ABSTRACT BOOKLET

14th International Symposium of EBIS/T
EBIST2022

June 14-17, 2022

Whistler, BC Canada

Dear Colleagues,

I would like to welcome you to the 14th International Symposium on Electron Beam Ion Source and Traps – EBIS/T2022. I am pleased that we can have the 14th event of the series fully dedicated to Electron Beam Ion Sources and Traps and their applications. The 13th EBIS/T symposium was held at Fudan University, Shanghai, China in 2018, the 12th symposium at MSU, East Lansing, USA in 2014.

The symposium provides an environment to identify common challenges and areas of research and development to advance the field and to nurture the interest of young researchers. I'm very happy to see that we have a good fraction of young researchers in the list of delegates. The EBIS/T 2022 program will cover fundamental topics of EBIS/T science and technology:

- Progress and status of EBIS/T facilities
- EBIS/T physics including electron and ion beam optics and related simulations
- EBIS charge state breeder developments and operational experience
- Charge breeding of stable and radioactive isotopes
- Atomic spectroscopy of highly charged ions
- Applications of highly charged ions from EBIS/T

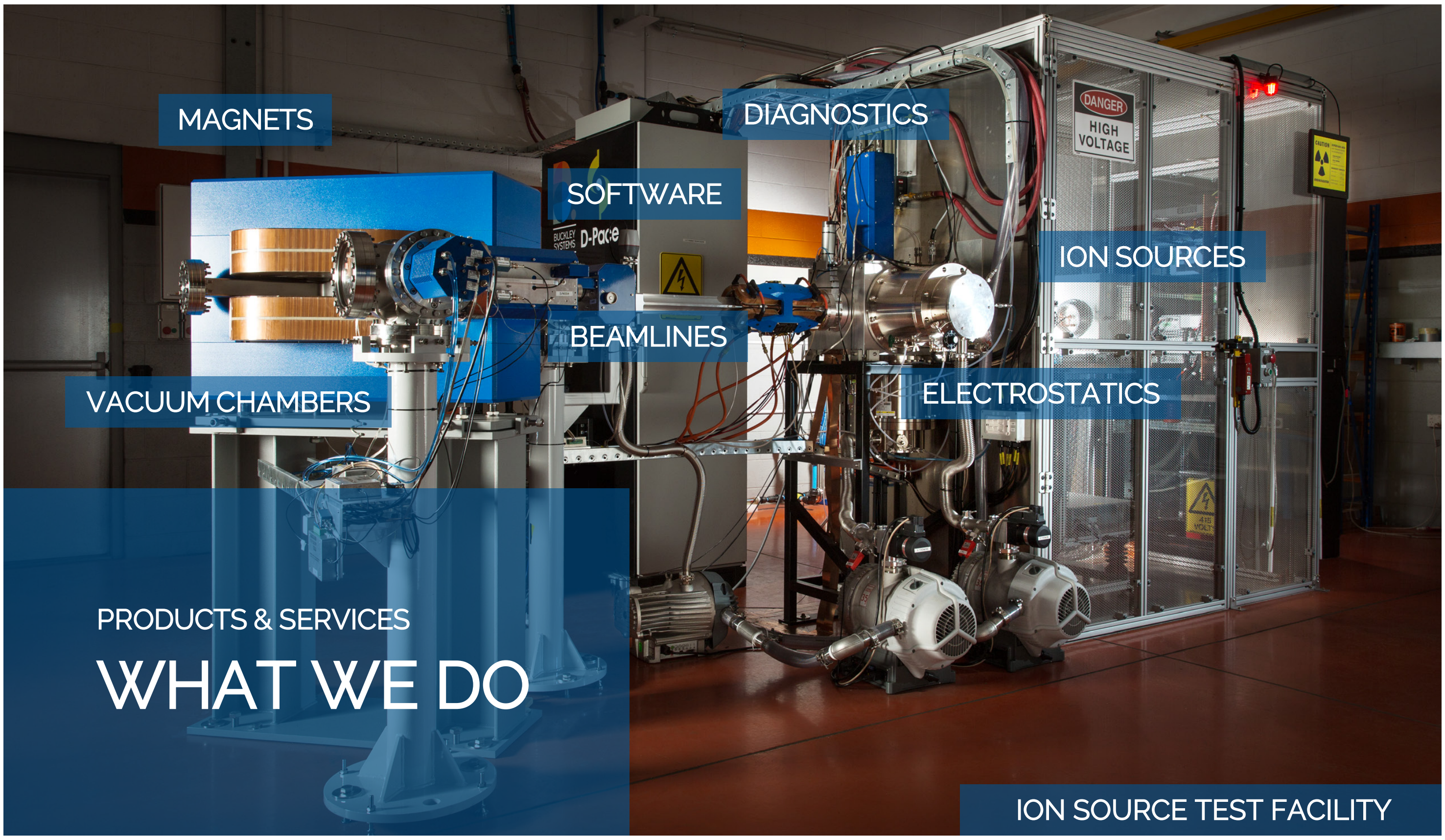
The symposium is hosted by TRIUMF (www.triumf.ca), Canada's Particle Accelerator Laboratory. TRIUMF employs a unique accelerator complex that comprises high intensity driver beams for secondary particle production and a world class rare isotope facility - ISAC. The Advanced Rare IsotopE Laboratory (ARIEL) project was conceived to provide a three-fold increase in the RIB delivery hours for the existing ISAC experimental facilities. ARIEL added a new beam preparation and charge state breeding system, CANREB. CANREB (CANadian Rare isotope facility with Electron Beam ion source) provides purification and preparation for post acceleration of rare isotopes at ARIEL. TRIUMF operates three charge state breeders, an operational ECRIS based charge state booster (CSB) and two EBIS based charge state breeders provided by the CANREB project, presently being commissioned, as well as an operational device, developed for the TITAN facility.

