtained state-selective cross sections to calculate X-ray emission cross sections for the first few Lyman lines of the outgoing projectile formed through electron capture. By accounting for the detector efficiency and other factors, we compare the resulting theoretical spectra with the experimental measurements at collision energies between 1 and 15 keV/u and find excellent agreement. This indicates that the underlying cross sections correctly reflect the n - and ℓ -distribution of the state-selective cross sections, where n and ℓ denote the principal and angular momentum quantum numbers of the final state, respectively. Somewhat unexpectedly, we find that the E1E treatment of the target is able to reproduce the measured spectra slightly better than its 2E counterpart at lower collision energies, though the total charge exchange cross section resulting from the 2E method agrees slightly better with experiment [4].

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Control Interface Design for the High-Voltage Platform for Dielectronic Recombination Experiments on HIAF-SRing

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A control interface for the high-voltage platform used in dielectronic recombination (DR) precision spectroscopy experiments at the HIAF-SRing electron-ion recombination facility has been developed. The interface is designed for experimental physicists to regulate the electron cooler voltage and monitor critical signals in real time. It provides real-time monitoring of the electron cooler high-voltage signal and the deflection plate voltage signal, along with parameter configuration for both the main high-voltage supply and the deflection plate power supply. The calculation logic for the deflection plate voltage is embedded in the program.

Three distinct modulation waveforms required for DR experiments are supported: low-voltage precise scanning, high-voltage fast scanning, and a hybrid mode combining both strategies. The program automatically generates the corresponding waveform based on user-adjustable single-cycle parameters (start voltage, voltage step, dwell time, cool point, cool time, period time, etc.). A real-time preview of the generated waveform is displayed within the interface, as shown in Figure 1.

Communication between the control interface and the terminal devices is based on the EPICS protocol, ensuring fast and stable data exchange. Voltage communication and parameter read/write tests have been successfully performed at the CSRm facility in Lanzhou. The program is currently under further development, with the experimental trigger signal module being the remaining part to be implemented.

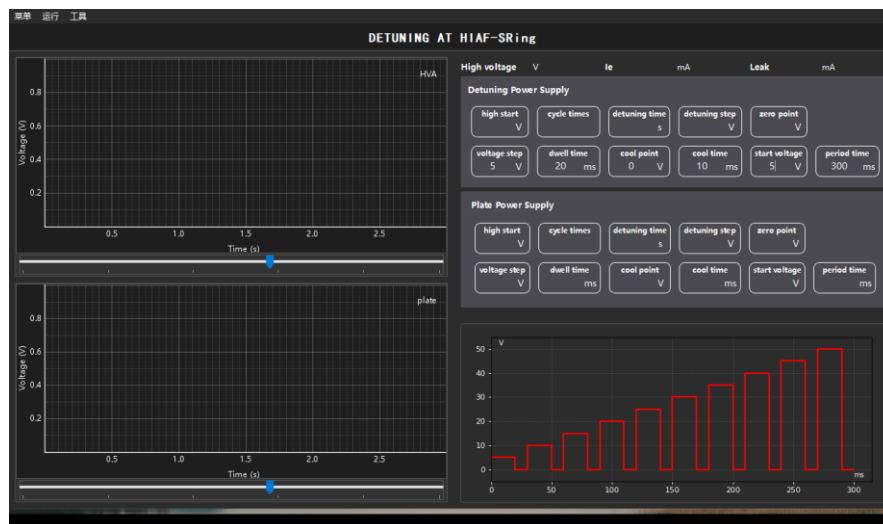


Figure 1. Screenshot of the control interface showing the waveform preview and real-time oscilloscope monitoring of the high-voltage signal

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Signatures of radiative recombination dynamics in highly charged ions: Photon polarization and ion alignment

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Radiative recombination (RR) of electrons with highly charged ions provides a sensitive probe of relativistic electron–photon interactions and angular momentum transfer in strong Coulomb fields. Among the observables accessible in RR, photon polarization and ion alignment characterize complementary aspects of the recombination dynamics. The former reflects the coherence of the emitted radiation, whereas the latter is determined by the magnetic sublevel population of the recombined ion.

So far, most of the polarization measurements concerned the capture of an electron into the K -shell of the projectile ions [1, 2], and demonstrated that the polarization properties of the emitted RR photons appears to be very sensitive to the spin state of the incident electrons [3]. If, in contrast, the electron is captured into some excited state of the ion, the nonstatistical population of the magnetic substates of the recombined ion gives rise to ion alignment. Till today, however, such studies on RR photon polarization and ion alignment have dealt with electron targets that are spin-unpolarized. Therefore, it remains unclear how the polarization properties of the RR photons and the magnetic sublevel population of the excited ion states are affected by the spin polarization of the target electrons.

In this work [4], we systematically explore the polarization of RR photons and the alignment of the recombined ions due to the capture of spin-polarized electrons into the bound states of bare, high- Z ions. For this purpose, a unified theoretical framework is established based on the relativistic Dirac theory and the density matrix approach. The numerical results clearly indicate that the stokes parameter P_2 and the rotation angle χ of the polarization ellipse of emitted RR radiation are very sensitive to the spin state of electron target, while alignment parameters remain unaffected. For the capture of spin-polarized electrons, to be specific, when the recombination channel changes from $1s_{1/2}$ state to $2p_{3/2}$ state, pronounced alignment of the recombined ions over a broad range of projectile energies is predicted; in parallel, a sizeable sign reversal of the stokes parameter P_2 is visualized, resulting in a corresponding change in the orientation of the polarization axis. In this sense, the combined analysis of photon polarization and ion alignment provides a more complete characterization of the recombination dynamics than either observable alone.

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Observation of QED Effects, Breit Interaction, and Electron Correlation in Highly Charged Au Ions Produced by a High-Power Laser

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We report on measurements of extreme ultraviolet (EUV) radiation from highly charged gold ions in laser-produced plasma to investigate the quantum electrodynamics (QED) effects, Breit interaction, and electron correlation (EC) effects which play a crucial role in determining the energy levels of high-Z, highly charged ions. Specifically, we analyse emission lines from the $4s\ ^2S_{1/2}$ - $4p\ ^2P_{1/2}$ and $4d\ ^2D_{3/2}$ - $4f\ ^2F_{5/2}$ transitions in Cu-like Au ions (Au^{50+}), where the ground state consists of a filled M-shell and a single $4s$ electron in the outermost shell. Utilizing the multiconfiguration Dirac-Hartree-Fock (MCDHF) method, we systematically calculated the energy levels and transition wavelengths. Our results show that only when QED effects, Breit interaction, finite nuclear size (FNS) corrections, and EC effects with sufficient electron configurations are included do the theoretical predictions align with experimental observations. By combining state-of-the-art experiments with high-precision computations, we resolve the long-standing discrepancies in the spectrum of Cu-like Au ions, providing the first quantitative delineation of QED effects, Breit interaction, FNS corrections, and EC effects on its energy levels. Our methodology is directly applicable to other highly charged ions, which are crucial for modelling astrophysical and laboratory plasmas.

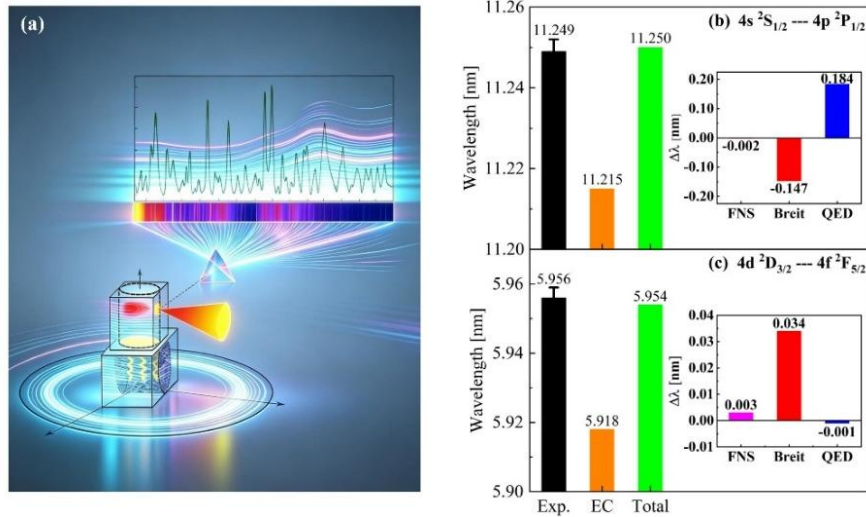


Figure 1. (a) Schematic diagram of the experimental setup; (b)-(c) The contributions of electron correlation (EC) effects, QED effects, Breit interaction, and finite nuclear correction to the transition wavelengths of $4s$ - $4p$ and $4d$ - $4f$ in Cu-like gold ion.

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Identification of Hydrogen-Like Fragments in ^{86}Kr Projectile Fragmentation Experiments at 400 MeV/u

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Fragments produced via projectile fragmentation at relativistic energies are predominantly stored as fully stripped ions in heavy-ion storage rings, while a small fraction are hydrogen-like ions. A hydrogen-like ion of the form $^A_Z X^{(Z-1)+}$ carries the same ionic charge as its neighboring isobar $^A_{Z-1} Y^{(Z-1)+}$. Their nearly identical mass-to-charge ratios pose a considerable challenge for unambiguous identification using conventional isochronous mass spectrometry. To overcome this, a higher-precision method based on velocity correction of in-flight ions was employed [1,2]. Agreement between the redetermined and reference mass values validated the particle identification, enabling the separation of hydrogen-like ions from their fully stripped isobars and the subsequent determination of their production cross sections. Figure 1 shows a clear distinction between $^{84}\text{Se}^{33+}$ and $^{84}\text{As}^{33+}$. A preliminary comparison demonstrates that the experimentally observed hydrogen-like cross sections are significantly larger than the LISE++ predictions employing the GLOBAL charge-state model [3]. This notable discrepancy suggests that current charge-state calculations for neutron-rich fragments call for further evaluation.

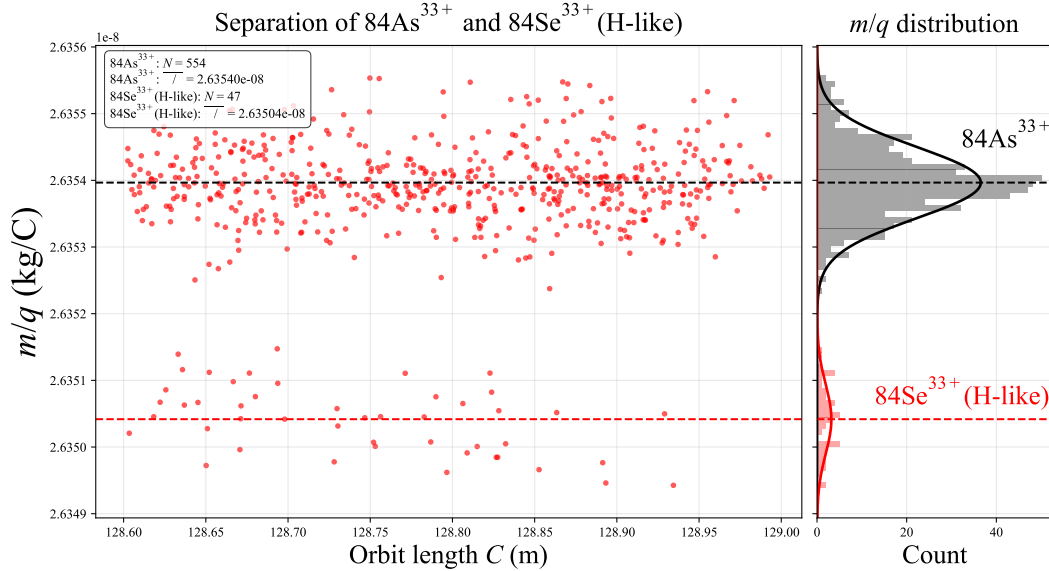


Figure 1: The hydrogen-like ions $^{84}\text{Se}^{33+}$ are clearly resolved from their fully stripped isobars $^{84}\text{As}^{33+}$.

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Digital Filters for Pulse Shape Analysis of Metallic Magnetic Calorimeters

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Metallic Magnetic Calorimeters (MMC) have emerged as excellent single photon detectors, exhibiting a broad spectral acceptance range from a few to hundreds of keV and a high energy resolution of $E/\Delta E(FWHM) \approx 6000$ [1]. Together with their fast signal rise time, they provide a superb opportunity for fundamental research in atomic physics. In the last years they have been utilised for example in precision x-ray spectroscopy of helium-like uranium [2] or light muonic atoms [3]. When an MMC detector absorbs an incident photon, the subsequent raise in temperature of the connected sensor leads to a change in magnetisability. In turn this gives rise to a measurable signal in an attached SQUID magnetometer. The pulse shape depending on the intrinsic detector response superimposed by noise and artefacts from various sources.

To exploit the outstanding performance of the MMCs it is necessary to extract the relevant pulse features while suppressing noise contributions. Therefore, a complex data analysis is required which contains among other features a pulse shape analysis, a temperature correction, and if required an analysis of the coincident measurement. Finally, the measured pulse amplitudes can be translated into a physically interpretable spectrum. This contribution focuses on the pulse shape analysis by comparing different filter algorithms. For this purpose, a typical pulse shape and noise of MMC signals including digitalisation effects of an ADC were simulated. These synthetic pulses were fed into four digital pulse shape analysis filters to test their resolving power: the Maximum Filter, the Integral Filter (IF), the Moving Average Deconvolution combined with a Moving average Filter and the Optimal Filter (OF). The filters were analysed with datasets containing signals with a fixed amplitude but one varied property; for example the uncertainty of the arrival time, an uncertainty in the determination of the decay time, a varying proportion of pink noise to the total noise and a variation in the signal to noise ratio. For a detailed offline analysis the OF was found to deliver the best resolving power while for online analysis the IF revealed the best compromise between achievable spectral resolution and processing time.

Since it is essential to perform the data analysis pixel wise and nowadays MMC detector chips featuring up to 64 pixels while more pixels are planned for upcoming experiments, methods for a scalable data analysis are necessary. To be able to represent the complex, large scale data analysis new machine learning (ML) approaches for the MMC detectors are developed. These developments together with the findings of the pulse shape analysis will substantially contribute to make the full use of the MMC detector technology. Both, the ML approaches and the pulse shape analysis will be presented.

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King-plot nonlinearity in calcium

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Isotope shifts measured at high precision provide sensitive access to nuclear structure effects and to hypothetical beyond-Standard-Model forces acting between electrons and neutrons. Recent measurements of the $^3P_0 - ^3P_1$ transition in Ca^{14+} and the $^2S_{1/2} - ^2D_{5/2}$ transition in Ca^+ , together with accurate nuclear masses, reveal a King plot nonlinearity at the $10^3 \sigma$ level. In this work, we analyze these experimental results to identify the dominant Standard Model contributions, namely the second order mass shift and nuclear polarization. Furthermore we perform a generalized King-plot analysis to translate the data into stringent limits on a new scalar boson coupling to electrons and neutrons in the mass range between $10 \text{ eV}/c^2$ and $10^7 \text{ eV}/c^2$.

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NEEC Candidates for Storage-Ring Recombination Experiments

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Nuclear excitation by electron capture (NEEC) is a resonant electron–ion recombination process in which a free electron is captured into a vacant atomic orbital and the sum of its kinetic and binding energies excites the nucleus. NEEC is the time-reversed process of internal conversion [1], but it still lacks decisive experimental evidence [2, 3]. For highly charged ion system, the charge-changing signature makes a storage-ring recombination experiment especially attractive for NEEC searches [4]. We survey NEEC into the $1s$ orbital of bare ions for the first isomeric state of each nuclide, using IAEA LiveChart data [5], GRASPC/FAC wave functions, and the formalism of Ref. [1].

Usable reduced nuclear transition probabilities $B(\lambda L)$ are available for 868 of the 2279 nuclides surveyed. We exclude 135 cases for which $1s$ capture is energetically forbidden, i.e., $E_c = E_{\text{nuc}} - E_{\text{bind}} < 0$, and another 13 because of ambiguous nuclear spins, leaving 720 valid resonance strengths for ranking. Of the 20 strongest candidates, only ^{194}Po ($T_{1/2} = 0.392$ s) and ^{164}W ($T_{1/2} = 6.3$ s) fail the requirement that the ground-state half-life exceed 1 h; the remaining 18 are highlighted in Fig. 1. Future work will extend the survey to NEECX, in which rapid x-ray stabilization can enhance the resonance strength [6].

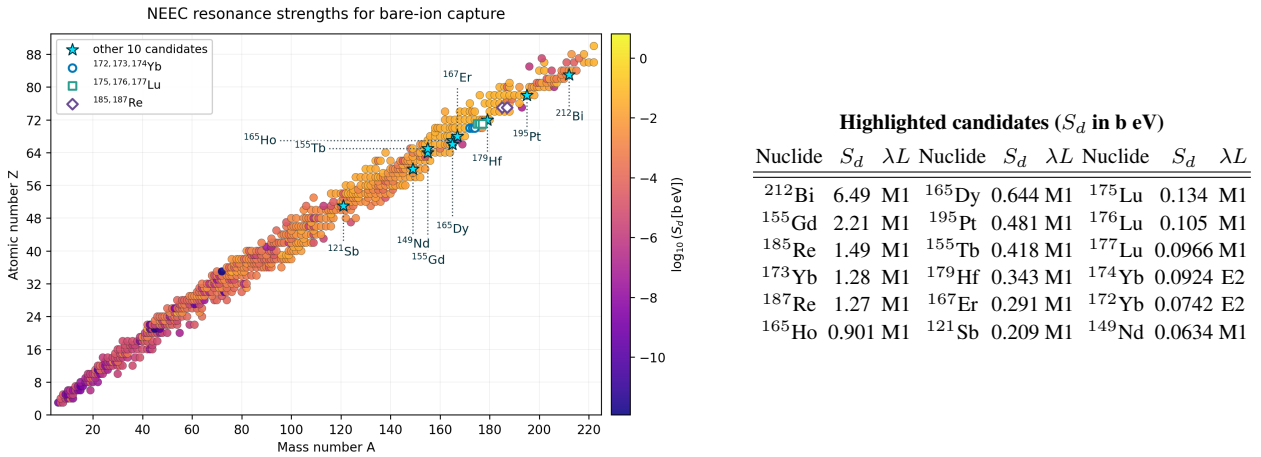


Figure 1: Bare-ion $1s$ -capture NEEC resonance strengths. Color shows $\log_{10}(S_d/[b \text{ eV}])$; marker shapes distinguish equal- Z candidates.

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Systematic MCDHF/RCI Calculation of Energy Levels and Radiative Properties for Chlorine-like Kr XIX Ions

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In this work, large-scale multiconfiguration Dirac–Hartree–Fock (MCDHF) method and relativistic configuration interaction (RCI) calculations are performed to determine the atomic structure and radiative parameters for chlorine-like Kr XIX. Breit interactions and rigorous quantum electrodynamic (QED) corrections are incorporated to account for higher-order relativistic effects and enhance computational accuracy. A total of 296 fine-structure levels are studied, with tabulated excitation energies, radiative lifetimes and transition data for E1, M1, E2 and M2 multipole transitions.

The calculations demonstrate exceptional gauge invariance between the length (form B) and velocity (form C) gauges, thereby ensuring high wavefunctional reliability and substantially suppressing truncation errors. Spanning a comprehensive energy spectrum exceeding $2,000,000\text{ cm}^{-1}$, the framework establishes a complete multi-level transition matrix tailored for complex plasma diagnostics. Consequently, this approach yields high-precision radiative rates and oscillator strengths across multiple orders of magnitude, effectively bridging critical data gaps within international atomic databases for complex ionic systems.

Ultimately, the high-precision atomic dataset generated in this study serves as benchmark values for krypton plasma spectral diagnostics and offers a robust reference for future computations of oscillator strengths and radiative transition probabilities.

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Commissioning and First Dielectronic-Recombination Measurements with the HIAF-SRing Electron-Ion Resonant Recombination Spectrometer

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The commissioning experiment of the HIAF-SRing Electron-Ion Resonant Recombination Spectrometer has been successfully completed, delivering energy-resolved dielectronic-recombination (DR) spectroscopy of highly charged, Na-like Kr^{25+} ions in a twin-electron-beam configuration comprising a 450-kV electron cooler and a dedicated 80-kV low-temperature electron target [1]. This measurement represents the first atomic-physics result from the HIAF-SRing commissioning campaign, accessing centre-of-mass electron-ion collision energies of up to 5 keV with electron-beam voltage modulation range of up to 40 kV, while achieving a collision-energy resolution better than 1.0 eV (FWHM) at 1 keV. The reliable operation of this DR facility enables high-precision DR spectroscopy of hydrogen-like high-Z ions up to uranium, allowing stringent tests of bound-state quantum electrodynamics (QED) in the strongest Coulomb fields accessible in laboratory atomic systems, while also supporting atomic-nuclear interplay studies, including nuclear excitation by electron capture (NEEC), and opening opportunities to probe nuclear properties with atomic-spectroscopic precision.

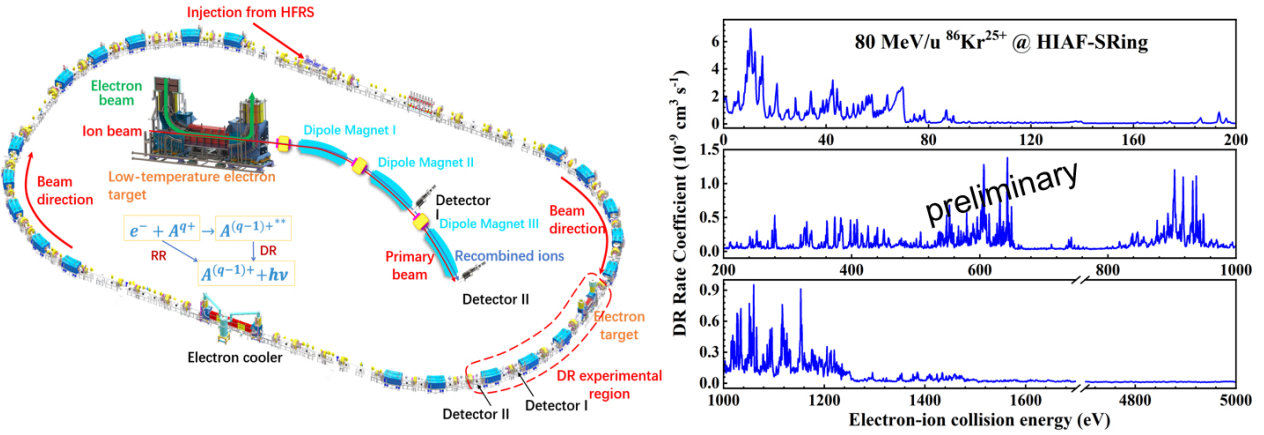


Figure 1. Figure 1.(Left) The sketch view of the electron-ion resonant recombination spectrometer at HIAF-SRing.(Right) The preliminary electron-ion recombination spectrum for Na-like Kr^{25+} measured at the HIAF-SRing.

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Theoretical Investigation of Electron-Impact Ionization of Li-like Fe^{23+} , Xe^{51+} , and U^{89+} at the HIAF-SRing Heavy-Ion Storage Ring

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Electron-impact ionization (EII) of highly charged ions is a fundamental charge-changing process in astrophysical and laboratory plasmas. For Li-like ions, the single-ionization cross section contains direct ionization (DI) as well as the indirect excitation-autoionization (EA) and resonant-excitation double-autoionization (REDA) channels [1]. Storage-ring merged-beams experiments reduce metastable-ion contamination and provide well-defined collision energies, but measurements at high energies remain scarce [2]. At HIAF-SRing, an independent 80-kV electron target operated together with a 450-kV electron cooler can extend merged-beams EII studies into the approximately 100-keV collision-energy regime while preserving high resolution [3].

We calculate EII cross sections for Li-like Si^{11+} , Fe^{23+} , Xe^{51+} , and U^{89+} using the Flexible Atomic Code within a relativistic distorted-wave and configuration-interaction framework [4]. DI, EA, and REDA are treated as independent pathways. The calculation is benchmarked against the TSR merged-beams data for Si^{11+} [5], reproducing the principal resonance features observed in the experiment.

For Fe^{23+} , Xe^{51+} , and U^{89+} , the calculated spectra exhibit resolvable $n = 3$ REDA resonance groups superimposed on a smooth DI+EA background. The strongest Fe^{23+} resonance increases the local total EII cross section by approximately 80%. The maximum enhancement decreases with nuclear charge because radiative stabilization increasingly competes with the sequential Auger cascade; nevertheless, several Xe^{51+} and U^{89+} resonance groups remain distinguishable under the expected HIAF-SRing resolution. The predicted REDA structures offer experimentally accessible benchmarks for testing the underlying resonant-ionization pathways. The results identify a favorable collision-energy range and provide practical guidance for future high-energy merged-beams EII measurements at HIAF-SRing.

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Laser cooling of HCI at the FAIR SIS100

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How to ‘cool’ intense beams of highly relativistic HCI? This is a very challenging task, especially when established ion beam cooling techniques (electron cooling & stochastic cooling) have profound difficulties under such conditions. At the heavy-ion synchrotron SIS100 of the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, we will apply ‘bunched beam laser cooling’ with a novel 3-beam concept [1]. Here, laser beams from 3 complementary laser systems (1x cw and 2x pulsed) will be overlapped in space, time and energy to interact simultaneously with the (initially) broad longitudinal velocity distribution of the ions in the rf-bucket (bunch). This concept will maximize the cooling efficiency and allow for fast (~10 seconds) and strong (factor ~1000) ion beam cooling. We will present this project, including the facility and the laser and detector systems, and show the latest results from our simulations [2].



Figure 1. Artistic impression of the SIS100 laser cooling facility @ FAIR

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POSTERS B

Spin-orbit induced excitation and quenching in collisions of protons with nitrogen and neon ions at various degree of ionization.

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The excitation and quenching in H^+-N^{q+} and H^+-Ne^{q+} collisions are discussed for the cases in which potential energy curves are coupled by the spin-orbit coupling mechanism. Ionization states q are chosen so that spin-orbit coupling was the only mechanism of coupling (Figure 1 shows one of those cases).

The cross sections are calculated with the two-dimensional wavepacket method and compared with the Landau-Zener method. The recently proposed two-dimensional nonadiabatic wavepacket dynamics can be used for both the excitation and quenching processes at energies ranging from 0.01-0.02 Hartree above the activation energy up to the energies of the order of tens of Hartrees (around 1 keV) and at high energies there are no numerical problems which can be present in plane-wave quantum scattering method [1, 2]. The potential energy curves and spin-orbit couplings are calculated fully ab initio with the MOLPRO software.

The calculated cross sections may be relevant for fusion plasma seeding with neon and nitrogen.

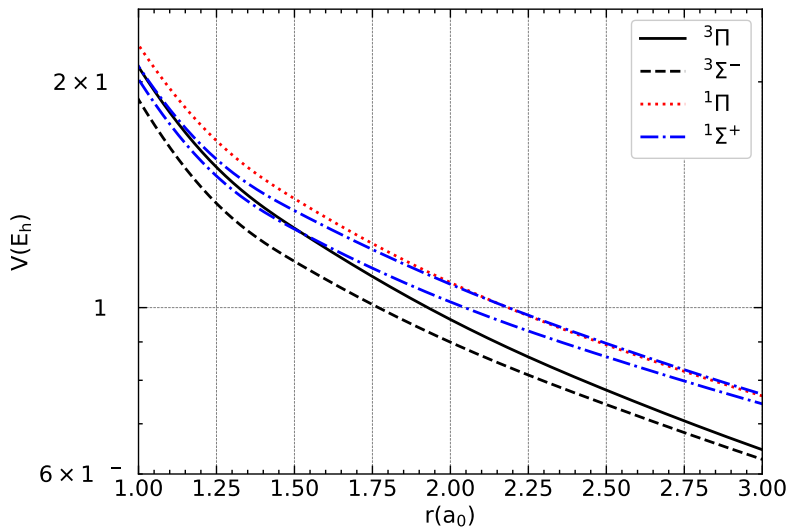


Figure 1. Potential energy curves describing two lowest dissociation limits of H^+-Ne^{2+} collisions.

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Experimental Study on Charge Exchange Cross Sections for Ar^{16+} Colliding with Ne at 1.2–10.0 keV u^{-1}

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Charge exchange (CX) between highly charged ions and neutral atoms is one of the fundamental atomic processes. At low energy collisions, CX exhibits a large cross section. The X-rays emitted from the cascade de-excitation of excited ions produced by CX exhibit distinctive spectral features. Reliable CX cross sections are of great significance for diagnostic and modeling studies of astrophysical and laboratory plasmas [1,2]. Currently, CX cross sections for highly charged ions ($q > 10$) remain scarce both theoretically and experimentally. Here, We present the cross section measurement for CX between Ar^{16+} and Ne at the collision energy range from 1.2 to 10.0 keV u^{-1} .

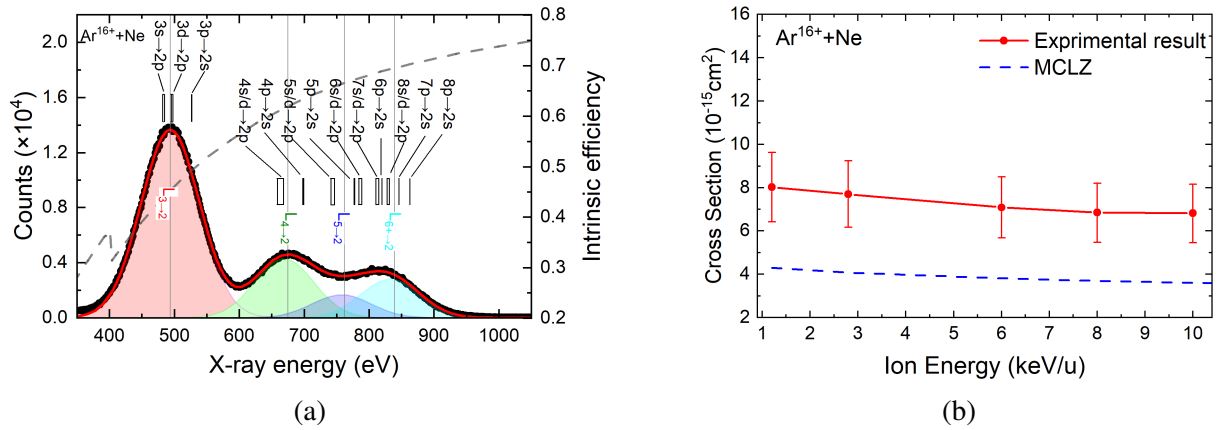


Figure 1: (a) X-ray emission spectrum from charge exchange between Ar^{16+} and Ne at 2.8 keV u^{-1} . (b) Determined CX cross sections from 1.2 to 10.0 keV u^{-1} , compared with the MCLZ prediction.

The CX cross sections are obtained by the measured L -shell X-ray emission yields. The CX induced X-rays were recorded using a Silicon Drift Detector (SDD). Fig. 1(a) shows a typical X-ray spectrum at 2.8 keV u^{-1} . By extracting L X-ray photons in the spectrum, combined with their detection efficiencies by the SDD, the monitored beam intensity and target thickness, the L X-ray emission cross sections are obtained. Given that the dominant CX process yields only a single L X-ray, the CX cross sections were determined accordingly and presented in Fig. 1(b). The MCLZ theoretical prediction is also plotted in Fig.1(b) for comparison. Further analysis is still in progress.

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On the two-frequency heating effect in Electron Cyclotron Resonance Ion Sources

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We use the NAM-ECRIS group of codes to study a response of the ECRIS plasma to injecting the microwaves with the relatively small intensity and lower frequency compared to the main heating microwaves. Empirically, it was found that such the technique allows increasing the extracted ion currents substantially. Different explanations are given to the effect; in particular, it is shown that the plasma micro-instability is suppressed by the two-frequency heating.

We calculate the plasma parameters for DECRIS-PM source when injecting 500 W of the main 14.5 GHz frequency (default mode) and in the mix of 450 W of 14.5 GHz and 50 W of 13 GHz microwaves. It is found that such the main values as the plasma density, electron energy distributions, and electron life-time are not changing in the mix. The most drastic changes are seen in the spatial distributions of electrons with the high ratio between velocities perpendicular and parallel to the magnetic field direction. Transversal profiles of density for electrons with energies above 1 keV and the anisotropy parameter $V_{\text{perp}}/V_{\text{long}} > 10.0$ are shown in Fig.1. The largest densities are localized close to the ECR zone, and the profiles in the mix are larger in the radial direction with the maximal values decreased by $\sim 20\%$. The smaller density of the anisotropic electrons suppresses the micro-instabilities, making the plasma stable and thus allowing to produce more ions.

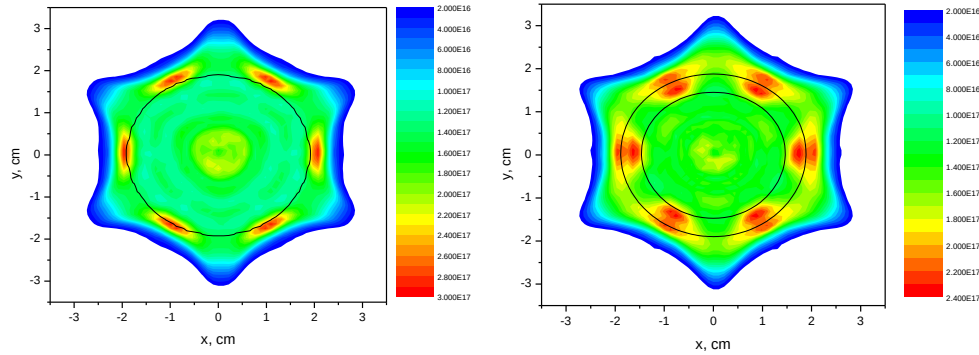


Figure 1. Calculated transversal profiles of the anisotropic electron density for the single (14.5 GHz) and the double-frequency (14.5+13 GHz) heating of ECRIS plasma. The peak density values are 3×10^{17} and $2.4 \times 10^{17} \text{ m}^{-3}$.

The reasons for such behaviour are traced to be connected to the strongly non-stochastic way of heating the electrons in the ECRIS plasma, with the smaller-frequency microwaves acting as a randomizing factor for those electrons, which gyromotion is in phase with the main microwaves.

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Determination of electron-phonon coupling in nonequilibrium warm dense gold via single-shot terahertz time-domain spectroscopy

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Warm dense matter (WDM) created by intense ultrashort laser pulses represents a highly excited state that lies at the intersection of solids, plasmas, and liquids and that cannot be described by equilibrium theories. The transient nature of this state when created in a laboratory, as well as the difficulties in probing the strongly coupled interactions between the electrons and the ions, make it challenging to develop a complete understanding of matter in this regime. The electron-phonon coupling of nonequilibrium WDM is a fundamental parameter for which various models and experimental data offer diverging predictions [1]. Using single-shot terahertz time-domain spectroscopy, we measure the electric conductivity with picosecond resolution. We find that the ions remain in their initial solid structure for several picoseconds, despite electron temperatures ranging from a few to several eV after the laser illumination. Using a combination of state-of-the-art Two Temperature Model (TTM), we extract the electron-phonon coupling of warm-dense gold, which is weakly dependent on the peak of electron temperature from $2.2 \times 10^{16} \text{ W m}^{-3} \text{ K}^{-1}$ to $5.0 \times 10^{16} \text{ W m}^{-3} \text{ K}^{-1}$ for maximal specific energy density to $0.66 \pm 0.02 \text{ MJ/kg}$. This work demonstrates a new method for experimental exploration of the exotic properties of WDM and the accurate electron-phonon coupling can constraint advanced theories on WDM.

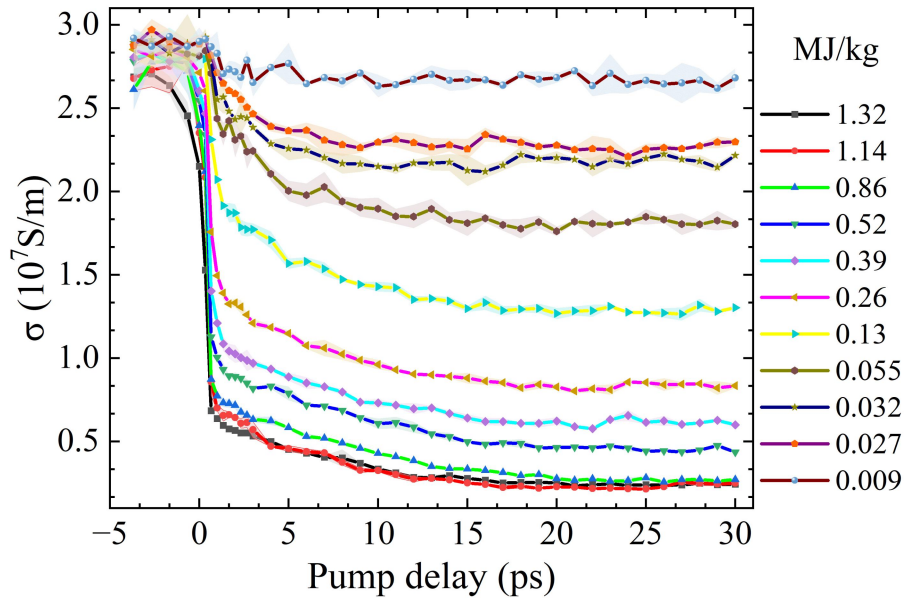


Figure 1. THz conductivity as a function of delay time under various absorbed energy density.

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First observation of M1 forbidden transition lines from W^{26+} ions in EAST tokamak with full tungsten divertor

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Tungsten (W, $Z=74$) is considered as potential candidate for plasma-facing components (PFC) in next-generation fusion devices such as BEST and ITER due to its excellent properties. How to controlling the tungsten content in the plasma is a key issue to maintain high-performance plasma for fusion devices because the tungsten ions cannot be fully ionized and emit line emissions in the plasma and cause serious radiation power loss owing to their strong cooling rate. The emission lines of tungsten ions play an important role in the spectroscopic diagnostics for understanding the impurity behavior and accurate determination of the tungsten concentration in the plasma. Visible magnetic-dipole (M1) lines can serve as a novel diagnostic method for tungsten. In magnetic confinement plasma, M1 lines from tungsten have so far only been observed in LHD device. Recently, the M1 lines of W^{26+} 389.41nm and Mo^{22+} 410.95 nm were successfully observed using a visible spectrometer [1-2] in the low-density and high-temperature plasmas on EAST, as shown in figure 1. This is the first-ever detection of tungsten M1 lines on a tokamak device. In addition, the temporal evolution of their profiles is highly consistent with that of the W^{26+} 49.0 Å and Mo^{23+} 70.726 Å measured by the extreme-ultraviolet (EUV) spectrometers [3-5]. Relevant studies illustrate that the M1 lines of W^{7+} - W^{52+} fall in the 270-850 nm, where optical technology is more advanced and can cope with the extreme environment of fusion devices. Besides, visible forbidden lines of tungsten ions are also valuable for plasma diagnostics, such as ion temperature and plasma rotation measurements via the Doppler effect, owing to their intrinsically narrow natural widths and low sensitivity to external fields. This study provides data support for the development of visible-band tungsten impurity diagnostics in future fusion devices.

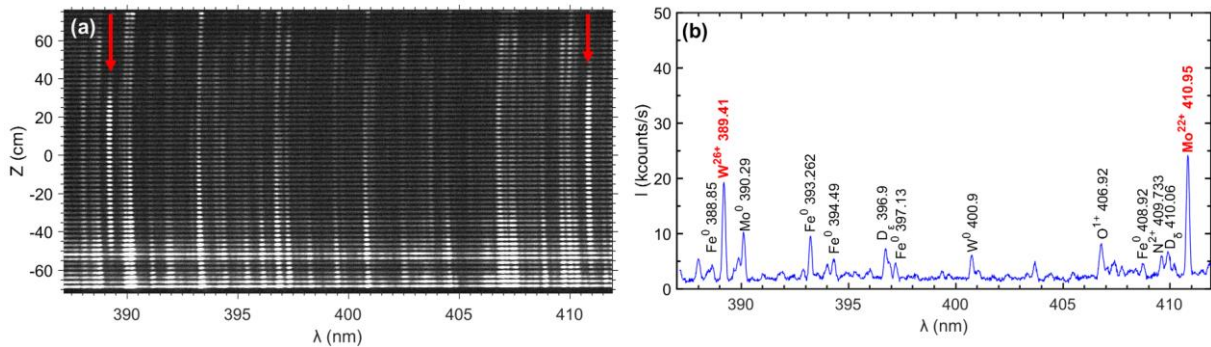


Figure 1. (a) Spectral images and (b) spectra in the wavelength range of 387-411 nm measured by visible spectrometer. The M1 lines from W^{26+} and Mo^{22+} ions are denoted with red arrows and labels.