EBIS/T 2022 will be held at Whistler in British Columbia, Canada (https://www.whistler.com/). Located in the spectacular Coast Mountains of British Columbia just two hours north of Vancouver, Whistler is Canada's favourite year-round destination. There are two majestic mountains with a vibrant base Village. The Whistler area is not only a place of scenic wonder, but also a region that is rich with a fascinating history and cultural background. The venue is the Delta Hotels Whistler Village Suites (https://www.marriott.com/hotels/travel/ysewv-delta-hotels-whistler-village-suites/) on Main Street in the heart of Whistler.

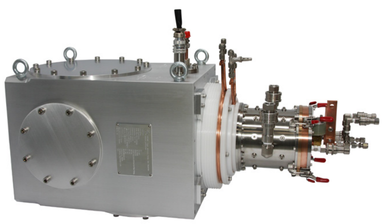
Thanks to all delegates and the team at TRIUMF who will make this 14th meeting a success. Again, welcome to EBIS/T2022 and to Whistler,

Oliver Kester
Director, Accelerator Division, TRIUMF

Chair EBIS/T2022



PRODUCT SPOTLIGHT



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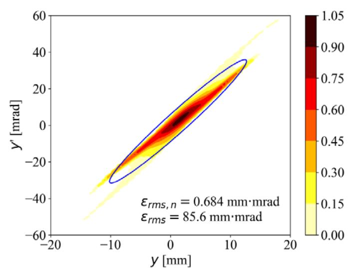

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ABOUT

D-Pace supplies products and services to the international commercial accelerator industry. Our products and areas of expertise include beamline systems, beam diagnostic devices, and ion sources for research, industrial, and commercial accelerator systems. Our knowledgeable staff are well-versed in the special details associated with designing accelerator-related equipment. D-Pace works with experts worldwide to meet our customer's needs, and is committed to **innovation**, **quality** and **customer satisfaction**.