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Transition wavelength measurements of Be-like Cl^{13+} toward laser spectroscopy

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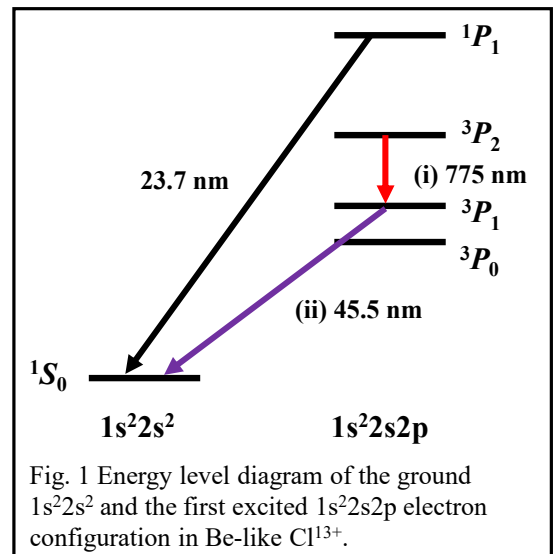
Be-like highly charged ions are a simple example of a many-body system to investigate electron correlation, relativistic, and quantum electrodynamics (QED) effects. In particular, Be-like Ar^{14+} has been thoroughly investigated using high-precision spectroscopy. Draganić *et al.* [1] and Soria Orts *et al.* [2] utilized the $2s2p\ ^3P_2 \rightarrow ^3P_1$ M1 transition to investigate QED effects and isotope shifts, respectively. Recently, we demonstrated time-resolved plasma-assisted laser spectroscopy of Be-like Ar^{14+} . In this method, we observe the laser-induced fluorescence (LIF) corresponding to the $2s2p\ ^3P_1 \rightarrow 2s^2\ ^1S_0$, triggered by pulsed-laser irradiation that induces the $2s2p\ ^3P_2 \rightarrow ^3P_1$ transition. This measurement provided the experimental values of the transition wavelength of $2s2p\ ^3P_2 \rightarrow ^3P_1$ [3] and the intercombination transition probability of $2s2p\ ^3P_1 \rightarrow 2s^2\ ^1S_0$ [4] by measuring the laser-wavelength dependence and temporal decay of the LIF signal. The intercombination transition probability can be a simple benchmark for theoretical calculations involving spin-orbit interaction in many-electron systems. However, a discrepancy exists between the experimental and theoretical transition probabilities, and the origin of this discrepancy remains unclear. Therefore, a systematic investigation along the Be-like sequence is important to understand the atomic structure of medium- Z ions in detail. As part of this investigation, we selected Be-like Cl^{13+} as the next target and performed emission spectroscopy of the relevant transitions toward future laser spectroscopy.

The energy levels of Be-like Cl^{13+} are shown in Fig. 1. Zhou *et al.* previously observed the extreme ultraviolet (EUV) $2s2p\ ^1P_1 \rightarrow 2s^2\ ^1S_0$ transition to test QED effects [5]. Their results showed excellent agreement between experimental and theoretical values. Here, we present the measurements of the transition wavelengths for (i) the visible M1 transition $2s2p\ ^3P_2 \rightarrow ^3P_1$ and (ii) the EUV intercombination transition $2s2p\ ^3P_1 \rightarrow 2s^2\ ^1S_0$. The experiment was performed with a compact EBIT [6], a Czerny-Turner type visible spectrometer, and a vacuum ultraviolet spectrometer [7]. The measured wavelengths are in reasonable agreement with the theoretical values reported in [5]. These results provide crucial benchmarks for atomic structure calculations.

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Testing strong-field QED to second-order in highly correlated berylliumlike Pb^{78+} by electron-ion collision spectroscopy in CRYRING@ESR

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Using the experimental technique of electron-ion collision spectroscopy at the electron cooler of the heavy-ion storage ring CRYRING@ESR [1] we have measured merged-beams rate coefficients for electron-ion recombination of berylliumlike Pb^{78+} ions. In the electron-ion collision energy range 10–16.5 eV, we have observed $2s2p$ (3P_1) $19l_j$ dielectronic recombination (DR) resonances associated with a $2s^2$ $^1S_0 \rightarrow 2p2p$ 3P_1 core excitation and a simultaneous capture of the initially free electron into the $n = 19$ shell of the boronlike Pb^{77+} product ion (Figure 1). A careful analysis of the systematic experimental errors reveals that the uncertainty of the measured resonance positions amounts to ± 30 meV. This uncertainty is lower than the theoretical uncertainty of the calculation of the $2s^2$ $^1S_0 \rightarrow 2p2p$ 3P_1 excitation energy by Malyshev et al. [2]. By considering second order QED effects and electron-electron correlation effects, which are particularly strong in berylliumlike ions, these authors obtained $E_{\text{exci}} = 244.942(52)$ eV. Within the uncertainties this agrees with our experimental finding [3], which thus constrains second order strong-field QED in a highly correlated atomic system.

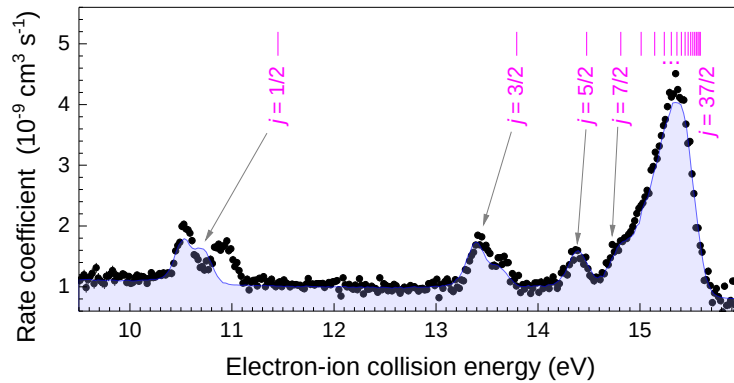


Figure 1: Experimental and theoretical DR rate coefficients exhibiting $2s2p$ (3P_1) $19l_j$ resonances [3].

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Detecting QED deviations in He-like ions: a Bayesian approach for current analysis and future experimental design

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Detailed comparisons between theory and experiment for quantum electrodynamics (QED) effects in He-like ions have been performed in the literature to search for hints of new physics. Different frequentist statistical analyses of the existing atomic transition energy data have shown contradictory conclusions as to the presence of possible deviations from the theory predictions. We present here an approach using Bayesian statistics which allows assigning quantitative probabilities to the different deviation models from theory for He-like ions for $Z = 5$ to 92. Potential deviations beyond the standard model or higher-order QED effects are modelled with $f(Z) \propto Z^k$ functions. Considering the currently available data, no significant difference between theory and experiment is found, and we show that recent experiments have reduced the possible deviations previously observed in the literature. Using past measurements and a weighted average on the different deviation models, we estimate the accuracy required for future measurements to investigate possible divergences.

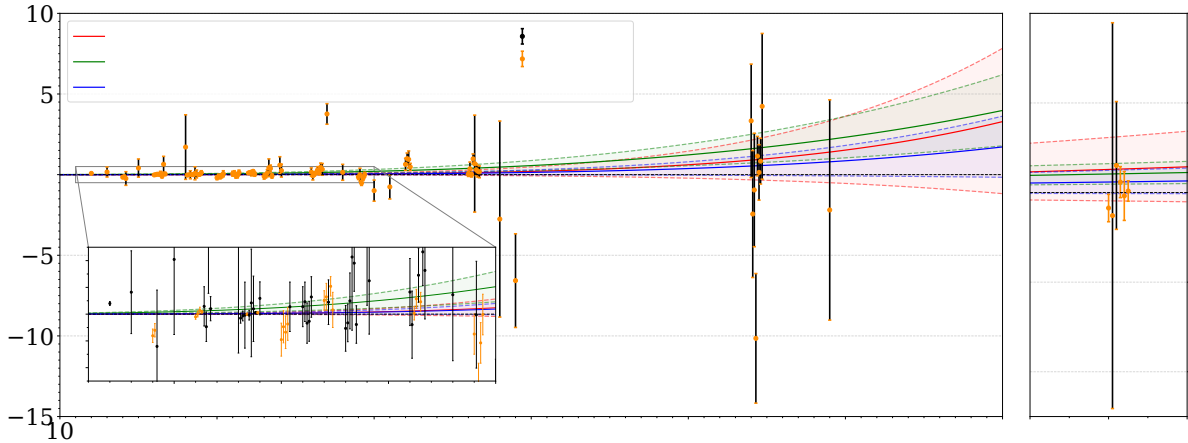


Figure 1: Most probable trend curves $f(Z) \propto Z^k$ for possible deviation from theoretical predictions of the different transitions in He-like ions for different sets of data (w spectral line only or all $n = 2 \rightarrow 1$ transitions, measurement before 2012 for comparison with the literature, etc.). The respective colored shadow regions display a 99% confidence interval for each fit.

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Metastable states in ion beams produced by an ECR ion source investigated by X-ray spectroscopy

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Obtaining accurate measurements of the electronic processes (capture, ionization, excitation) cross sections in ion-ion/atom collisions depends crucially on knowledge of the initial electronic states of the collision partners. The ion sources used for these collision experiments usually generate ion beams that contain not only ions in their ground state but also in a multitude of excited states. Although many of these species decay during the transport between the ion source and the collision chamber, the lifetime of some metastable species is long enough to allow them to reach the collision zone. Different schemes exist to extract the metastable fraction in an ion beam based on Auger spectroscopy techniques [1, 2]. Our installation at INSP is equipped with an ECR ion source delivering keV/u ion beams connected to a beam line that ends up with an experimental chamber. The ions thus travel a distance of 6 m. Our technique for measuring fractions of metastables consists of recording the number of X-rays produced during the ion-atom collision as a function of the atomic pressure in the collision chamber. Under the single-collision conditions, an affine evolution is expected, with a non-zero origin coordinate if metastable ions are present. Figure 1 (Right) shows such an evolution in the case of collisions between Ar^{8+} ions and Ar atoms. Figure 1 (Left) is an example of a X-ray spectrum exhibiting the main $n = 3 \rightarrow n = 2$ transition at 250 eV. In this case, the metastable state involved is the $1s^2 2s^2 2p^5 3s^3 P$ state with a lifetime of 332 μs . An ion fraction of this state of 8.4% is deduced. Measurements with O^{6+} and Ne^{8+} ions will be also presented at the conference.

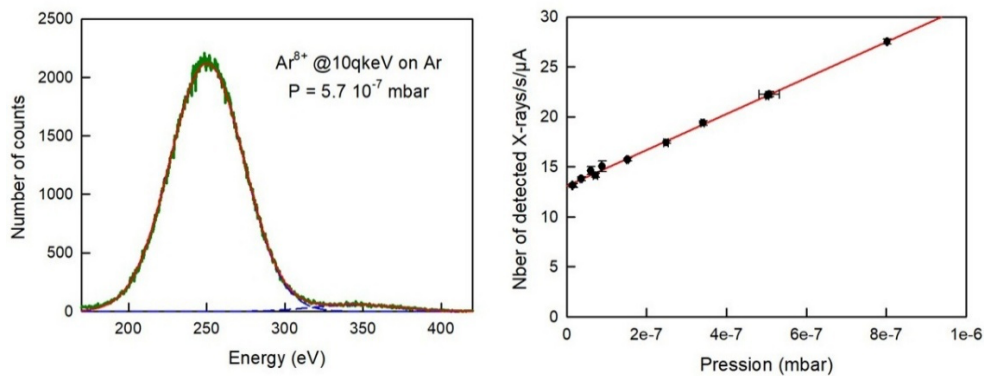


Figure 1: X-ray spectrum recorded at a given pressure (Left) by a solid-state detector. Evolution of the number of recorded X-rays (/s/μA) as a function of the pressure (Right).

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Debris Mitigation in Laser-Produced Sn Plasma by Means of a Hydrogen Atmosphere for EUV Light Sources

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Laser-produced tin plasma is a promising extreme ultraviolet (EUV) light source for next-generation lithography. However, energetic ions, atoms, and particulate debris can degrade collector mirrors and shorten the optical component lifetimes. Hydrogen gas is used as a buffer medium because it reduces Sn ion energy through collisional stopping and modifies charge states via ion–molecule collisions and charge exchange. Therefore, understanding the interaction between expanding Sn plasma and hydrogen gas is essential for optimizing debris mitigation. [1,2]

In this study, laser-produced Sn plasma in a hydrogen atmosphere was investigated using time- and space-resolved visible emission spectroscopy, EUV spectroscopy, and pinhole imaging. A Nd:YAG laser at 1064 nm with a pulse width of approximately 7.6 ns and an energy of approximately 120 mJ was focused onto the Sn slab target. The visible emissions from Sn I, Sn II, and hydrogen Balmer lines were measured using a 50-cm visible spectrometer equipped with an ICCD detector. To examine the pressure dependence of the Sn–H₂ interactions, the hydrogen gas pressure was controlled in the range from 0.1 to 100 Pa using a mass flow control system.

The pressure-dependent Sn I and II emissions were analyzed to examine the charge-state evolution and neutralization of tin species. H α emission was used to evaluate the hydrogen excitation and energy transfer from the expanding Sn plasma. These measurements clarify the roles of ion–molecule collisions, collisional stopping, charge exchange, and recombination in hydrogen-assisted debris mitigation, contributing to the optimization of H₂ gas conditions for EUV-light sources.

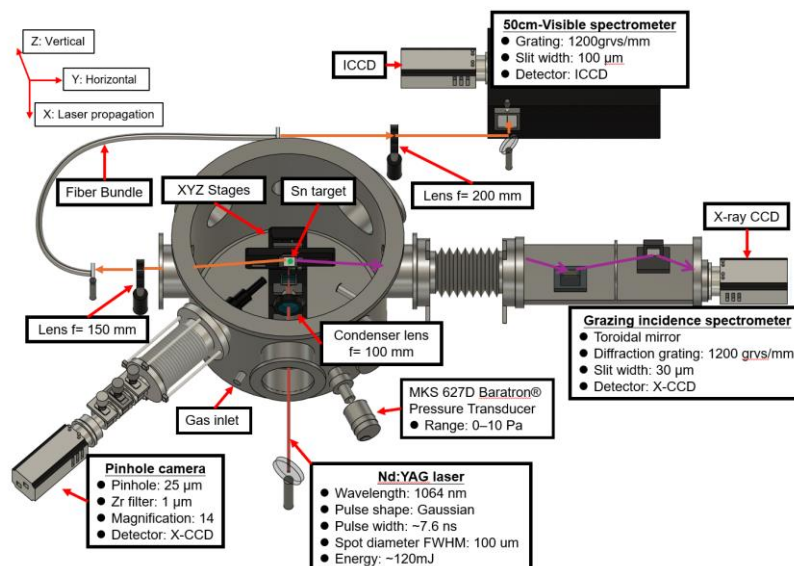


Figure 1. Schematic of the experimental setup for emission spectroscopy of laser-produced Sn plasma in a hydrogen atmosphere.

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Mitigation of Fast Highly Charged Ion Debris from Laser-Produced Tin Plasmas in Hydrogen and Argon Atmospheres

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In extreme ultraviolet (EUV) lithography, a 13.5-nm wavelength is used, which is emitted from highly charged tin (Sn) ions (Sn^{8+} – Sn^{14+}) produced by laser-irradiating Sn droplets [1]. However, fast Sn ion debris severely damages Mo/Si collection mirrors and degrades their reflectivity. To mitigate this, H_2 gas is introduced for deceleration and chemical reactions with hydrogen radicals to form and evacuate SnH_4 gas [1] [2]. However, the current mitigation efficiency remains insufficient. To optimize mitigation, this study aims to measure the charge state and kinetic energy distributions of fast Sn ions under vacuum and H_2 atmospheres and quantitatively elucidate the atomic and molecular processes involved.

The experimental setup is illustrated in Figure 1. A pulsed Nd:YAG laser (1064 nm, 7.6 ns) was focused on a solid plate Sn target at $\sim 10^{11} \text{ W/cm}^2$ to generate highly charged Sn plasmas under H_2 and Ar buffer gases. The fast ion debris was characterized using a Faraday cup and Thomson parabola.

This approach clearly resolves the charge state and energy-dependent attenuation of Sn ions under H_2 and Ar atmospheres. We discuss the mitigation of both elastic momentum loss, recombination, and charge exchange processes due to Sn^{q+} - H_2 or H and Sn^{q+} -Ar collisions. These insights will provide crucial data for collisional/radiative processes in plasmas and clear design guidelines for optimizing debris mitigation in future high-power EUV sources.

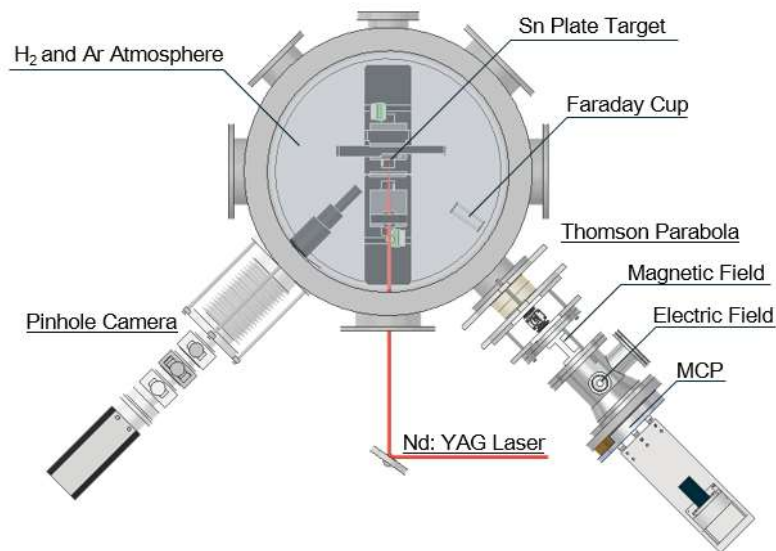


Figure 1. Experimental setup.

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Precision Spectroscopy of Highly Charged Heavy Ions: Towards a Quantum Logic Clock Based on a Cryogenic Monolithic Paul Trap

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Quantum logic spectroscopy (QLS) enables optical clocks based on atomic and molecular ions that lack direct laser cooling or state detection transitions [1]. Consequently, QLS has emerged as a central technique enabling major advances in optical frequency metrology [2–6]. Heavy hydrogen-like and lithium-like ions provide optical transitions with strongly suppressed systematic shifts and enhanced sensitivity to physics beyond the Standard Model [3, 7, 8]. Although substantial progress has been demonstrated in medium-mass highly charged ions (HCIs) such as Ar¹³⁺ [4, 5] and Ca¹⁴⁺ [6], extending QLS to the heaviest HCIs remains an open challenge.

In this contribution, we present a QLS platform under development at GSI in Darmstadt for accelerator-produced heavy HCIs, such as ²⁰⁷Pb⁸¹⁺ [9], featuring optical hyperfine-structure transitions. The setup is located downstream of the HITRAP decelerator, enabling low-energy ion capture in precision traps. Long ion storage times will be achieved using a low-vibration 4 K cryostat [10], developed at the Max Planck Institute for Nuclear Physics, Germany, in combination with a strictly separated ion-trap vacuum system employing cryogenic valves. Furthermore, the setup employs laser systems for in-situ production of the logic ion Be⁺, ground-state laser cooling, and coherent manipulation of qubit and HCI clock transitions. Based on these ingredients, quantum-logic-assisted state preparation and clock state detection will be implemented. An advanced monolithic linear Paul trap is currently being developed in collaboration with the Physikalisch-Technische Bundesanstalt, Germany, and Leibniz University Hannover, Germany. Its design aims to minimize unwanted excess micromotion and thus plays a central role in the suppression of leading systematics.

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Analysis of Visible Forbidden Emission Lines from Highly Charged Tungsten Ions in EAST Plasma

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Tungsten (W) is the leading candidate plasma-facing material for ITER and future fusion reactors. And the transport and control of tungsten ions is one of the critical issues for compatibility of the tungsten divertor and steady-state high-performance plasma sustaining. Visible forbidden lines from highly charged W ions potentially provide a promising diagnostic tool for studying tungsten behavior in fusion plasmas, because intensity of magnetic-dipole (M1) transitions maybe comparable to that of E1 transitions and can be measured with visible spectroscopy using optical fibers.