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Time (start)	Tuesday June 14	Wednesday June 15	Thursday June 16	Friday June 17	Saturday June 18
09:00		Opening words (OK, BS)	(V, Fredrik Wenander) Latest EBIS development activities at CERN	(V, Peter Micke) An optical atomic clock based on a highly charged ion	TRIUMF tour
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09:20		(V, Hyock-Jun Son) Status of the High-Current EBIS and ReA EBIT Electron-Gun Upgrade at the Facility for Rare Isotope Beams			
09:30			(Richard Vondrasek) Performance of ANL EBIS and Radioactive Beam Production	(V, Roshani Silwal) Spectroscopy of Co-like highly charged ions with the NIST EBIT complementing the study of QED and higher order effects	
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09:50		(Amy Gall) Update on the SAO EBIT facility			
10:00			(Clayton Dickerson) The nuCARIBU Upgrade to the ATLAS Reaccelerated Beam Program	(Phillip Imgram) Collinear Laser Spectroscopy of 12C4+: First results towards an all-optical nuclear charge radius determination at COALA/TU Darmstadt	
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10:20		Coffee (30 min)	Coffee (30 min)	Coffee (30 min)	
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10:40					
10:50		(Edward Beebe) Extended Ebis Development at Bnl	(V, Shunsuke Ikeda) Development of a double-sided electron beam loss detector for ExtendedEBIS at BNL	(Naoki Kimura) Hyperfine-structure-resolved laser spectroscopy of highly charged ions in a compact EBIT	
11:00					
11:10					
11:20		(Sergey A. Kondrashev) Picosecond Laser Ablation and Ion Clusters for External Injection into the Extended EBIS	(Brad Schultz) Status of CANREB EBIS at TRIUMF	(Reinhold Hans Schuch) Excitation and Recombination Studies with Astrophysically Relevant Ions at S- EBIT	
11:30					
11:40					
11:50		(Seongjin Heo) Beam study of RFQ cooler buncher for EBIS charge breeder at RAON	(Mathieu Cavenaile) Pulse stretching out of the CANREB EBIS	*(Yang Yang) Charge-Exchange Factor in EBIT Spectral Analysis*	
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12:10		Lunch (90 min)	(Christopher Charles) Simulations of the CANREB EBIS: Where might the issue(s) be?	Lunch (90 min)	
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12:30			Lunch (90 min)		
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13:40		*(Endre Takacs) Nuclear charge Radius Measurements by Precision Extreme Ultraviolet Spectroscopy of Highly Charged Ions*		(Yutaka Tsuzuki) Polarimetry of hard X-rays from highly charged ions using a Si/CdTe Compton camera	
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14:00			IAB meeting (hybrid)		
14:10		(Friedrich Aumayr) Probing and Manipulating 2D-Materials With Highly Charged Ions		(Young-Ho Park) Progress and Status of RAON EBIS Charge Breeder	
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14:40		(Tino Morgenroth) The HI-Jena S-EBIT facility		*(René Steinbrügge) PolarX-EBIT -- A versatile tool for x-ray resonant spectroscopy*	
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15:30		(Anna A. Kwiatkowski) Studies with highly charged radionuclides at TITAN		*(Aung Sis Naing) Miniature Electron Beam Ion Trap and Penning Trap for Highly Charged Ions with Low Ionization Thresholds*	
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16:00		(Jaime Damiany Cardona) On the development of a new electron gun for the TITAN EBIT		(Sungnam Park) Highly Charged Argon Ion Spectroscopy Experiment at PAL-XFEL With the UNIST-EBIT	
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16:20		(Zachary Hockenbery) In-Trap Decay Spectroscopy Experiments at the TITAN EBIT		(Kyoung-Hun Yoo) Offline Test of EBIS Charge Breeder for RAON Facility Using Cs1+ Ion Beam	
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16:40		(Yilin Wang) Absolute nuclear charge radius measurements with EUV spectroscopy at TITAN EBIT		(Patrick R Johnson) Momentum Resolved Charge Exchange Cross Section Measurements and X-Ray Spectroscopy	
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17:00	Registration & reception				
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Table of Abstracts

WE1WH — Wednesday - Oral Session 1

WE1WH01 09:20 30 **Status of the High-Current EBIS and ReA EBIT Electron-Gun Upgrade at the Facility for Rare Isotope Beams**

***H.J. Son**, D.B. Crisp, A.I. Henriques, C. Knowles, A. Lapierre, S. Nash, S. Schwarz, C. Supangco, A.C.C. Villari (FRIB) E.N. Beebe (BNL)*

The ReA post-accelerator of the Facility for Rare Isotope Beams (FRIB) employs an Electron-Beam Ion Trap (EBIT) as a charge breeder to reaccelerate RIB up ~10 MeV/u. The ReA-EBIT uses a Pierce-type electron gun, partially magneto-immersed with a Ba-dispenser cathode, to produce an electron current of ~600 mA. It corresponds to a current density of ~340 A/cm^2 in the ion trap and a trap capacity of 10^{10} charges, which can be insufficient to handle future high RIB rates. To increase the trap capacity, a High-Current Electron-Beam Ion Source (HCEBIS) has been built based on the TestEBIS obtained from BNL. By using a 4-A electron beam launched from a LaB6 convex cathode immersed in a magnetic field, a current density of 298 A/cm^2 and a maximum capacity of 2.4×10^{11} charges are predicted. In parallel, the ReA-EBIT e-gun is being upgraded. A new insert is being fabricated to include a large-area dispenser cathode to achieve higher electron-beam current and density. A 2-A electron-beam is projected to reach a capacity of 5×10^{10} charges. In simulations a current density of 432 A/cm^2 was obtained in the trap region. This paper presents the status of the HCEBIS and the ReA-EBIT upgrade.

WE1WH02 09:50 30 **Update on the SAO EBIT Facility**

***A.G. Gall**, N.S. Brickhouse, A.R. Foster, E.S. Silver, R.K. Smith (CfA) E.T. Takacs, Y. Yang (Clemson University)*

The portable electron beam ion trap (EBIT) at the Smithsonian Astrophysical Observatory (SAO) was commercially purchased from Physics & Technology* in 2008. The first experimental campaign took place at Argonne National Laboratory where the SAO EBIT was paired with the Advanced Photon Source to observe the photoionization of highly charged Kr ions**. A leak in the collector cooling line following the transport back to SAO compromised the vacuum system, requiring total disassembly and detailed cleaning of the device. We report on the progress of the SAO EBIT facility, including design improvements made during the recommissioning process and our recent 'first light' measurements made with a broadband solid-state X-ray detector.

WE2WH — Wednesday - Oral Session 2

WE2WH01 10:50 30 **Extended EBIS Development at BNL**

E.N. Beebe, *G. Atoian, B.D. Coe, S. Ikeda, T. Kanesue, S.A. Kondrashev, M. Okamura, D. Raparia, J. Ritter, T. Rodowicz, R. Schoepfer, S.M. Trabocchi, A. Zelenski (BNL)*

The Extended EBIS will provide 2.10^9 Au^{32+}/pulse at the Booster ring entrance, a 40-50% intensity upgrade compared with the existing RhicEBIS at BNL. The axial magnetic field for an extended ion trap is achieved by using two closely coupled 5T superconducting solenoids. Initial operation will also provide beams of He^{2+} and H^+ from gas injection. With a future upgrade, beams of $3He^{2+}$ with intensity up to $2.5{\cdot}10^{11}$ ions per pulse and 70% polarization will be produced for the future Electron Ion Collider. Electron and ion beam tests were made using a novel external drift tube structure and gas injection module. 8A, 5ms and 5A, 100ms e-beams have been propagated. A fast pulsed valve and gas handing system, installed within the magnetic field of the first solenoid, was used to transfer ions to the downstream ion trap regions, with subsequent extraction of ions from the EBIS. The final configuration of the Extended EBIS drift tube structure and vacuum system has been installed and testing is in progress. External ion injection and ion extraction tests will be made after the Extended EBIS is installed using existing RHIC beam lines at the accelerator location.