Visible M1 transitions from W^{26+} have been investigated on EAST [1] using the space-resolved visible spectrometer with 2400 grooves/mm grating [2, 3]. Several previous theoretical studies have reported atomic data for W^{26+} , including calculations based on the relativistic configuration interaction (RCI) method [4] and the multi-configuration Dirac-Fock (MCDF) method with a restricted active-space treatment [5]. In the present work, detailed FAC calculations were performed to interpret the visible spectra observed on EAST. The W^{26+} energy levels were calculated using the relativistic many-body perturbation theory (RMBPT) method, and the corresponding radiative transition data, including E1, M1, E2, and M2 transitions, as well as electron-impact excitation and de-excitation processes, were incorporated into a collisional-radiative model (CRM). The level populations and photon emission coefficients (PECs) of the visible M1 transitions were then obtained under EAST-relevant plasma conditions. Finally, radial ion density distributions of W^{26+} were derived from the vertical profiles of the M1 line intensities on a horizontally elongated poloidal cross section, together with the calculated PECs and the experimental electron temperature and density radial profiles. These results demonstrate the potential of visible M1 spectroscopy as a quantitative diagnostic method for highly charged tungsten ions in EAST plasmas.

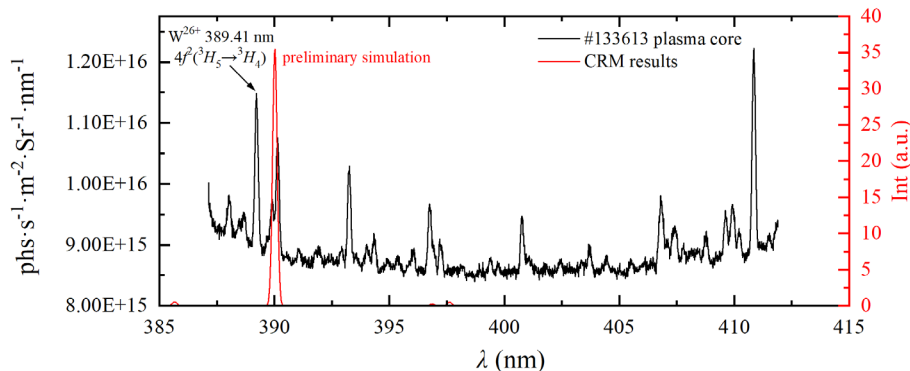


Figure1. Comparison between the measured visible spectrum in the plasma core of EAST discharge #133613 and the CRM calculated W^{26+} M1 emission.

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QED Corrections and Muonic Cascade Simulation: from ^{208}Pb to ^{238}U

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Muonic atoms are known to be the most sensitive probes of nuclear structure. By comparing theoretical predictions with experimental X-ray spectra, one can extract nuclear properties such as the charge distribution parameters and the root-mean-square (rms) charge radius. Recently, a wide experimental campaign for heavy muonic systems has been announced by the MuX collaboration [1].

A recent reanalysis of muonic ^{208}Pb , which employed improved QED calculations including the Wichmann-Kroll vacuum polarization [2] and the hadronic vacuum polarization [3], yielded $r_{\text{rms}} = 5.5062(5)$ fm — a value 3σ – 4σ larger than the commonly accepted tabulated result [4]. A similar approach was used to obtain new rms values for other magic nuclei, ^{90}Zr and ^{120}Sn [5].

To extend this approach to arbitrary nuclei, however, one also needs to account for the dynamical hyperfine structure arising from the coupling of the muonic and nuclear subsystems. We use muonic ^{238}U as a benchmark system, where both experimental spectral data and reference theoretical calculations from [6] are available for direct comparison. We have developed a new muonic cascade simulation code in Python, which combines a Monte Carlo simulation of the cascade process with a treatment of the hyperfine structure including electric quadrupole and hexadecapole interactions. The comparison of our results with the reference data shows agreement at the level of 0.1–0.4 keV (below 0.01%) in line positions and within 2% in relative intensities, validating the correctness of our approach. The code will be applied to heavy muonic systems of direct relevance to the MuX experimental program.

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Dissociation Dynamics of Gas-Phase Ferrocene Probed by Coulomb Explosion Imaging

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We employ Coulomb explosion imaging to investigate the ultrafast dissociation of gas-phase ferrocene driven by intense femtosecond laser-field. The experiments were performed using 26 fs, 800 nm laser pulses at a 1 kHz repetition frequency and an average power of 50 mW. The fragment ions were detected by time-of-flight (TOF) mass spectrometry and photoion-photoion coincidence (PIPICO) map. Coincident analysis reveals that ferrocene dissociates primarily through two two-body channels [1]: $C_5H_5^+ + FeC_5H_5^+$ corresponding to the direct cleavage of one cyclopentadienyl-iron bond; and $Fe^+ + (C_5H_5)_2^+$ representing a dissociation pathway where the iron atom is detached and two cyclopentadienyl rings combine to form a dimer cation. This study observes the cleavage process of the metallocene coordination bonds and provides direct dynamical insights into the photophysics and photochemistry of organometallic complexes [2].

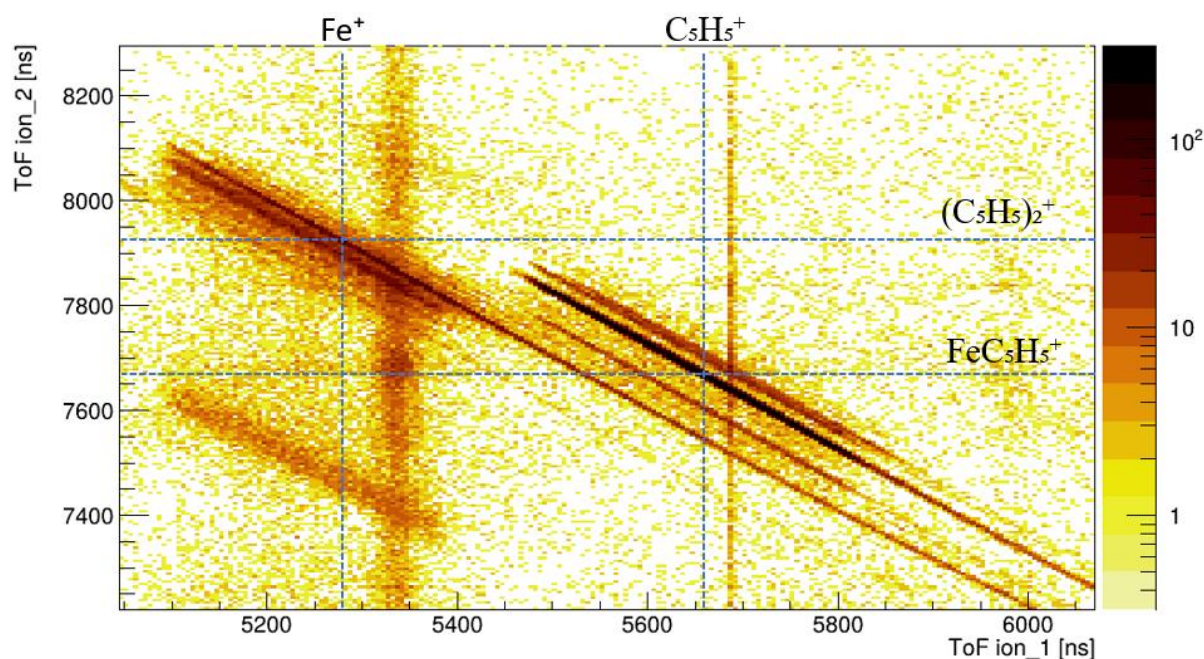


Figure 1. PIPICO map of ferrocene.

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Advance in direct nuclear reaction studies with in-ring reaction spectrometer at HIRFL-CSR

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In-ring reaction experiments serve as a powerful tool for studies in nuclear structure and nuclear astrophysics. Featuring low background and low-momentum sensitivity, this novel method allows high-resolution measurements of direct nuclear reactions in inverse kinematics at very low-momentum transfer. The cooler storage ring at the heavy ion research facility in Lanzhou (HIRFL-CSR), as an internationally representative facility, provides an opportunity for performing in-ring direct nuclear reactions with an internal gas target. Over the past decade, we have built an in-ring reaction spectrometer and performed successfully several measurements on elastic proton-nucleus scattering at low-momentum transfer at HIRFL-CSR. Recently, elastic proton scattering experiment on stable ^{112}Sn nucleus was also conducted to obtain its matter radius. The latest technological advance is the development of a ultra-low background technological for light-ion productions detection, to achieve nuclear reactions measurements involving unstable nuclei. In this paper, we report the technological development of in-ring reaction spectrometer and the corresponding elastic proton scattering experiments at HIRFL-CSR. Finally, future research plans on the matter radii measurements of the N=20 isotones ^{38}Ar and ^{36}S nuclei are also introduced.

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H_3^+ Formation through Three-Body Dissociation of Excited Ethane Dication

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As the simplest polyatomic molecular ion and one of the most abundant molecular ions in the universe, H_3^+ is considered an important proton donor in interstellar chemistry. This ion can be generated from the fragmentation of organic molecular dications [1], in which two main formation pathways have been observed [2]: the minimum energy path based on transition state (TS) theory and a roaming mechanism involving H_2 . Both mechanisms are believed to start from the ground state of the parent dication [3], as ground states have barriers that prevent instantaneous fragmentation, allowing sufficient time for energy redistribution and H_3^+ evolution. In contrast, the excited states, with high internal energy and repulsive potential energy surfaces, were thought to induce direct dissociation of C-C bonds or of C-O bonds, quenching the formation of H_3^+ [4].

In this study, we explore H_3^+ formation from the excited states of ethane dication. We perform electron collision ionization experiments on ethane using a reaction microscope and obtain three-dimensional momentum information for all fragments. The detailed analysis of the momentum correlation among these fragments is conducted using Dalitz plots and Newton diagrams. Combined with static energy calculations of transition states and ab initio molecular dynamics simulations, the corresponding dynamic mechanism is determined. We reveal that the sequential fragmentation mechanism serves as an energy dissipation pathway for the excited-state parent ion $\text{C}_2\text{H}_6^{2+}$; via the emission of an H atom in the first step, metastable precursors of $\text{C}_2\text{H}_5^{2+}$ ions are formed and ultimately dissociate into H_3^+ .

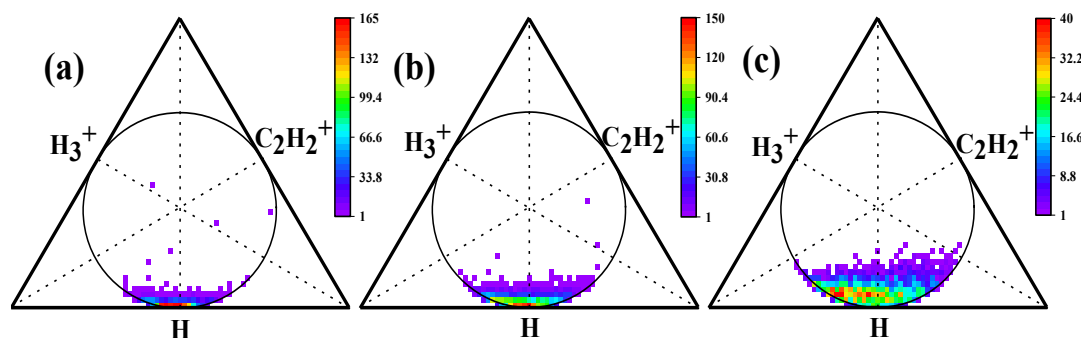


Figure 1. Dalitz plots for $\text{C}_2\text{H}_2^+/\text{H}_3^+/\text{H}$ ion pair from $\text{C}_2\text{H}_6^{2+}$ parent ion. Panels (a), (b), and (c) correspond to KER ranges of 0–5 eV, 5–6.5 eV, and 6.5–11 eV, respectively.

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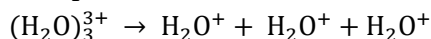
Laser-Induced Coulomb Explosion Imaging of Water Trimers

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Molecular clusters bridge isolated molecules and condensed-phase matter, making them ideal systems for studying weak intermolecular interactions, energy redistribution, and charge migration. Water clusters are especially important as prototypes of hydrogen-bond networks, providing microscopic insight into liquid water, aqueous environments, and water-mediated biological processes. Previous infrared spectroscopic studies have provided important insight into the hydrogen-bond structures and size-dependent evolution of neutral water clusters.[1] Recent time-resolved ion coincidence measurements on water dimers further demonstrated that the kinetic energy release and correlated fragment-ion signals can directly track ultrafast proton transfer and geometrical rearrangement after ionization.[2] Here, we investigate laser-induced Coulomb explosion of water trimers using COLTRIMS reaction microscope spectrometer. Neutral water clusters are generated by supersonic expansion and intersected with intense femtosecond laser pulses in the interaction region. The ionic fragments are detected in coincidence enabling event-by-event reconstruction of their three-dimensional momenta.

We observed the three-body breakup channel of the water trimer,



The Newton diagram and the kinetic energy release distribution were obtained for this channel. The Newton diagram shows a clear triangular momentum-correlation pattern, which is consistent with Coulomb explosion from a triangular arrangement of the water trimer.

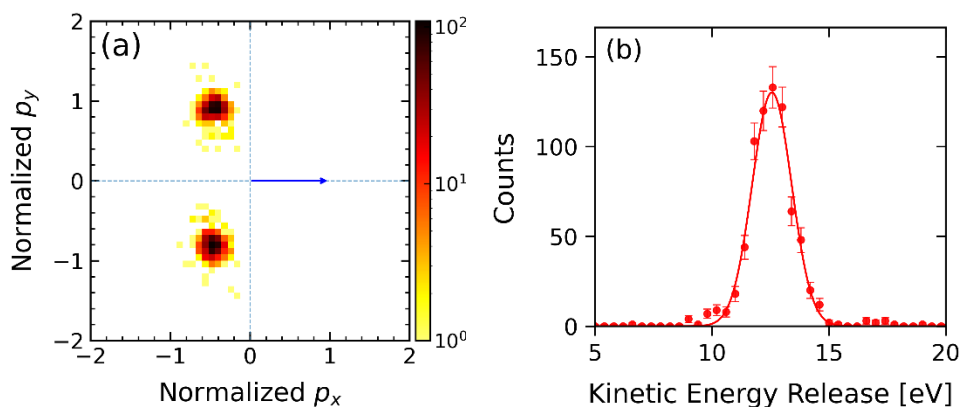


Figure. 1. (a) Newton diagram and (b) kinetic energy release distribution of $(\text{H}_2\text{O})_3^{3+} \rightarrow 3\text{H}_2\text{O}^+$

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Electron capture cross-sections for slow highly charged Xe^{q+} ($q = 24-30$) ions interacting with N_2 gas target.

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The study of charge exchange processes between slow highly charged ions and neutral gas targets has gained significant attention due to its wide range of applications, including fusion plasma diagnostics, EUV lithography [1] and understanding of inelastic processes in materials [2,3].

In this work we investigated charge exchange processes of highly charged Xe^{q+} ($q=24-30$) ions at kinetic energies of $4.4 \times q$ keV interacting with N_2 gas target. An electrostatic analyser detects the charge state distribution of the transmitted ions, across a range of different target gas pressures. Single and multiple electron capture cross-sections are extracted using both the growth rate method in the thin target regime and a coupled rate equation framework applied to the full pressure evolution of the charge state distributions. The results are compared with scaling law predictions to examine the relative contributions of sequential single electron capture and direct multi-electron capture processes.

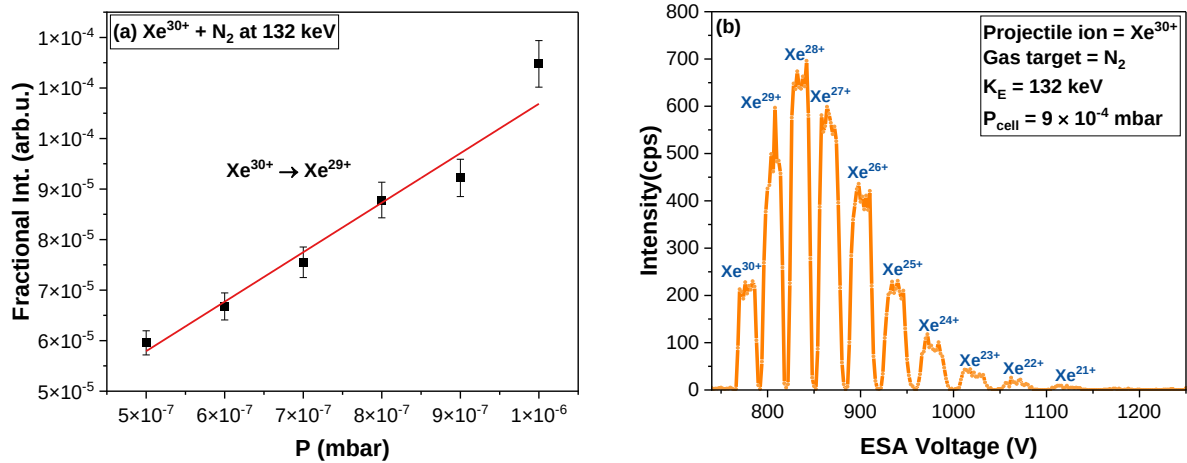


Fig1: (a) Pressure dependence of the fractional intensity of transmitted Xe^{29+} ions at 132 keV during interaction with N_2 gas target and (b) Charge state distribution of incident Xe^{30+} ions during interaction with N_2 gas target at 9×10^{-4} mbar.

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Test of the many-electron bound-state quantum electrodynamics model with Co-like ions

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Accurate QED calculations for many-electron systems remain challenging. Co-like $3d^9$ highly charged ions with Layzer-quenched configurations provide favorable systems for investigating bound-state QED effects because of their reduced correlation contributions. Here, we report direct measurements of the $3d^9\ ^2D_{3/2}-^2D_{5/2}$ transition energies for Co-like ions with $Z=38-46$. An average precision better than 10 ppm was achieved. Small discrepancies between the present measurements and available theoretical calculations are observed[1][2]. The present measurements provide important experimental data for testing QED effects in relativistic many-electron systems.

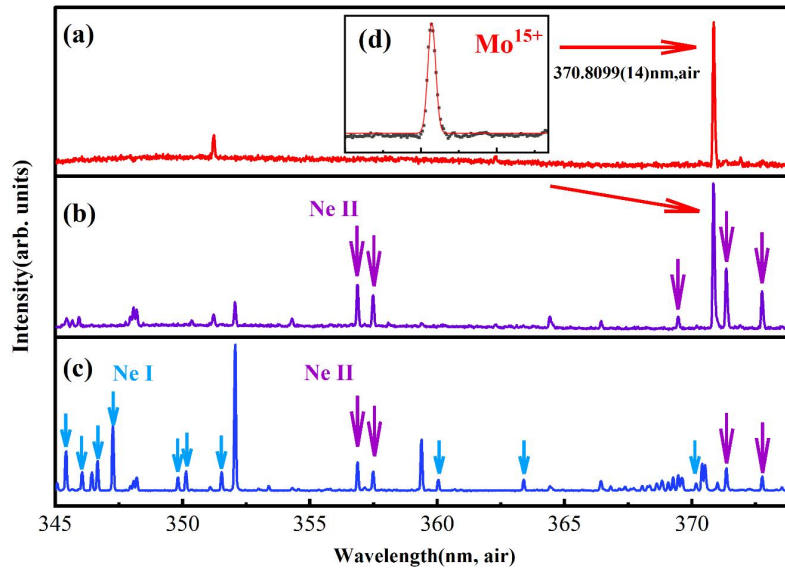


Figure 1. (a) Typical spectrum obtained with simultaneously Mo injection at the electron energy of 480 eV. Peaks marked with red arrow was Mo¹⁵⁺ lines. (b) The spectrum of Mo with neon injection at the same energy. Peaks marked with purple arrow were Ne II lines used for wavelength calibration verification. (c) Calibration spectrum of the V-Ne hollow cathode lamp. Peaks marked with purple arrow were Ne II, peaks with blue arrow were Ne I lines. (d) Gaussian fit (red curve) of the Mo¹⁵⁺ line.

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Chirality Switching in $1T$ -TaS₂ with Slow Highly Charged Ions

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Ions in elevated charge states at keV energies can interact predominantly with the electronic system of a surface upon impact. Heavy highly charged ions (HCIs) can carry a potential energy of several keV, which is the sum of the ionization potentials needed to reach a certain charge state. Upon neutralization, the potential energy is released by surface electron emission and excitation [1]. HCIs are known for their surface sensitivity in creating permanent nanostructures at insulating bulk surfaces [2] and in perforation of freestanding transition metal dichalcogenide 2D materials [3].

We used a combination of an HCI source, providing 22.5 keV Xe⁸⁺ ions, and an angle-resolved photoelectron spectroscopy (ARPES) setup at the P04 soft X-Ray beamline of the PETRA III synchrotron at DESY. With this setup we performed *operando* ion beam irradiation of the surface of a $1T$ -TaS₂ bulk sample at 50 K, i.e. in the commensurate charge density wave phase (cCDW). The cCDW was confirmed by ARPES and the influence of the ion beam on the material's band structure was monitored continuously.

The cCDW on $1T$ -TaS₂ is a static electron density modulation along the surface, which has a relative orientation, i.e. handedness/chirality, to the atomic surface structure. We observe a gradual chiral switch from one to the other handedness with increasing ion fluence (ions per area) up to a full switch of the chirality [4]. From the gradual change in the photoelectron intensity across the k -space with applied ion fluence we can determine the switching cross section per ion of ~ 250 nm². This value is in good agreement with the energy barrier between the two chiral orientations (200 meV/Ta) compared to the potential energy of Xe⁸⁺ (417 eV), which was used for the experiment. Even more so, the potential energy and cross section per ion yield an energy density of about 0.03 mJ/cm², well comparable to known laser fluences in optically-driven chiral switching. Our results show that strong electronic excitations are a universal tool to drive phase transitions in quantum materials, adding ion beams to the available toolbox. Ion beams may further enable nanoscale control of heterochiral structures, an interesting testbed for novel quantum material properties.

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Precision mass measurements of heavy highly charged ions

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In a Penning trap, a mass is determined by measuring the free cyclotron frequency of an ion in a strong magnetic field. It can be used to measure mass ratios to high precisions with relative uncertainties of 10^{-11} . Such measurements can find applications, among others, in neutrino physics [1], searches for physics beyond the Standard Model [2] and in tests of bound state quantum electrodynamics (QED).

We are presenting the design of a new Penning trap experiment, which will be set up at GSI Helmholtz Center for Heavy Ion Research in Darmstadt to perform precision mass measurements with heavy and highly charged ions (for e.g.: U^{92+} or U^{91+}), either from local ion sources or the accelerator facility. The latter allows for the first time to test QED in strong fields by determining the binding energy of electrons in heavy, highly charged ions with high precision mass measurements. The local ion source, an electron beam ion trap (EBIT) [3], provides ions in lower charge states.

The trap design includes four cylindrical traps, each with seven electrodes, which allows us to measure different ion species simultaneously. The trap setup will be cooled down to cryogenic temperatures with a liquid helium reservoir. Motional frequencies of the ions will be determined using dedicated image current detection system. The local ions from the EBIT will be used for performing measurements with ions of lower charge states for various applications.

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Linear polarization of 3B and 3C lines following electron-impact excitation of Ne-like ions Ba⁴⁶⁺ to Pb⁷²⁺

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Ne-like ions are of great importance in atomic physics, x-ray astrophysics, plasmas and fusion research [1]. For the unique closed shell structure, Ne-like ions offer a stable state for various fundamental studies. Besides, the stable state result in a widespread existence in a broad range of plasma temperatures and densities. Therefore, x-ray lines emitted from Ne-like ions are often used for diagnosing the state parameters of fusion and astrophysical plasmas [2]. To get an accurate diagnosis, reliable calculations and simulations are necessary, with comprehensive and precise treatment of various physical effects.

We present a systematic theoretical calculation on the polarization of spectral lines emitting following the electron-impact excitation of Ne-like isoelectronic sequence ions, using the configuration-interaction plus many-body perturbation theory method and density matrix theory. The electron-impact excitation process of interest is from their ground state to the excited levels $[(2p^5)_{1/2}3d_{3/2}]_{J=1}$ and $(2s_{1/2}3p_{1/2})_{J=1}$, which are the upper levels of 3B and 3C lines, respectively. It has been found that the linear polarization of the 3B line is extremely sensitive to the configuration mixing effect, while that of the 3C line is not affected much by the mixing. Specifically, the aligned upper level of 3B line is significantly weakened by the strong configuration mixing around $Z=68$, driving a more than 110% depolarization.

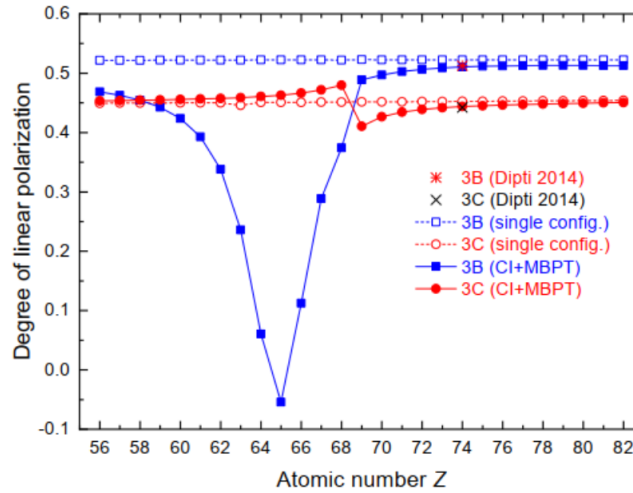


Figure 1. The degree of linear polarization of the 3B and 3C lines as function of the atomic number Z . Other available results of Wu^{64+} ($Z=74$) ion from Dipti *et al.* [3] are also shown for comparison.

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Candidate Charge-Exchange-Induced Rydberg Transitions of Highly Charged Tungsten Ions Observed in LHD Plasmas

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Tungsten spectroscopy is essential for fusion plasma diagnostics because tungsten can cause substantial radiative losses even at low concentrations in the core plasma. In the Large Helical Device (LHD), many visible emission lines from highly charged tungsten ions have been observed after tungsten pellet injection, but several lines remain without firm transition assignments [1].

Charge exchange between highly charged tungsten ions and energetic neutral hydrogen atoms from neutral beam injection can populate high-lying Rydberg states, leading to visible emission through radiative cascades. Such transitions have been identified in JET spectra and suggested as possible origins of some unidentified LHD tungsten lines [2]. Here, we analyse visible spectra from additional LHD discharges with tungsten injection. Several unidentified lines are found to agree well in wavelength with Rydberg transitions of tungsten ions in charge states expected for the electron-temperature range of the core plasma (Figure 1). This suggests that part of the unidentified visible tungsten spectrum may arise from Rydberg-state transitions rather than ordinary low-lying magnetic-dipole (M1) transitions. We also reconstruct the spatial emission distributions from line-integrated intensities using Gaussian process regression, accounting for the poloidal magnetic flux-surface geometry. The inferred profiles are compared with the expected formation regions of the relevant charge states, providing an additional constraint on the proposed assignments.

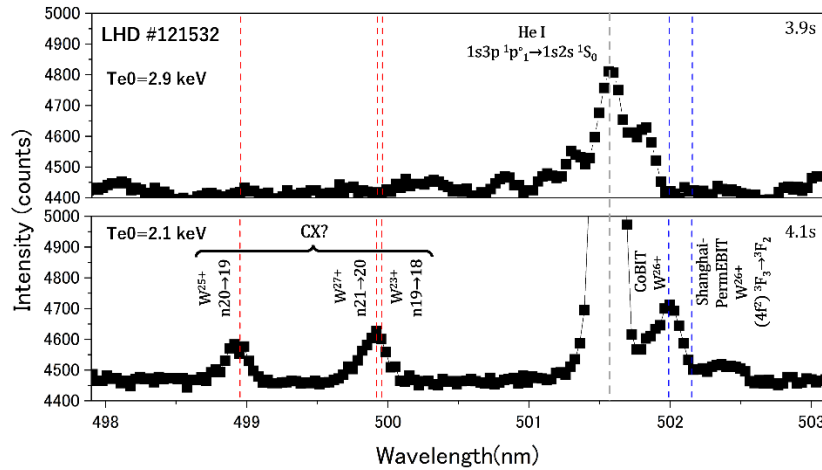


Figure 1. Visible spectra from an LHD tungsten-pellet injection discharge before (upper) and after (lower) tungsten injection. Blue dotted lines indicate EBIT wavelengths [3,4] assigned to ground-configuration M1 transitions of W^{26+} , and red dotted lines indicate candidate transitions along the yrast Rydberg sequence.

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High-resolution charge-exchange X-ray spectra from Fe^{25+} -He collisions

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Charge exchange (CX) X-ray spectroscopy is a vital diagnostic tool for astrophysical and fusion plasmas. We conducted Fe^{25+} -He CX experiment at the Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, using a TES microcalorimeter. Figure 1 shows a typical X-ray spectrum from Fe^{25+} -He collisions at 1.79 keV/u. The z , y , x , and w lines of the $\text{He}\alpha$ multiplet are fully resolved, together with $\text{He}\beta$ - $\text{He}\kappa$ lines corresponding to high- n transitions ($1snp-1s^2$, $n = 3-11$), which contribute less than 5% of the total emission. The observed $\text{He}\eta$ - $\text{He}\kappa$ lines arise almost purely from direct single CX decay, while $\text{He}\alpha$ - $\text{He}\zeta$ lines reflect a cascade dominated by single CX with additional double CX contributions. The line profiles were fitted using the Bortels function due to the distinct low-energy tail, which arises from incomplete thermalization in the TES bismuth absorber [1]. The resulting FWHM is ~ 8 eV at 6.7 keV. The present work improves our understanding of CX collisions, provides valuable experimental benchmarks for Fe XXV CX models at keV/u, and facilitates CX diagnostics for high-resolution X-ray observatories like XRISM and Athena.

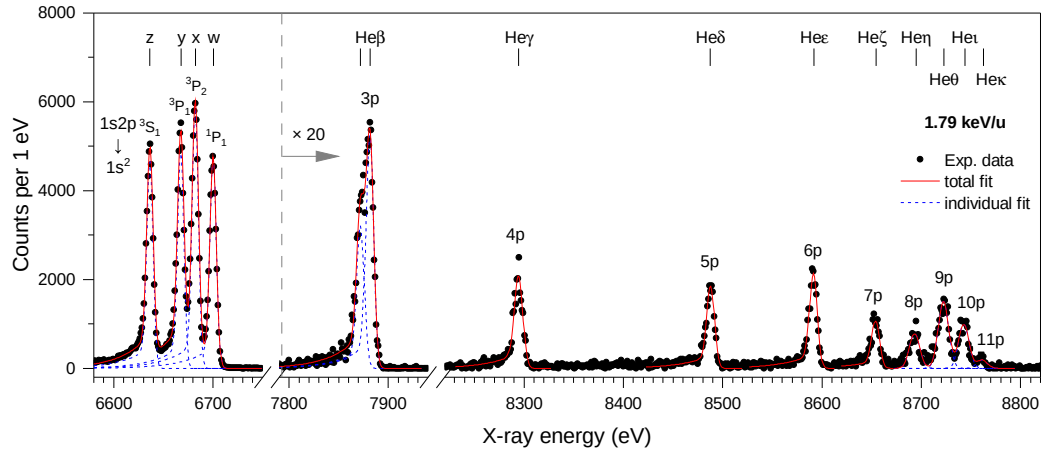


Figure 1: Typical CX X-ray spectrum from Fe^{25+} -He collisions at 1.79 keV/u. Solid circles denote the experimental data. Red and blue lines represent spectral fitting curves obtained by the Bortels function for $\text{He}\alpha$ - $\text{He}\epsilon$ lines and Gaussian function for $\text{He}\eta$ - $\text{He}\kappa$ lines. Vertical lines mark the positions of all spectral features.

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Decay dynamics of neon dimers induced by low-energy heavy ions

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Using a cold-target recoil-ion momentum spectrometer [1, 2], we investigated decay dynamics in low-energy collisions of 15 keV/u O⁶⁺ ions with Ne₂. Correspondingly, the kinetic energy release (KER) spectra were obtained (Fig. 1): the left panel presents the KER distribution for the Ne⁺+Ne⁺ dissociation channel, while the right panel displays the KER spectrum for Ne²⁺+Ne⁺.

Four distinct peaks (A, B, C, and D) are observed in the left plot for Ne⁺+Ne⁺. According to potential energy curves [3], Peak A (4.5 eV, 3.2 Å) results from interatomic Coulombic decay (ICD) and direct Coulomb explosion (CE), while Peak B (7.2 eV, 2 Å) originates from radiative charge transfer (RCT). Peak C (8.5 eV, 1.7 Å) and Peak D (9.7 eV, 1.5 Å) occur at higher KER, corresponding to short internuclear distances per the reflection approximation, which are attributed to the radiationless charge transfer [3].

Three peaks (A, B, and C) are also observed in the right plot for Ne²⁺+Ne⁺. Based on potential energy curves, Peak A (9 eV, 3.2 Å) is contributed by CE and direct ICD (d-ICD). The other two weak peaks, B (13 eV, 2.21 Å) and C (16 eV, 1.8 Å), are prominent in pure capture and lie in the high-KER region. So, they are assigned to charge transfer via nonadiabatic coupling, namely the radiationless charge transfer [3, 4].

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Guiding Fast Highly Charged Ions in Macroscopic Capillaries by Suppressing Secondary Ion Sputtering

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The self-organized guiding of ion beams through insulating capillaries has attracted significant interest for developing passive ionic fibers. However, guiding fast ions (keV/ q and above) in capillaries has long been hindered by premature saturation of the deflection potential, limiting deflection angles to below 1° [1]. In this work, we identify that secondary ion sputtering from the inner capillary walls is the dominant mechanism responsible for charge redistribution and field saturation. These sputtered secondary ions are accelerated by the guiding field and deposit charge onto the opposite wall, effectively canceling the desired deflection potential.

To suppress this charge spraying, we introduce grooved inner surfaces that reabsorb secondary ions and minimize cross-wall charge transfer. Combined with externally connected resistors to stabilize surface conductivity against ion irradiation, our macroscopic guiding channel achieves a stable deflection potential exceeding 1 kV — a two-order-of-magnitude improvement comparing to previous stable guiding experiments [2]. Using a 20-keV/ q O^{5+} beam, we demonstrate beam steering at offset angles up to 15° , with transmitted ions retaining their initial charge state and energy. The transmission current reaches hundreds of nanoamperes, three orders of magnitude higher than typical picoampere levels in prior stable guiding studies.

We further present a self-consistent field model that incorporates ion-induced charge spraying, accurately reproducing experimental results and offering a robust design framework for optimizing resistor networks under withstanding-voltage constraints. Our findings resolve a long-standing limitation in fast-ion capillary guiding and lay the groundwork for developing passive, adaptive ionic fibers for compact ion-beam applications.

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Two-body fragmentation dynamics of NO^{q+} ($q=2-6$) induced by 0.25-MeV/u C^{2+} impact

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We investigate the fragmentation dynamics of NO^{q+} ($q=2-6$) ions produced by 0.25-MeV/u C^{2+} impact. The experiment was performed using a COLTRIMS setup at Sichuan University [1, 2, 3, 4]. The ion-ion time-of-flight (TOF) coincidence map is shown in Fig. 1(a). Three-dimensional momenta of correlated fragments were reconstructed to obtain channel-resolved kinetic energy release (KER) spectra and relative intensities. A key difficulty is the fragment identification in channels with nearly identical mass-to-charge ratios. This occurs in the $\text{NO}^{2+} \rightarrow \text{N}^+ + \text{O}^+$ channel, where the detection sequence cannot be determined directly from the TOF map. To solve this problem, we developed a momentum-angle correlation method, as shown in Fig. 1(b). This method separates the two possible detection sequences and enables reliable KER reconstruction.

The reconstructed KER spectrum of the $\text{N}^+ + \text{O}^+$ channel is shown in Fig. 1(c). It shows a main peak near 9 eV, a shoulder from 12 to 19 eV, and weak structures below 6 eV, indicating contributions from several dissociative electronic states. For NO^{3+} , the $\text{N}^{2+} + \text{O}^+$ channel is about twice as intense as the $\text{N}^+ + \text{O}^{2+}$ channel. For higher charge states, the fragmentation channels of NO^{4+} - NO^{6+} are identified. NO^{4+} is dominated by $\text{N}^{2+} + \text{O}^{2+}$, NO^{5+} mainly dissociates into $\text{N}^{3+} + \text{O}^{2+}$ and $\text{N}^{2+} + \text{O}^{3+}$, and NO^{6+} only produces $\text{N}^{3+} + \text{O}^{3+}$. The branching ratios reveal a tendency toward charge-symmetric fragmentation at high charge states. In asymmetric channels, the positive charge is preferentially localized on the nitrogen fragment.

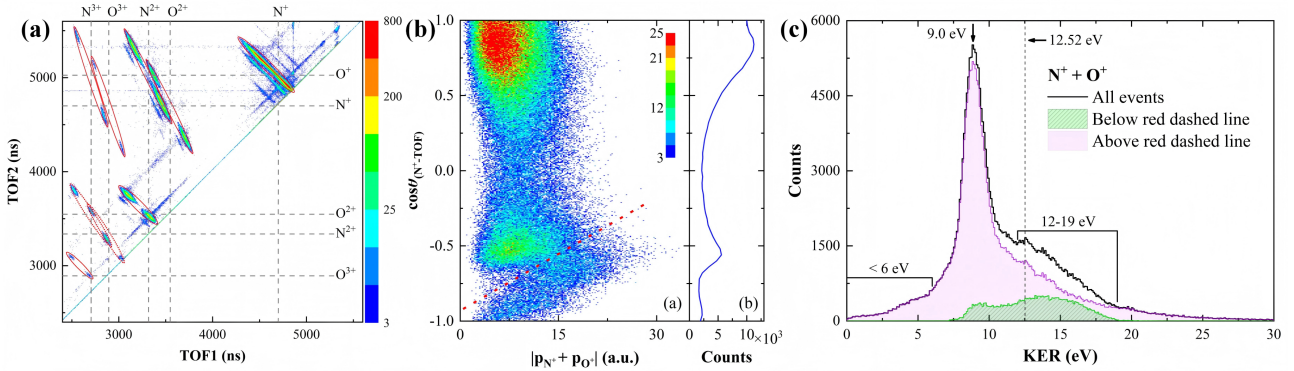


Figure 1: (a) Ion-ion TOF correlation map. (b) Momentum-angle correlation map for the $\text{N}^+ + \text{O}^+$ channel. (c) KER spectrum of the $\text{N}^+ + \text{O}^+$ channel.

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Studies on molecular fragmentation dynamics induced by ion collisions using a 3 MV tandetron accelerator

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Ion-induced molecular fragmentation dynamics is a frontier research area in the field of atomic and molecular physics. Relevant research achievements provide essential foundational underpinnings for such domains as radiation biological effects, interstellar molecular evolution, and fusion plasma physics. Fast ion collisions can efficiently produce multiply charged molecular ions. However, key scientific issues including the mechanisms of chemical bond breaking induced by such collisions, ultrafast hydrogen migration dynamics, and the competition mechanisms between concerted and sequential fragmentation still lack systematic experimental investigations and clear mechanistic explanations.

Based on the 3 MV tandetron accelerator and the cold-target recoil-ion momentum spectroscopy (COLTRIMS) [1] at Sichuan University, we have systematically conducted studies on ion-induced molecular fragmentation dynamics in the several-MeV energy range. The three-body fragmentation dynamics of propene trications $[(\text{H}_3\text{C}-\text{CH}=\text{CH}_2)^{3+}]$ induced by 1-MeV/u C^{4+} ion impact is investigated [2]. Complete kinematical information is obtained for four three-body fragmentation channels: $\text{H}^+ + \text{CH}_2^+ + \text{C}_2\text{H}_3^+$, $\text{H}^+ + \text{CH}_3^+ + \text{C}_2\text{H}_2^+$, and the channels involving H_2^+ production, i.e., $\text{H}^+ + \text{H}_2^+ + \text{C}_3\text{H}_3^+$ and $\text{H}_2^+ + \text{CH}_2^+ + \text{C}_2\text{H}_2^+$. By analyzing the fragment momentum correlations visualized in Dalitz plots, Newton diagrams, and native frames, each channel exhibits two distinct sequential processes, with a concerted process uniquely identified in the $\text{H}_2^+ + \text{CH}_2^+ + \text{C}_2\text{H}_2^+$ channel. The sequential pathways with CH breakage prior to CC breakage predominate in the channels $\text{H}^+ + \text{CH}_2^+ + \text{C}_2\text{H}_3^+$ and $\text{H}^+ + \text{CH}_3^+ + \text{C}_2\text{H}_2^+$. Due to comparable timescales, the H_2 formation kinetically competes with the molecular fragmentation. This competition enables fragmentation pathways featuring initial H_2^+ emission, which contribute to two H_2^+ production channels.

Our studies [3, 4] have unambiguously revealed that ion collisions in the MeV and keV energy regimes exhibit significant dynamical differences, systematically elucidated the dynamical laws governing several-MeV ion-induced fragmentation of small molecules and hydrocarbon molecules, and provided critical experimental evidence and mechanistic explanations for relevant application fields.

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Status of the development of NIFS-EBIT

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An electron beam ion trap (EBIT) is a powerful tool for studying highly charged ions (HCI). Over the past three decades, several EBITs have been commissioned in Japan. In recent years, Tokyo-EBIT [1], CoBIT-I [2], CoBIT-II [3], and JAXA-EBIT [4] have been actively operated. Recently, we started the development of a new EBIT, NIFS-EBIT, at National Institute for Fusion Science (NIFS).