WE2WH02 11:20 30 **Picosecond Laser Ablation and Ion Clusters for External Injection into the Extended EBIS**

S.A. Kondrashev, *E.N. Beebe, T. Kanesue, M. Okamura (BNL) R.H. Scott (ANL)*

The Extended EBIS is currently going through final development and offline testing and will replace RHIC EBIS as a main ion injector for both RHIC and NASA Space Radiation Laboratory in the beginning of 2023. Due to its longer ion trap, the Extended EBIS will enhance the maximum available beam intensity of Au^{32+}ions by 40 - 50% compared to RHIC EBIS. With a further upgrade, the Extended EBIS will also produce polarized $3He^{2+}$ ions for the future electron-ion collider. Two attractive options for external ion sources of singly charged ions which can significantly improve the operational flexibility and stability of Extended EBIS are a picosecond laser ion source and a cluster ion source. A laser with high rep-rate can produce quasi continuous singly charged ion beams from elements of solid targets for periods of tens of milliseconds, making it possible to take advantage of the ability of the EBIS to trap singly charged ions in accumulation injection mode. For most of gaseous elements, a source of cluster ions is quite an attractive option. Cluster ion beams have multiple advantages for external injection into EBIS trap in comparison with atomic ion beams.

WE2WH03 11:50 20 **Beam Study of RFQ Cooler Buncher for EBIS Charge Breeder at RAON**

S. Heo, *T. Hashimoto, J.H. Lee, Y.H. Park, K.H. Yoo (IBS) C. Lim (Korea University Sejong Campus) K.H. Yoo (UNIST)*

The beamline of Isotope Separation On-Line (ISOL) system at RAON was constructed. Currently, the beamline is commissioning using 133Cs and 120Sn ion beam. The produced ion from Target Ion Source(TIS) is delivered to Electron Beam Ion Source (EBIS) charge breeder through the Radio Frequency Quadrupole Cooler Buncher (RFQ CB). The RFQ CB handles and delivers the beams required by EBIS. A sufficiently cooled and bunched beam improves the charge breeding efficiency of EBIS. The RFQ CB cools and bunches DC beam from the TIS, delivering 10^{+8} ions per bunch to the EBIS. In order to increase the efficiency, the beam optics were optimized in consideration of the space charge effect. As a result, 10^{+8} ions could be sent in a bunch with a length of several ten microseconds. In this presentation, the beam commissioning results for RFQ CB and EBIS will be discussed.

15-Jun-22 13:40 – 15:00	Whiskey A/B for Plenary talks

WE3WH — Wednesday - Oral Session 3

WE3WH01 13:40 30 **Nuclear Charge Radius Measurements by Precision Extreme Ultraviolet Spectroscopy of Highly Charged Ions**

E.T. Takacs, *A. Hosier (Clemson University) D. Dipti, A.S. Naing, Yu. Ralchenko, J.N. Tan (NIST) J.D. Gillaspy (NSF) G. Gwinner (University of Manitoba) A. Lapierre (NSCL) A. Lapierre (FRIB) R. Silwal (TRIUMF) S.B. Steven (Université Grenoble Alpes)*

Accurate atomic calculations that account for many-body quantum electrodynamics (QED) in one- and two-valence electron highly-charged ions* ** allow for precise comparison between experiment and theory. Especially intriguing is the comparison of the wavelength separation of nearby spectral lines in different systems, because both the theoretical and experimental uncertainties can be considerably reduced for this quantity. Recent measurements in the extreme ultraviolet (EUV) range at the electron beam ion trap (EBIT) facility at the National Institute of Standards and Technology (NIST) demonstrated that these comparisons allow the determination of the nuclear charge radii differences between the ions involved.*** **** These measurements can emerge as a viable new method to determine nuclear radii of atoms in trace amounts of samples, including short lifetime rare isotopes.