NIFS-EBIT has been designed for the production of few-electron heavy HCIs, such as H-like, He-like, and Li-like ions, using a high-energy, high-density electron beam. NIFS-EBIT has an option to use a hollow cathode for active spectroscopic methods such as laser spectroscopy [5] and synchrotron radiation spectroscopy [6]. By employing a cryogen-free superconducting magnet, it can potentially be installed at synchrotron radiation facilities.

In this poster, we will report details of the ongoing developments.



Figure 1. A vacuum chamber (Left) and a cryogen-free 5 T superconducting magnet (Right) for NIFS-EBIT.

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Estimation of Mean-Charge-State of energetic projectile ions inside the target sample using Electron-Capture Mechanism

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The knowledge of the dynamics of the projectile charge-states inside a target material has become increasingly important in various fields of physics. The projectile ions interact with the material while passing through the target and reach to an equilibrium charge-state through charge-exchange procedure due to repeated interaction on the way which could be named as mean-charged-state (mcs). However, most of the empirical models that have been [1–5] derived from experimental data essentially measure the projectile mean charge state after exiting the target material. But during the exit from the target the charge-state alters from this equilibrium value due to surface effect of the target material. Fermi-Gas model [6] is the only exception where the Fermi velocity of the target material and electron-density enhancement factor γ is used to determine the inside mean-charge-state. Experimental approach in this regard has not almost been done except for Sharma et al. [7] where the group has studied projectile X-ray spectra to understand the projectile charge state dynamics inside the target sample. However, the drawbacks in this approach are the necessity of crystal spectrum meter for precise peak position measurement which is time consuming and multiple vacancy creation in the projectile ion is necessary for not losing information about any charge state. So, our goal is here to take an indirect approach to determine the mean-charge-state inside the solid target material through determination of Electron-Capture cross-section, which depends on the fractional distribution of charge-state inside the target sample. For inside charge-state we have taken into account the Fermi-Gas-model which is a function of γv_F and by tuning the γ factor the mcs can be determined. We have tried to make a consistent relationship between inside and outside mean charge state by considering a fitting function of γ and fitted it with one of the most recent empirical models established on the basis of more than 800 data points namely Schiwietz Model [5] and the fluctuation has been seen to be not more than 2%.

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Design and commissioning of the third Japanese compact electron beam ion trap: CoBIT-III

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Spectroscopic studies of moderate charge state ions have recently become important due to a variety of applications, such as plasma diagnostics of fusion reactors [1], developments of short-wavelength light sources [2], and investigations of HCI atomic clock transitions [3]. Compact electron beam ion traps (compact EBITs) that can operate at low electron-beam energies are useful devices for emission or laser spectroscopy of moderate charge state ions. In Japan, two compact EBITs: CoBIT-I at the University of Electro-Communication (UEC) in Tokyo [4] and CoBIT-II at the National Institute for Fusion Science (NIFS) in Gifu [5], have been actively operated.

Recently, we started the development of the third Japanese compact EBIT (CoBIT-III) at Tokyo University of Science (TUS). CoBIT-III has specifications similar to those of CoBIT-I and CoBIT-II, but it employs a flat cathode, which differs from the previous electron-gun design. Recently, we achieved the first-beam operation and observed visible emission spectra from Xe HCIs. CoBIT-III has an option to use a hollow cathode for laser spectroscopy. The collinear geometry of the laser and electron beams is expected to provide higher-statistics laser-induced fluorescence (LIF) measurements than our previous crossed-beam experiments [6].

In this poster, we will report details of the development, the recent spectroscopic results, and future plans.



Figure 1. Photo of CoBIT-III.

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Optical emission spectroscopy of multiply charged heavy ions using buffer-gas-assisted charge-state control in a compact EBIT

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Optical transitions of heavy ions in moderate charge states have recently attracted considerable attention because of new motivations: investigations of HCI atomic clock transitions [1] and analyses of kilonova emission [2]. Optical emission spectroscopy using an electron beam ion trap (EBIT) is a powerful method for addressing these topics; however, it is generally difficult to maintain low electron beam energy conditions suitable for keeping multiply charged heavy ions whose ionization energies are below 100 eV.

Here, we demonstrate optical emission spectroscopy of multiply charged heavy ions with a compact EBIT (CoBIT-III), which we recently developed at Tokyo University of Science (TUS) [3]. Figure 1 shows a typical emission spectrum of Xe^{5+} , which has an ionization energy of 67 eV. To maintain the low charge state ions in the EBIT, we injected Ne buffer gas ($\sim 10^{-6}$ Pa) and shifted the charge-state distribution toward low charge states. This technique actively applies insights into charge-exchange processes in an EBIT, obtained during the development of a buffer-gas wavelength-calibration method [4], to the preservation of low-charge-state ions.

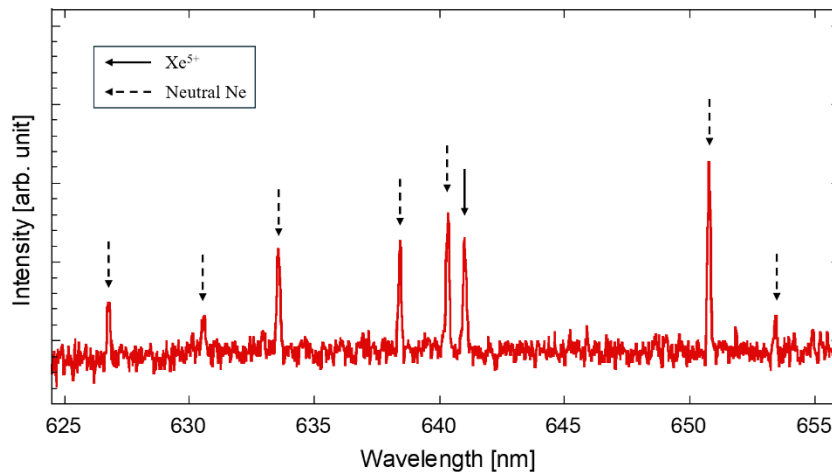


Figure 1. A typical emission spectrum of Xe^{5+} observed by a buffer-gas-assisted charge-state control technique. The electron beam energy was 180 eV. Ne gas pressure was $\sim 10^{-6}$ Pa.

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Measurement of dielectronic recombination of Ne^{3+}

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Dielectronic recombination for the process $\text{Ne}^{3+} + e^- \rightarrow \text{Ne}^{2+}$ was investigated in a merged-beams setup [1] at the heavy-ion storage ring CRYRING@ESR. The energy-dependent merged-beams recombination rate coefficient, $\alpha(E)$, associated with dielectronic recombination (DR), was measured and compared with our quantum mechanical calculations [2] over the collision energy range from 0 to 25 eV. The measurements cover the complete set of $\Delta N = 0$ DR resonance series arising from $2s \rightarrow 2p$ core excitations. The primary ion beam is estimated to have consisted of approximately 44% of the ions in the ground state, with the remainder distributed among long-lived metastable levels. The theoretical treatment therefore includes dielectronic recombination contributions from the ground and excited metastable initial levels, weighted according to a modeled mixed beam composition. From the experimental spectra, we derive a temperature dependent DR plasma recombination rate coefficient (PRRC) $\alpha(T)$. In the temperature domain where Ne^{3+} is abundant in collisionally ionized plasmas, the present results show a good agreement with previous theoretical predictions [3]. In the low-temperature regime characteristic for photoionized plasmas, the experimentally derived DR plasma rate coefficient is slightly higher than the published theoretical ones, but agrees within the error bars. Parametrized fits of the experimentally derived DR PRRC are presented in order to facilitate an easy inclusion into astrophysical modelling codes. The results are particularly important for the understanding of planetary nebulae [4].

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State-dependent C–F bond cleavage dynamics of fluoromethane dication

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The electronic and nuclear dynamics governing the ionization and fragmentation of polyatomic molecules are fundamental to a broad range of disciplines across physics, chemistry, and biology [1]. Highly charged ion (HCI) collisions provide an exceptionally brief interaction window that preserves unperturbed potential energy surfaces without the distortions typical of intense laser fields, serving as an ideal probe of intrinsic molecular dissociation dynamics [2]. In this work, combined experimental and theoretical studies of state-dependent C–F bond cleavage dynamics in CH_3F^{2+} induced by collisions with highly charged Ar^{8+} ions are reported. The CH_3F^{2+} to $\text{CH}_3^+ + \text{F}^+$ dissociation channel is explicitly isolated via Cold Target Recoil Ion Momentum Spectroscopy [3], yielding detailed kinetic energy release (KER) values and fragment angular distributions (FADs). High-level quantum chemical calculations are employed to construct highly accurate potential energy surfaces (PESs), elucidating state-specific dissociation mechanisms. Two distinct dissociation pathways, i.e., prompt direct and delayed indirect ones, are identified. High-KER fragments with directional ejection arise from prompt direct C–F bond breaking on highly excited dicationic states, whereas low-KER fragments require Jahn–Teller-induced hydrogen migration and isomerization on the lowest singlet PES, leading to isotropic angular distribution and exemplifying the complexity of carbon-halogen bond dissociation dynamics.

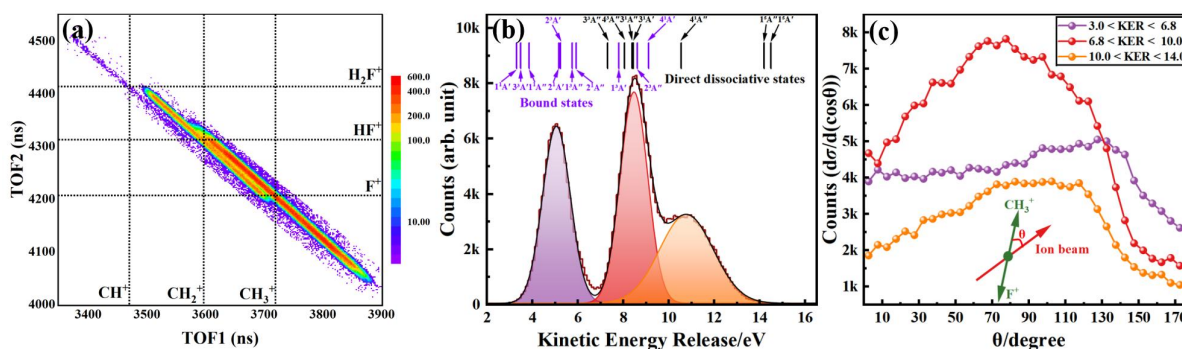


Figure 1. (a) Ion-ion coincidence TOF map for the two-body fragmentation of CH_3F^{2+} involving the C–F bond breakup. (b) Comparison of experimental and theoretical kinetic energy release distributions for the $\text{CH}_3^+ + \text{F}^+$ dissociation channel. (c) Fragment angular distributions of $\text{CH}_3^+ + \text{F}^+$ ion.

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Doubly differential cross sections for ionization in C^{6+} –He collisions

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Differential ionization of the helium atom by fully stripped carbon ions remains one of the most widely studied topics in atomic physics. Measurements of the fully differential cross section (FDCS), particularly in planes outside the scattering plane, exhibit clear and pronounced structures [1]. However, most theoretical approaches fail to reproduce these features. This discrepancy is especially pronounced in the perpendicular plane. A theoretical explanation of the experimental results remains a long-standing challenge. We investigate this scattering problem using the two-center wave-packet convergent close-coupling (WP-CCC) method. In this approach, the total scattering wave function is expanded in terms of target-centered and projectile-centered pseudostates. This allows a unified treatment of all underlying target excitation and charge exchange processes, including direct ionisation (DI) and electron capture into the continuum (ECC). The FDCS, which depends on the projectile scattering angle and the electron emission energy and angle, is calculated using a combination of the DI and ECC amplitudes. The singly and doubly differential cross sections (SDCS and DDCS) are then obtained by integrating the FDCS over all but one and all but two of these variables, respectively.

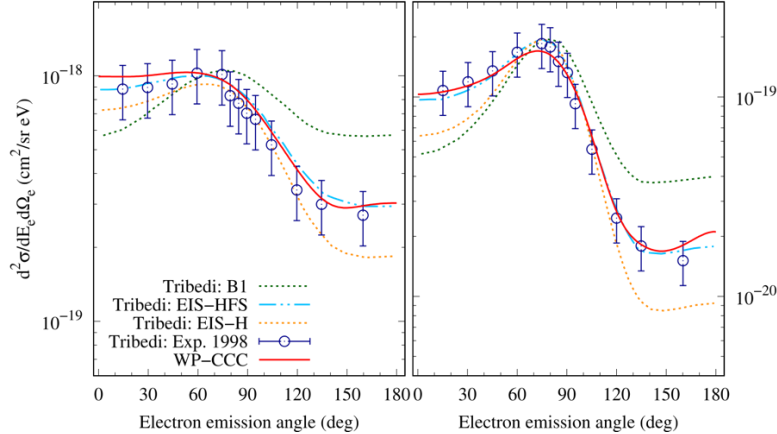


Figure 1. DDCS as a function of ejected-electron angle for ionization in 2.5 MeV/u C^{6+} –He collisions. The WP-CCC results are compared with the experimental data and theoretical results from Ref. [3] for electron energies of 10 eV (left panel) and 50 eV (right panel).

In our previous work, we investigated the SDCS for C^{6+} –He collisions [2]. Here we extend this study to the DDCS. Fig. 1 shows the DDCS as a function of electron angle at two emission energies for 2.5 MeV/u C^{6+} –He collisions. Our results are in good agreement with the available experimental data [3]. Calculations for more electron energies and collision energies will be presented. These results provide further insight into the ionization dynamics in highly charged ion-atom collisions and establish a foundation for future, more detailed FDCS calculations.

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Investigation of Beam Lifetime and Radiative Recombination Rate Coefficient of U^{91+} ions stored in CRYRING@ESR

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We investigate the ion-beam lifetimes and radiative recombination (RR) rates of U^{91+} ions at a kinetic energy of 11.5 MeV/u interacting with electrons in the electron cooler of the low-energy storage ring CRYRING@ESR [1] at the GSI accelerator facility. The beam lifetime of highly-charged ions at relatively low beam energies can be a limiting factor for experiments, as beam losses due to electron capture from the residual gas strongly increase with decreasing ion velocity [2]. We investigate the signal strength of the beam profile monitor as well as the hits of down-charged ions on a particle counter as a function of time for different electron cooler currents. Both signals are proportional to the ion beam intensity, thus their decrease over time reveals the beam lifetime.

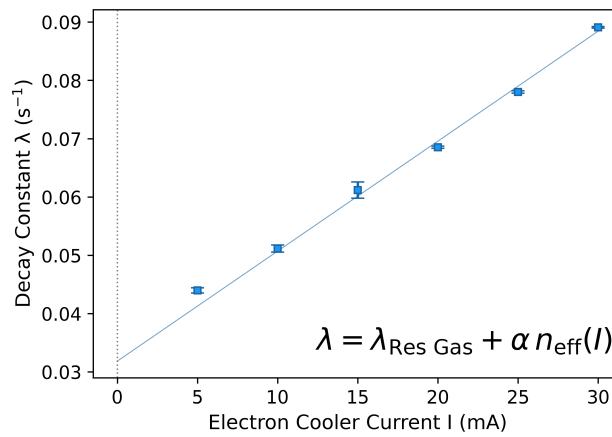


Figure 1: Decay constant of the ion beam as a function of the electron cooler current.

By estimating the decay constant for different electron cooler currents, it is possible to disentangle the beam loss contributions from charge-changing collisions in the residual gas and the contribution of RR in the electron cooler (Fig. 1). We extrapolate a beam lifetime solely due to the residual gas of about 30 s. Moreover, both the beam lifetimes as a function of electron cooler current as well as the rate in the particle counter provide access to the RR rate coefficient α . The resulting values are $3.316 \cdot 10^{-7} \text{ cm}^3/\text{s}$ and $3.288 \cdot 10^{-7} \text{ cm}^3/\text{s}$. It is noteworthy that the well-known enhancement of α at close to zero collision velocities between ions and electrons is still not fully understood [3]. In the present case, an enhancement factor of 1.65 is found compared to the prediction of basic RR theory.

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Composite Radiation Shielding Materials under Mixed Space Radiation Spectra: Recent Advances, Design Principles, and Numerical Investigation

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Future space exploration requires reliable shielding materials capable of mitigating the effects of mixed-field space radiation spectra while minimizing the generation of secondary radiation. This study reviewed state-of-the-art radiation shielding architectures and numerically investigated candidate composite materials, with a focus on multifunctional Z-graded multilayer concepts for future spacecraft and planetary habitats. Experimental data from the ISS, accelerator irradiation campaigns, planetary analog studies, and Monte Carlo simulations were used to select candidate materials and assess their radiation attenuation efficiency and secondary particle production. Attention is given to high-charge, high-energy (HZE) nuclei, which constitute one of the most challenging components of the space radiation environment due to their high penetration capability, elevated linear energy transfer (LET), and the significant secondary particle cascades they generate within shielding materials, making the design of effective multilayer shielding systems a major challenge. The proposed framework can be adapted to different mission phases, including Earth orbit e.g. Russian Orbital Station (ROS), cis-lunar transportation, lunar surface habitation, and future Mars exploration missions. The NICA complex at the Joint Institute for Nuclear Research represents one of the facilities capable of providing a broad spectrum of charged-particle irradiation conditions relevant to the space radiation environment within a single experimental infrastructure.

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Benchmarking Instrumental Systematic Uncertainties in a Longitudinal Reaction Microscope: Double-Electron Capture Followed by Auger Single Ionization in $O^{5+} + He$ Collisions

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Using the double-electron capture followed by Auger single ionization in 3.5 MeV/u $O^{5+} + He$ collisions as a benchmark process, we investigate instrumental systematic uncertainties in a longitudinal reaction microscope operated on a 320 kV platform in HIRFL [1]. For the Auger electrons emitted in the transition $2p^2(^1D)3p^2F_{J=5/2,7/2} \rightarrow 1s^22s^2^1S_0$, the measured target-position uncertainty is convoluted with a theoretically predicted Lorentzian line shape with an intrinsic width of 25 meV. The resulting simulated energy spectrum reproduces the measured spectrum well, indicating that the finite target size is a major contributor to the energy resolution. Furthermore, simulations of the two-dimensional momentum distributions include the finite target size, detector position offsets, and a small misalignment between the electric and magnetic fields. The simulated momentum distributions show good agreement with the experimental data and successfully reproduce the observed distribution features. These results demonstrate the importance of properly accounting for instrumental systematic uncertainties in reaction-microscope measurements, providing a more realistic assessment of experimental accuracy and greater confidence in the extracted collision-dynamics information.

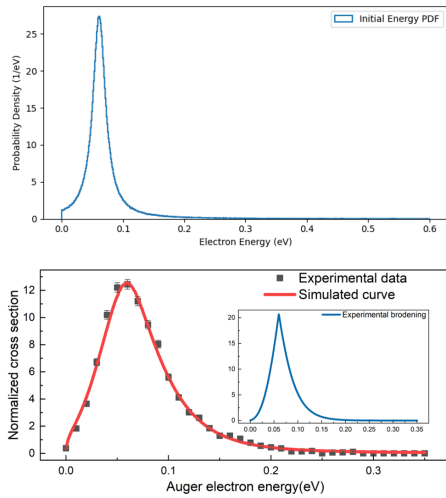


Figure 1: Auger spectrum in $O^{5+}-He$: intrinsic 25 meV Lorentzian (top) and convolution with target-induced response vs experiment (bottom), with instrumental broadening inset.

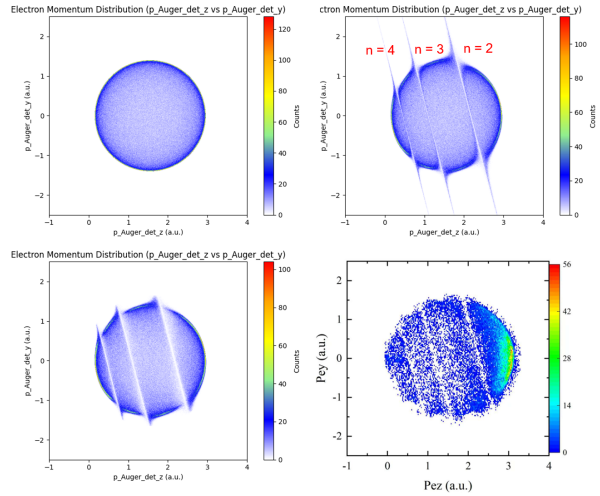


Figure 2: Auger momentum distributions: ideal simulation (UL), with full instrumental effects and all simulation parameters were chosen to match the experimental conditions (UR), energy-gated simulation (LL), and experiment (LR) for 25–37 eV.

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Multiple Electron Capture Effects of Highly Charged Ions Transmitted through Monolayer Graphene

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Monolayer graphene provides an atomically thin target for studying charge exchange of highly charged ions in “single collision modes” with solids. During transmission through graphene, the interaction time is in the femtosecond scale. So the exit charge state distribution provides information on ultra-fast electron capture and de-excitation processes, such as Inter Coulomb Decay (ICD [1]). In this work, we focus on experimental studies how the shell structure of the projectile influences electron capture and determines the related charge neutralization processes in the fs interaction with graphene

Highly charged Xe^{q+} ions with $q = 15-17$ and a kinetic energy of approximately 147 keV, with a beam current about 0.05 pA and size of $2 \text{ mm} \times 2 \text{ mm}$ were provided by the EBIS at IMP. The ions transmitted monolayer graphene target were analyzed in both energy and charge state by a 127.3° cylindrical electrostatic analyzer. Before each measurement, a laser beam was used to evenly clean the monolayer graphene target.

The measured spectra show that the Xe ions capture and stabilize more than ten electrons following the 1-3 fs of passing through monolayer graphene, as illustrated by the Xe exit charge state distribution in Fig. 1. At the same charge state and velocity, Ar ions [1] capture more than one electron fewer on average than Xe ions. The most obvious difference between the two cases is that Ar^{15+} and Ar^{17+} ions exhibit a shift from L-shell to K-shell vacancies, while Xe^{15-17+} ions have N-shell vacancies, which may open different steps in the de-excitation. This striking difference needs to be investigated further.

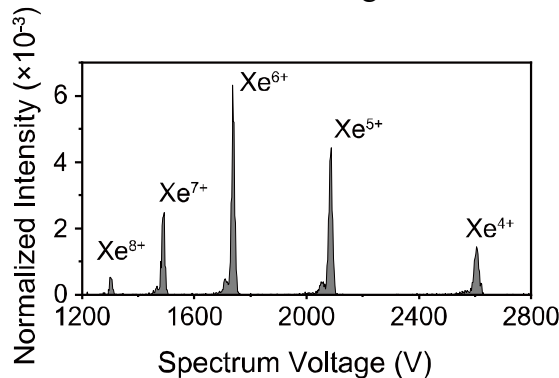


Figure 1. Charge state distribution of 147 keV Xe^{17+} transmitted through monolayer graphene.

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Compact Atomic Configuration-Interaction Blocks for ADAPT-VQE Energy Calculations

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Accurate quantum simulations of atomic structure require basis functions that capture essential properties of bound states, such as angular momentum conservation and electron correlation. In this work, we construct a configuration-interaction (CI) Hamiltonian symmetry-adapted for quantum circuits that conserves electron number N , parity, and total angular momentum quantum numbers (L , M_L , S , M_S) within block sectors. This restricts the variational search to physically allowed atomic energy sectors and reduces the Hilbert space dimension prior to quantum-circuit optimization. These compact atomic blocks are then solved with the VQE [1] and ADAPT-VQE [2] quantum algorithms.

The single-particle basis functions are Slater-type orbitals [3] grouped by angular momentum. Because these functions are non-orthogonal, we construct linear combinations that diagonalize the one-electron Hamiltonian, providing a good initial point for the VQE. This is achieved by solving the generalized eigenvalue problem within each angular momentum subspace, first reducing it to a standard eigenvalue problem via Löwdin orthogonalization [4]. The resulting orthogonal orbitals are used to transform the one- and two-particle integrals before the CI Hamiltonian is assembled for the target electron number and filtered by N , M_L , M_S , parity, L , and S .

The selected d -dimensional block is embedded in $\lceil \log_2 d \rceil$ qubits and optimized using a compact-state ansatz and an ADAPT operator pool restricted to the same physical sector, implemented in Qiskit [5]. Results for the helium 1S_0 block sector with convergence analysis using ADAPT-VQE will be shown. For this ground-state block, ADAPT-VQE converges to $E = -2.878315$ Ha, within 10^{-4} Ha of the classical compact-CI energy after diagonalization, with a final state fidelity of 0.999962.

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Charge transfer in Ar^{3+} and Ar^{4+} ion collisions with helium

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Collisions between highly charged partially stripped ions and atoms are fundamental to various applications, ranging from fusion plasma modelling to astrophysical studies of the interaction of the cometary atmosphere with the solar wind. The techniques used by plasma modellers to analyse the emission spectra from these environments rely on an understanding of the underlying interactions in these systems. Over the past decades, collisions involving fully and partially stripped projectiles have been extensively studied experimentally (see, e.g., Ref. [1] and the references therein). In particular, measurements of the state-selective electron-capture cross sections [2] in collisions with He have been performed. We employ the two-centre wave-packet convergent close-coupling (WP-CCC) method [3] to calculate state-selective electron-capture cross sections in collisions of Ar^{3+} and Ar^{4+} ions with He at low energies. We use a model potential approach to treat the interactions with the partially stripped projectile ions. We represent the target atom using an effective-one-electron and a full two-electron approach [4]. The latter accounts for correlations between the two electrons in the helium atom. We compare the obtained results with recent and ongoing measurements. We find that for both collision systems, capture into the $n = 3$ shell dominates, where n denotes the principal quantum number of the final state of the captured electron. However, the ℓ -distribution of the cross section appears to strongly depend on the charge of the projectile, where ℓ denotes the angular momentum quantum number of the final state of the captured electron. For Ar^{3+} , capture into the $3p$ subshell is dominant, whereas capture into the $3d$ subshell dominates for the Ar^{4+} projectile. By modelling the post-collisional radiative cascades, we use the calculated state-selective cross sections to generate the emission spectra for the Ar^{2+} and Ar^{3+} ions formed in these collisions. The comparison with experimental results will be presented in this contribution.

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Precision X-ray spectroscopy of muonic atoms at CiADS: towards probing strong field QED and nuclear properties

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on behalf of collaboration of Precision measurement physics of muonic atoms at CiADS

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A muonic atom is an exotic atomic system consisting of a single negative muon and an atomic nucleus. With a mass approximately 207 times that of the electron, the muon orbits much closer to the nucleus, resulting in an atomic radius significantly smaller than that of ordinary atoms or highly charged ions. Consequently, the electric field strength experienced by the muon is up to 40,000 times stronger than in conventional atoms, providing an exceptional platform for testing quantum electrodynamics (QED) effects in extreme electromagnetic fields. Moreover, due to the muon's proximity to the nucleus, nuclear structure effects are enhanced by a factor of about 10^7 compared to ordinary atoms, making muonic atoms ideal systems for probing nuclear properties. The figure below outlines the ongoing research directions in muonic atom precision spectroscopy around the world with different experimental methods.

The high-intensity muon beam terminal under construction at CiADS ^[1] (China Initiative Accelerator Driven System) offers unique experimental conditions for precision muonic atom spectroscopy. We plan to employ the recently developed TES (Transition-Edge Sensor) microcalorimeter at the Institute of Modern Physics, which covers an energy range of 10–200 keV, for precision X-ray measurements of muonic atoms in extreme electromagnetic fields. Compared to conventional semiconductor detectors, advanced cryogenic TES microcalorimeters improve X-ray energy resolution by a factor of 5–10. This leap in resolution will enable more stringent tests of strong-field QED effects, precise extraction of nuclear charge radii, magnetization distribution radii, and magnetic dipole moments, detailed studies of nuclear properties, and exploration of new physics beyond the Standard Model ^[2,3].

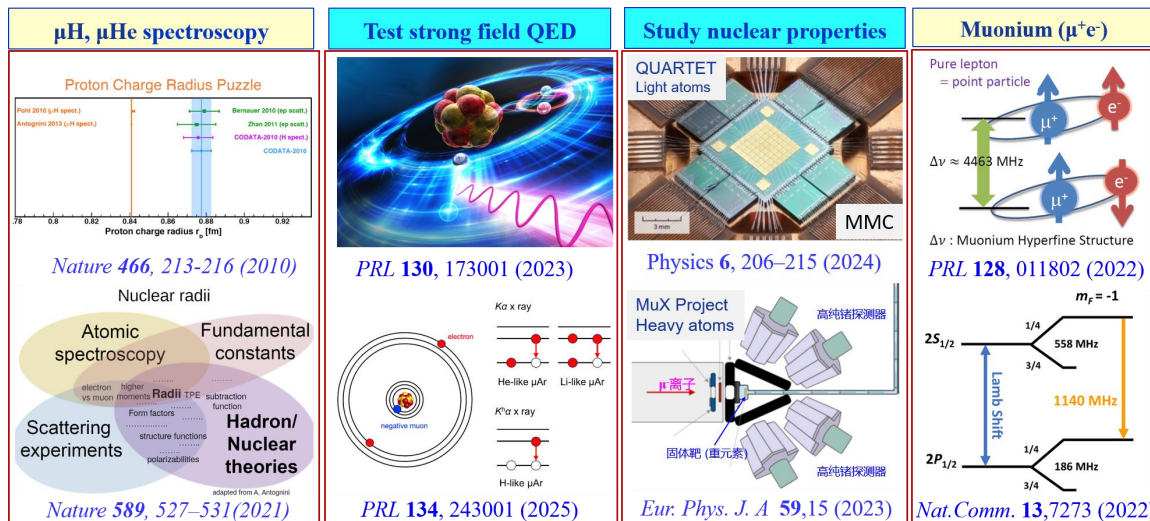


Fig. 1 Precision spectroscopy and theory of muonic atoms enable tests strong field QED effects, investigation of nuclear properties, and searches for new physics.

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Study of ionization process of a PAH molecule, acenaphthene under fast highly charged Si ions

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Polycyclic aromatic hydrocarbon (PAH) molecules are composed of fused benzenoid rings of sp^2 hybridized carbon atoms, where each carbon contributes a π electron to a delocalized cloud spread over the carbon cage. They are present in the interstellar medium (ISM) [1, 2] and important in the field of astro-physics and astro-chemistry being the source of some specific features of the observed absorption spectra from ISM. PAH molecules are found to be responsible for the giant dipole plasmon resonance (GDPR) due to strong e-e correlation under the impact of external perturbation. Such GDPR has been detected for coronene and fluorene [3-5] via the study of electron spectrum in MeV energy Si and O ions impact. In this work, the ionization study of a relatively smaller PAH molecule, acenaphthene ($C_{12}H_{10}$) has been performed under the impact of 94 MeV Si^{13+} (3.36 MeV/u) ions obtained from the Pelletron accelerator TIFR, Mumbai. The target gas jet has been mounted from outside of the chamber along with a x-y-z manipulator. To avoid the density fluctuations of the vapor jet, we kept a constant temperature ($\sim 40^\circ C$) of the target molecules. The relative double differential cross section (DDCS) has been measured for an energy range of 1-360 eV at the scattering angles in the range of 20° - 160° . By integrating the DDCS data, the single differential cross section (SDCS) and the total cross section (TCS) have been derived subsequently. Absolute cross sections have been obtained by the normalization procedure using the absolute value of C-KLL Auger cross section for methane (CH_4). The absolute data has been compared with the continuum distorted wave-eikonal initial state (CDW-EIS: CNDO) model. Calculations are found to be underestimating the data specially in case of lower electron energy region. This calculation is very new to compare with the results for this type of large molecule. The expected plasmon peak was not visible in the low energy part of the spectrum perhaps due to the large contribution of the Coulomb continuum in this soft collision energy regime. The complementary experiments at much lower beam energy are in progress in order to explore the plasmon resonance peak.

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Ionization, electron emission asymmetry and interference in 150 keV/u He²⁺ collisions with oxygen

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Absolute double differential, single differential, and total electron emission cross sections (DDCS, SDCS, and TCS) have been measured for the ionization of the multi-electron molecule O₂ by 150 keV/u He²⁺ ion impact. Angle-resolved DDCS measurements were performed using electron spectroscopy and the data compared with continuum distorted wave-eikonal initial state (CDW-EIS) calculations employing molecular orbital (MO) description of the target. The present projectile velocity ($v_p \sim 2.5$ a.u.) lies in the intermediate-to-high velocity regime, providing a stringent test of the applicability of the CDW-EIS model in this sensitive energy region. The measured energy distributions exhibit noticeable deviations from the theoretical predictions over most emission angles. Similarly, the angular distributions show significant discrepancies beyond 80°, in contrast to the reasonable agreement reported for much faster collisions (MeV energies, $v_p \sim 10$ a.u.). A comparison with earlier measurements for O₂ ionization by highly charged ions of MeV energy is also presented. There is a drastic difference in the shape of the angular distributions at keV and MeV energy collisions for this molecule. The forward backward asymmetry parameter derived from the spectrum obtained at 30° and 150° was found to be overestimated grossly by the calculation. The asymmetry parameter is drastically lower compared to that for methane for the similar collision velocity, indicating the sensitiveness of the of the asymmetry parameter on the molecular structure.

Furthermore, the DDCS ratio, O₂/O, exhibits an oscillatory behaviour indicative of Young-type interference, which has been debated in earlier studies using MeV energy ion beams as well as keV energy electrons [1-4].

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Charge transfer in intermediate-energy $H^+ + H_2$ collisions

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The single electron charge transfer process in $H^+ - H_2$ collisions is investigated using a fully correlated two-active-electron semi-classical atomic orbital close-coupling (SCAOCC) method in the energy range of 0.1 - 100 keV/u, and the orientation and vibronic effects of the molecular target are taken into account under the sudden approximation. Total and state-selective charge exchange cross sections for this system are provided, and excellent agreement is found between our calculations and the available experimental data for total charge transfer cross sections in the energy range of 0.2 - 100 keV/u. The vibronic effect from the molecular target has a big contribution to the total charge transfer cross sections for energies below 2 keV/u, and it leads to an increase of 8% - 185% for the total charge exchange cross sections in the 0.1 - 1 keV/u range. Furthermore, absolute angular differential cross sections at different energies are reported for the first time, and their oscillatory structures are inferred to originate from Fraunhofer-type diffraction.

B47

Magnetic Field Enhanced Color Center Formation in LiF irradiated by GeV Heavy Ion

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We report a significant enhancement of color center formation in LiF crystals irradiated with 450 MeV/u Sn ions in a strong magnetic field of 14.5T. The experiment has been carried out at HIRFL-IMP, as showed in Figure 1. Post-irradiation optical absorption spectroscopy reveals that the F-center (250 nm) and F₂-center (440 nm) [1, 2] bands increase by a factor of 1.5–2.0 relative to field-free irradiation, with the strongest effect localized near the Bragg peak region.

Using the Smakula formula [3], we quantify absolute defect concentrations. Combined Geant4 and LAMMPS simulations further rule out direct energy-deposition or Lorentz-force effects as the primary cause. The rate-equation modeling based on the radical pair mechanism (RPM) [4] quantitatively reproduces the observed enhancement. In this framework, F and H centers form spin-correlated Frenkel pairs. The applied 14.5 T field suppresses hyperfine-driven S-T⁺ and S-T⁻ mixing through Zeeman splitting, while the S-T₀ channel remains fully active due to LiF's strong hyperfine coupling, preserving 50% of recombination-competent encounters. This spin-blockade effect provides a unified explanation for the experimental data, highlighting magnetic fields as non-thermal tuning knobs for radiation-induced defect chemistry in insulators.

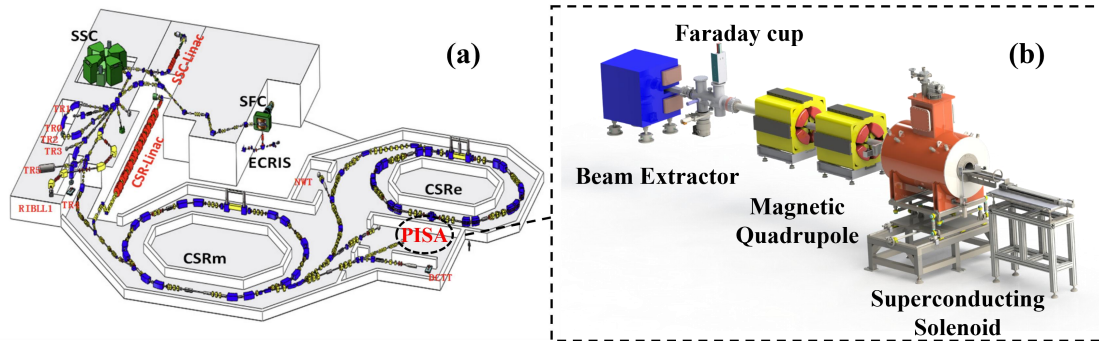


Figure.1 Schematic diagrams of experimental setup, (a) 450 MeV/u $^{112}\text{Sn}^{33+}$ ion beam by HIRFL, (b) high-energy heavy ion irradiation terminal.

Keywords: LiF; color centers; magnetic field effects; heavy ion irradiation; radical pair mechanism

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Production of a Titanium Ion Beam Using Fluorides and Fluorine-Forming Precursors in an ECR Ion Source

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The production of multiply charged titanium ions is of considerable interest for accelerator-based experiments, surface modification technologies, and applications in nuclear physics. However, due to the low saturated vapor pressure of titanium at temperatures below 1000 °C, the generation of charged titanium ion beams from an electron cyclotron resonance ion source (ECRIS) remains a challenging task. The choice of titanium vapor injection methods into the ECR plasma plays a key role in achieving high ionization efficiency, plasma stability, and reliable long-term source operation.

Currently, three main methods are employed for refractory metal injection into ECR ion sources: MIVOC (Metal Ions from Volatile Compounds) — injection of volatile organometallic compounds into the plasma; Sputtering — plasma-assisted sputtering of a metallic sample placed inside the plasma chamber; High-Temperature Oven (HTO) — evaporation of metals at elevated temperatures using resistive or inductive heating.

In this work, alternative approaches for the injection of neutral titanium atoms into the ECR plasma have been investigated, focusing on the use of fluorine-containing compounds. Titanium fluorides (TiF₃, TiF₄) possess a relatively high saturated vapor pressure at moderate temperatures, allowing the use of standard resistively heated ovens operating up to 1000 °C. Another method explored involves the in-situ formation of titanium fluorides inside the plasma chamber via chemical reactions between titanium foil and the dissociation products of sulfur hexafluoride (SF₆). These approaches enable controlled and efficient titanium injection into the ECR plasma, providing satisfactory ion beam stability.

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Radiative Cascade Effects on Metastable-state initiated Dielectronic Recombination of Be-like ions with $Z=10-30$

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Metastable levels play an important role in electron–ion recombination processes in finite-density dynamic plasmas, such as impurity plasmas near plasma-facing components in fusion devices and high-energy astrophysical plasmas. Within the generalized collisional–radiative (GCR) framework, metastable populations in each ionization stage may deviate from quasi-static equilibrium with the ground state and can provide significant contributions to dielectronic recombination (DR). Therefore, metastable-state initiated DR processes must be accurately considered in non-local thermodynamic equilibrium (NLTE) plasma modeling. However, comprehensive DR data involving metastable initial states remain limited for many highly charged ions.

In this work, we investigate metastable-state initiated DR processes of Be-like ions with $Z=10-30$, with particular emphasis on the influence of radiative cascade transitions. Detailed configuration interactions, autoionization channels, and radiative stabilization pathways are included to evaluate the contributions of metastable levels to DR rate coefficients. To ensure the reliability of the calculations, two independent theoretical approaches are employed for cross-validation: the relativistic distorted-wave (RDW) method implemented in the Flexible Atomic Code (FAC) and the multi-configuration Breit–Pauli (MCBP) distorted-wave method implemented in AUTOSTRUCTURE (AS). The comparison between the two methods provides a reliable evaluation of resonance structures and DR rate coefficients.

This study provides improved metastable-state initiated DR data for Be-like $Z=10-30$ and highlights the importance of radiative cascade effects on metastable-state initiated DR process. The results will contribute to more accurate NLTE simulations of astrophysical plasma.

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Dielectronic Recombination in H-like and He-like Bismuth Ions

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Hyperfine splitting (HFS) of highly charged ions is a robust probe for strong-field QED [1, 2]. We investigate the feasibility of measuring HFS via storage-ring dielectronic recombination (DR) at HIAF-SRing. Using the Jena Atomic Calculator (JAC), we calculated the DR for H-like $^{209}\text{Bi}^{82+}$ and He-like $^{209}\text{Bi}^{81+}$. Our results indicate that while the $2s^2 [^1S_0]$ resonance linewidth (11.24 eV) in He-like ions washes out the splitting, the narrower $1s2s^2 [^2S_{1/2}]$ resonance (0.88 eV) allows for resolution under low beam temperatures ($T_{\parallel} = 0.02$ meV, $T_{\perp} = 1$ meV), as shown in Fig. 1. Conversely, the splitting remains unresolved. With the interference between DR and radiative recombination found to be negligible (Fano $Q \gg 1$), we conclude that $^{209}\text{Bi}^{81+}$ is a promising candidate for measuring $1s$ -electron HFS.