WE3WH02 14:10 30 **Probing and Manipulating 2D-Materials with Highly Charged Ions**

F. Aumayr, *A. Niggas, R.A. Wilhelm (IAP TUW)*

With their reduced dimensionality, 2D materials exhibit exotic electronic and optical properties due to strong electron confinement and correlation effects. Modern synthesis techniques enable stacking of various 2D materials (semiconductors, semimetals, and insulators) in predefined sequences, leading to a wealth of novel devices & applications. Tailoring the properties of these so-called van der Waals heterostructures postgrowth would greatly benefit from a modification technique with a monolayer precision. To achieve such control, slow highly charged ions (HCI) appear ideal as they carry high amounts of potential energy, which is released rapidly (i.e. within the first few atomic layers) upon ion neutralization. Indeed, when irradiating a free-standing MoS2/graphene heterostructure with HCI we find that nm-sized pores are only produced in the MoS2 monolayer facing the ion beam, while the graphene underneath stays intact*. This contribution will show recent results on HCI-driven perforation of 2D materials and vdW heterostructures and discuss possible damage mechanism.

WE3WH03 14:40 30 **The HI-Jena S-EBIT Facility**

T. Morgenroth, *S. Bernitt, T. Stöhlker (HIJ)* ***T. Morgenroth***, *T. Stöhlker, S. Trotsenko, G. Vorobyev (GSI)* ***T. Morgenroth***, *T. Stöhlker (IOQ) R.H. Schuch (Stockholm University, Department of Physics)*

EBITs are versatile tools for spectroscopic studies of partially ionized atomic systems, mainly in the x-ray domain. This yields valuable information for fundamental atomic physics as well as astrophysics. Ion charge state distributions, resulting from ionization and recombination processes, can be observed and used to benchmark plasma dynamics. Furthermore, EBITs can be used as small stand-alone ion sources, as they are already used for example at the HITRAP facility. The Jena S-EBIT facility are two EBITs, the former R- and S-EBIT from Stockholm*, which both are suitable for x-ray spectroscopy studies and ion extraction. The S-EBIT I has been used as a tool for x-ray spectroscopy, including the testing of newly developed x-ray detectors, like the magnetic metallic microcalorimeter maXs30**. In addition, the setup was expanded by a testing beamline, to evaluate the potential of the S-EBIT I as an ion source. The S-EBIT II is currently in commissioning for operation as a standalone ion source for HITRAP in the near future. This will provide new opportunities for local experiments, like the ARTEMIS experiment, independently from the GSI accelerator infrastructure.

WE4WH — Wednesday - Oral Session 4

WE4WH01 15:30 30
Studies with Highly Charged Radionuclides at TITAN

A.A. Kwiatkowski *(TRIUMF)*

Radioactive highly charged ions are of intrinsic interest in nuclear physics. High charge states can modify the available decay channels, for example forcing decay through highly suppressed modes or opening otherwise inaccessible decays. The subsequent change in nuclear lifetime is relevant to nucleosynthesis studies, which occur in hot, ionizing astrophysical environments. All requisite ingredients for such studies are united at the TITAN facility. Its EBIT, with electron beam energies up to 64 keV and currents up to 5A, charge breeds radionuclides produced at ISAC-TRIUMF. The trap ions are viewed through ports by a suite of germanium detectors or an extreme ultraviolet spectrometer for in-trap spectroscopy. Separately, the charge breeding capabilities are essential to boost the performance of the Penning trap mass spectrometer. The high charge states improve the resolving power and precision while the charge breeding itself can be used to improve beam purity. These enhancements are critical in studies of fundamental symmetries. TITAN's program of radioactive highly charged ions will be presented.

WE4WH02 16:00 20
On the Development of a New Electron Gun for the TITAN EBIT

J.D. Cardona, *K. Dietrich, J. Dilling, O.K. Kester, A.A. Kwiatkowski (TRIUMF) G. Gwinner (University of Manitoba)*

To improve the charge breeding capabilities of the TITAN EBIT a new electron gun has gone into development. Increasing electron beam quality and its control were the sought-after attributes with this updated design. The electron gun within its TITAN EBIT environment was simulated using the TREK package. A switch to a Wehnelt electrode geometry was chosen and optimized to extract up to 5 A, 66 keV electron beams. Due to the strong fringe field of the unshielded 6 T magnet, options for the passive and active shielding of the gun were explored. During the design process, careful attention was paid to safety and mechanical considerations. Simulations and the status of the new electron gun will be presented.