Table 1: Calculated results of the DR process of H-like $^{209}\text{Bi}^{82+}$ and He-like $^{209}\text{Bi}^{81+}$ ions.

Ions	DR channel	E_{res} (eV)	DR strength ($\text{eV} \cdot \text{cm}^2$)	Linewidth [*] (eV)
$^{209}\text{Bi}^{82+}$	$1s [^2S_{1/2}, F=5] \rightarrow 2s^2 [^1S_0, F=9/2] \rightarrow \dots$	50975.9	7.3744×10^{-21}	11.24
	$1s [^2S_{1/2}, F=4] \rightarrow 2s^2 [^1S_0, F=9/2] \rightarrow \dots$	50981.0	6.0330×10^{-21}	11.24
$^{209}\text{Bi}^{81+}$	$1s^2 [^1S_0, F=9/2] \rightarrow 1s2s^2 [^2S_{1/2}, F=4] \rightarrow \dots$	50222.4	1.0551×10^{-20}	0.883
	$1s^2 [^1S_0, F=9/2] \rightarrow 1s2s^2 [^2S_{1/2}, F=5] \rightarrow \dots$	50227.5	1.2895×10^{-20}	0.883

* The natural linewidths of the resonance states.

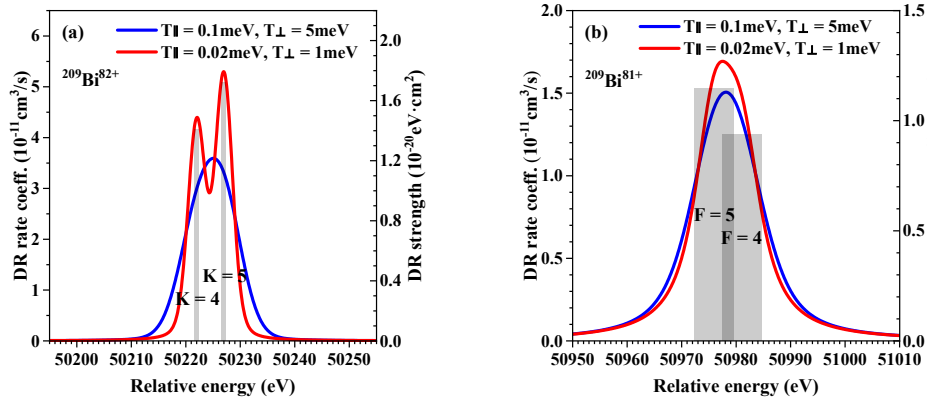


Figure 1: DR spectra of H-like $^{209}\text{Bi}^{82+}$ (left) and He-like $^{209}\text{Bi}^{81+}$ (right) ions, convoluted with electron beam temperatures. Gray bars give the calculated DR strengths (height) and linewidths (width).

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A high-temperature superconducting compact Shanghai–Lanzhou electron beam ion trap for precision measurement of highly charged ions

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Precision spectroscopy of highly charged ions (HCIs) plays a crucial role in plasma diagnostics, tests of quantum electrodynamics (QED), exploration of nuclear structure, and development of optical atomic clocks. Electron beam ion traps (EBITs) can produce and confine HCIs of any element under well-controlled laboratory conditions. As they integrate the functions of both an ion source and a light source, EBITs serve as ideal platforms for high-precision spectroscopic studies of HCIs. For this purpose, we have developed a high-temperature superconducting EBIT device, namely the Shanghai-Lanzhou Electron Beam Ion Trap (SL-EBIT). This apparatus comprises an electron gun, drift tubes, ion extraction electrodes, high-temperature superconducting coils, and a liquid nitrogen cooling system. It is equipped with a differentially pumped gas injection system, spectroscopic access ports for both X-ray and visible wavelengths, and a conjugate optical calibration system. A pair of high-temperature superconducting coils generates an axial confining magnetic field of up to 0.24 T. The electron beam energy ranges from 80 to 8000 eV, with a beam radius better than 65 μm and a maximum beam current of 10 mA. To benchmark the spectroscopic capabilities of the SL-EBIT, the magnetic-dipole (M1) fine-structure transitions in fluorine-like $\text{Ar}^{9+} 1s^2 2s^2 2p^5 \ ^2P_{3/2} - ^2P_{1/2}$ and boron-like $\text{Ar}^{13+} 1s^2 2s^2 2p \ ^2P_{1/2} - ^2P_{3/2}$ were measured. The resulting wavelengths, 553.3274(54) nm and 441.2550(24) nm, are consistent with previously reported values to within the combined uncertainties, confirming the accuracy of the instrument's calibration and data acquisition. These commissioning experiments confirm that the SL-EBIT is capable of conducting precision spectroscopy of HCIs, laying a solid experimental foundation for future studies on charge-state-selective extraction, external laser spectroscopy, and hyperfine structure measurements.

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Line Ratio Measurements of K X-Ray Emission following Charge Exchange Between S^{15+} and He

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Charge exchange (CX) between highly charged ions (HCIs) and neutral atoms constitutes a fundamental atomic process [1]. It is a process in which one or more target electrons are transferred to an excited state of the resulting ion. The subsequent radiative de-excitation of excited HCIs results in X-ray emission whose line ratio is markedly distinct from other collisional mechanisms. The line ratio can serve as a diagnostic tool in astrophysical environments. However, accurate experimental line-ratio data remain scarce, limiting the diagnostic power of CX X-ray emission. Therefore, we measured line-ratio data following CX between S^{15+} and He at collision energies of 0.23-9.38 keV u^{-1} .

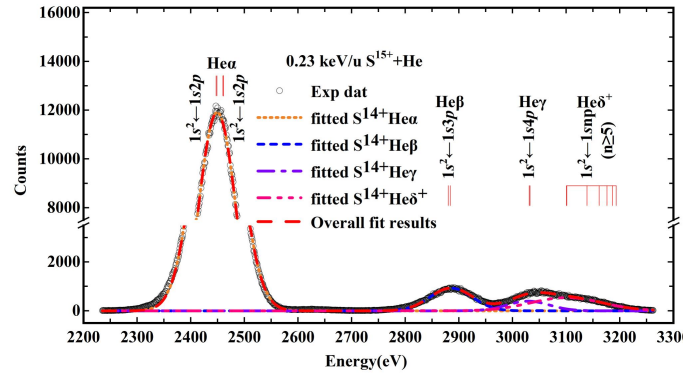


Figure 1. X-ray emission spectrum induced in $S^{15+} + He$ collisions.

The experiments were performed at the terminal of an ECR ion source facility. The X-ray emission was recorded using a Silicon Drift Detector. Figure 1 shows a typical X-ray emission spectrum at 0.23 keV u^{-1} . The peaks were simultaneously fitted with four Gaussian distributions. Detailed analysis of the spectral features is currently underway. The line ratios are expected to be used to deepen our understanding of the underlying CX mechanisms and interpret astrophysical X-ray observations.

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Experimental and simulation studies of laser cooling of $^{16}\text{O}^{5+}$ ion beams at CSRe

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Laser cooling of $^{16}\text{O}^{5+}$ ion beams with an energy of 275.7 MeV/u was achieved at the storage ring CSRe in Lanzhou, China [1]. This experiment represents the highest ion charge state, highest beam energy, and shortest rest-frame transition wavelength reached so far in direct storage-ring laser cooling. During the experiment, the cooling process was monitored in real time by employing a high-sensitivity Schottky resonator. To interpret the experimental observations, a multi-particle phase-space tracking code was developed to simulate the longitudinal Schottky spectra of the bunched and laser-cooled $^{16}\text{O}^{5+}$ ions. By detuning the bunching frequency, the longitudinal dynamics of laser cooling processes have been investigated systematically both by experimental and simulation methods. Figure 1 compares the selected experimental and simulated spectra without laser cooling and near the optimum cooling condition. The simulation reproduces the main spectral evolution, particularly the suppression of high-order synchrotron sidebands and the concentration of spectral power near the bucket center. With most ions laser-cooled to the center of the bucket, the relative longitudinal momentum spread of $^{16}\text{O}^{5+}$ ion beams reached $\Delta p/p \approx 2.0 \times 10^{-6}$, approximately one order of magnitude smaller than that achieved by electron cooling under comparable conditions. The laser cooling technique and the simulation method developed in this work will pave the way for laser cooling and precision laser spectroscopy experiments at HIAF in China and FAIR in Germany [2].

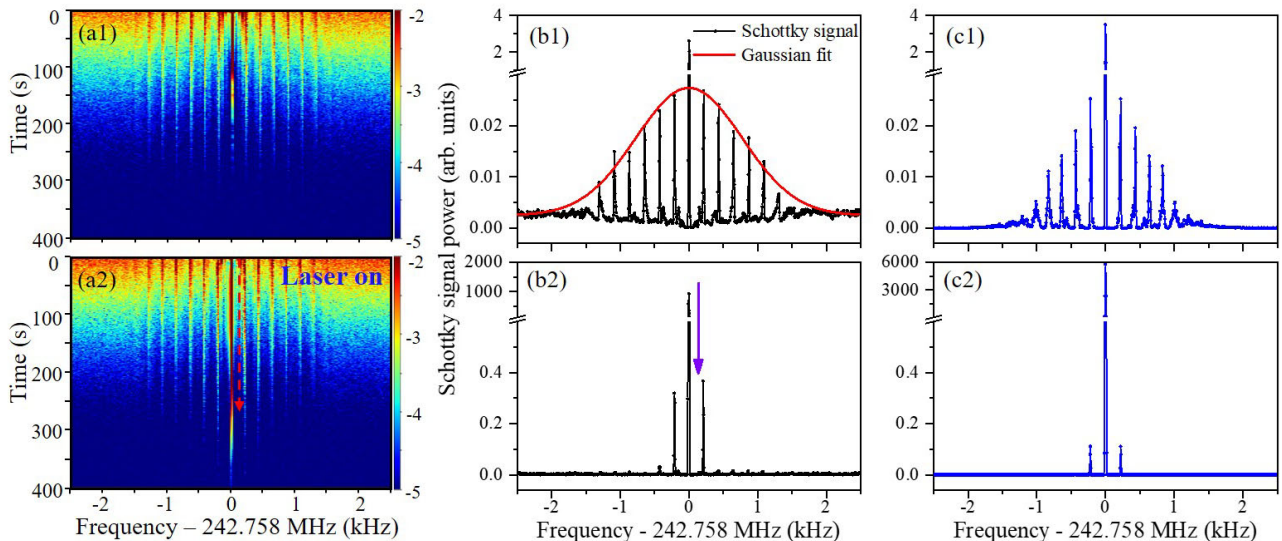


Figure 1. (a1, a2) Experimental Schottky spectra of RF-bunched O^{5+} ions at CSRe without laser cooling and near the optimum cooling condition, respectively. (b1, b2) Corresponding experimental spectra extracted at selected times. (c1, c2) Simulated spectra under the same conditions.

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Calculations of L-shell dielectronic recombination rate coefficients for Fe^{18+} ions

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Dielectronic recombination (DR) is an important process in collisions of electrons with highly charged ions, it exists widely in astrophysical, laboratory, and fusion plasmas. As iron is a highly abundant element in the universe, high-precision cross sections and rate coefficients for DR processes of Fe ions are crucial for interpreting and simulating the ionization balance and radiative spectra in relevant astrophysical plasmas, as well as for gaining deeper insights into the excited-state structures and decay dynamics of highly charged ions [1, 2].

In this work, employing the Flexible Atomic Code [3] based on the relativistic configuration interaction method within the relativistic distorted-wave approximation, with considering the complex electron correlation, Breit interaction and QED effects. We perform detailed calculations of wave functions and energy levels for inner-shell excited states $2s2p^5nl'$ ($n = 2-30$, $l' \leq n-1$), $2s^22p^33lnl'$ and $2s2p^43lnl'$ ($l = s, p, d$; $n = 3-15$, $l' \leq n-1$) formed via the L-shell $\Delta n = 0$ and 1 DR processes of O-like Fe^{18+} ions in the ground state. The state-resolved DR strengths, cross sections and rate coefficients are obtained, and the properties of DR spectra are investigated. The present theoretical calculations show excellent agreement with the experimental measurements carried out by Savin et al. [1] and Schippers et al. [4] at TSR.

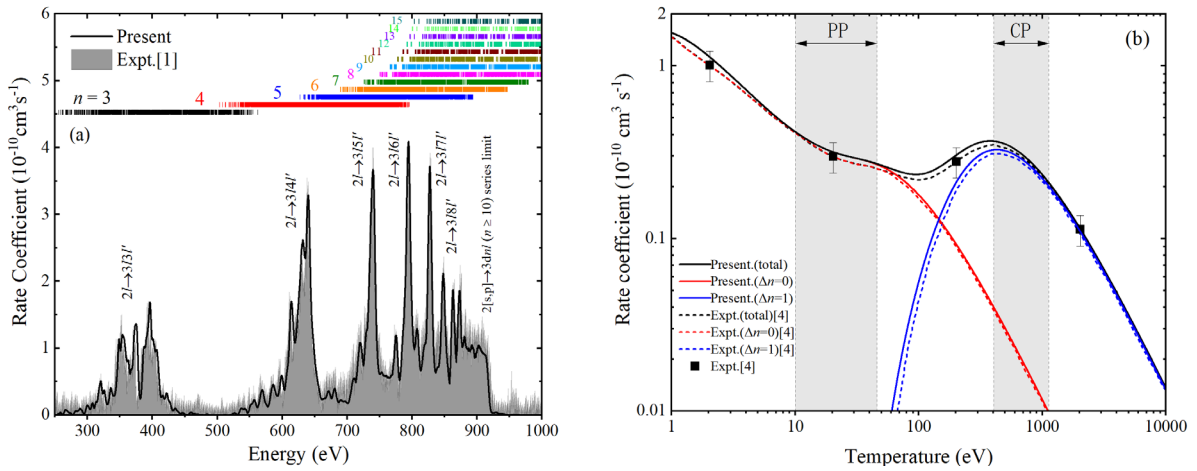


Figure 1. (a) Comparison of the theoretically calculated $\Delta n=1$ DR spectrum (solid line) of Fe^{18+} ions with the experimental results (shaded area) measured at the TSR facility [1]. The colored vertical bars show the resonance positions for each of the individual resonances. (b) Comparison of the calculated DR rate coefficients against the available experimental data [4]. The shaded regions denote the temperature ranges corresponding to photo ionization (PP) and collisional ionization (CP).

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Evolution of Laser-Produced Aluminum Plasma under Different Background Gas and Pressure Conditions

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The evolution of laser-produced aluminum plasma under different background gases and pressures was investigated using fast photography, shadowgraphy, and spatiotemporally resolved optical emission spectroscopy. A high-purity Al target was irradiated by a 1064 nm, 8 ns Nd laser pulse with an energy of 30 mJ and a focused spot diameter of approximately 300 μm . The measurements were compared with simulations performed using the two-dimensional radiation-hydrodynamic code RHDLP [1].

At 1 atm, the luminous-plume size followed the order $\text{He} > \text{Air} > \text{Ar}$, while the shock wave propagated farther in Air than in Ar, indicating stronger confinement by Ar. In Air at 10^{-4} Pa, the plasma underwent nearly free expansion with an axial velocity of approximately 4.3×10^6 cm s^{-1} . At 500 Pa, the initially quasi-spherical plume separated after approximately 75 ns into a slow near-target region and a faster outer region, eventually forming a cap-shaped structure. At 10^5 Pa, axial expansion was strongly suppressed and the plume became flattened.

The spectroscopic measurements further connected the macroscopic dynamics with microscopic plasma evolution. Electron temperatures determined using the Saha-Boltzmann method decreased with delay time but increased with background pressure; at 500 ns and 0.6 mm from the target, the temperatures were 14958, 14199, and 12317 K at 10^5 , 10^4 , and 10^3 Pa, respectively. Electron densities derived from Stark broadening exhibited an approximately exponential temporal decay and remained higher in Ar than in Air, as well as at higher Air pressures, owing to the suppression of plume expansion and particle dilution [2]. The experimental and simulated results showed consistent overall trends in plume expansion, shock propagation, and electron-parameter evolution. The results establish a direct relationship between background-gas-induced macroscopic confinement and microscopic thermodynamic evolution, and provide an experimental benchmark for radiation-hydrodynamic modeling of moderate-intensity nanosecond laser-produced plasmas.

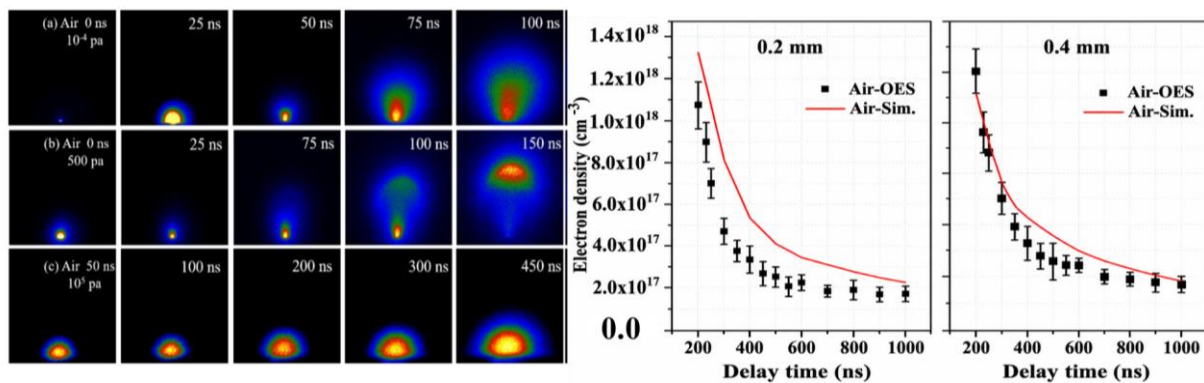


Figure 1.(A) Time-resolved plume emission images of laser-produced Al plasma in Air at 10^{-4} Pa (a), 500 Pa (b), and 10^5 Pa (c). Figure 1.(B) Experimental and simulated electron densities of laser-produced Al plasma in Air at 0.2mm, 0.4 mm from 200 to 1000 ns. Black solid squares denote the OES results, and red curve represents the RHDLP simulation.

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Polarization studies of X-rays from radiative recombination by means of diffraction spectrometry

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Precision measurements of x-rays emitted in radiative recombination (RR) of bare or few-electron ions with electrons carry information on the QED and relativistic effects [1] in this fundamental process of photon-matter interaction. The linear polarization of RR photons [2] was recently studied in experiments in ion storage rings [3] and ion traps [4-5]. It is particularly important when the RR x-rays are measured with a diffraction crystal spectrometer sensitive for polarization state of observed radiation. We discuss here the polarization of x-rays emitted in RR of mid-Z bare ions with cooling electrons at the CRYRING@ESR [6] storage ring to be measured by the developed asymmetric von Hamos (AvH) spectrometer [7]. Generally, the polarization of observed RR photons depends on three factors: 1) polarization of photon emitted in free-bound transition for a fixed electron velocity, 2) polarization averaged over electron velocity distribution in the electron cooler, and 3) diffraction of polarized photons by a crystal.

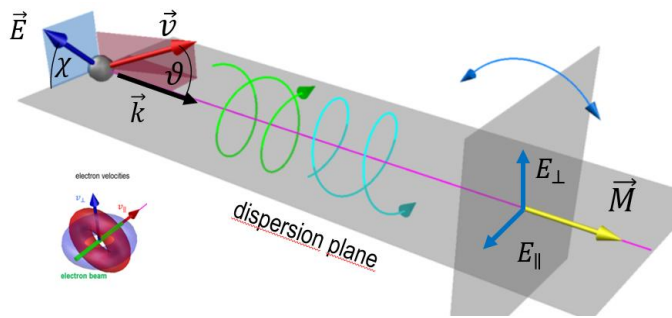


Figure 1. Schematics of polarized RR X-rays propagating in the dispersion plane of a diffraction spectrometer.

For cold electron beam at CRYRING@ESR electron cooler, $kT_{\perp} \approx \text{meV}$, the RR can be treated in the nonrelativistic low energy approximation [8]. Within this approach the polarization of K-RR x-

rays expected to be measured by a diffraction spectrometer will be discussed in terms of ray-tracing simulations. In particular, a possibility to study the circular and elliptical polarization of RR X-rays will be considered by using the reversed magnetic circular dichroism (MCD).

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