WE4WH03 16:20 20
In-Trap Decay Spectroscopy Experiments at the TITAN EBIT

Z.M. Hockenbery, *A.A. Kwiatkowski, K.G. Leach (TRIUMF) C. Andreoiu (SFU)*

Highly Charged Ions (HCI) provide a unique probe that can be used to study the properties of radioactive nuclei. This is due to an interaction between the nucleus and the orbital electrons and has been used to uncover new nuclear decay modes, leading to observations of decay lifetimes different than the atomic lifetimes. Due to the unique challenge of producing and storing radioactive HCI, these types of experiments are quite rare. Here we report the commissioning of a new HPGe array for in-trap decay spectroscopy on radioactive HCI. The HPGe array is built around TITAN's Electron Beam Ion Trap (EBIT), which receives radioactive ion beams, charge breeds them, and stores them as HCI. Two future experiments are discussed: 1) the resonant stimulation of Nuclear Excitation via Electron Capture (NEEC) in ^{129}Sb and 2) the observation of nuclear two-photon emission in ^{98}Zr and ^{98}Mo.

WE4WH04 16:40 20
Absolute Nuclear Charge Radius Measurements with EUV Spectroscopy at TITAN EBIT

Y. Wang *(UBC & TRIUMF) J.D. Cardona, A.A. Kwiatkowski (TRIUMF) G. Gwinner (University of Manitoba) A. Lapierre (NSCL) A. Lapierre (FRIB) R. Silwal (Appalachian State University) E.T. Takacs (Clemson University)*

Nuclear charge radii, a quantity crucial in many nuclear physics studies, can be extracted from H^- and Li-like electronic transitions, even in heavy ions, when combined with atomic theory * **. The latter has progressed to permit such calculations from transitions in Na-like ions *** ****. Charge breeding to Na-like charge state eases experimental requirements. To this end, at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility, we are developing a high-efficiency, flat-field grazing incidence extreme-ultraviolet (EUV) spectrometer, for the measurement of absolute nuclear charge radii of short-lived nuclides. It will be installed to the Electron Beam Ion Trap (EBIT), which is capable of electron beam energies up to 66 keV. The spectrometer is designed to optimize transmission efficiency in the EUV regime. The ray-tracing simulations done in Shadow3 ***** will be presented. The first measurement candidates are ^{211}Fr and a suitable spin-0 isotope of Ra, which are relevant for atomic parity violation (APV) experiments and searches for time-reversal violating permanent electric dipole moments (EDM).

16-Jun-22 09:00 – 10:20 | Whiskey A/B for Plenary talks

TH1WH — Thursday - Oral Session 1

TH1WH01 **Latest EBIS Development Activities at CERN**
09:00 30

F.J.C. Wenander, *V. Bencini, N. Bidault, G. Khatri, H. Pahl (CERN) A.I. Pikin (BNL)*

REXEBIS is an on-line device used for charge breeding of radioactive isotopes for the REX/HIE-ISOLDE post-accelerator. At REXEBIS, a gun using a nonadiabatic magnetic element to increase the electron current density has been installed. We will report on the results from the electron beam commissioning and present findings from various charge breeding studies. TwinEBIS is a test stand for the development of high current-density electron guns and for rapid production of bunches of $12C^{6+}$ for cancer treatment. Early tests with a Brillouin type electron gun installed at TwinEBIS were encouraging, with very low electron losses recorded. The ion extraction commissioning phase confronted us with unforeseen obstacles; only a fraction of the expected ion number is extracted and only moderate charge states are reached when injecting noble gases. We could demonstrate that some of the ions are lost at the ion extractor. In this respect, we will present the design concept of a new electron beam collector. Finally, we will briefly comment on the performance of a traditional IrCe cathode installed at REXEBIS, and a relatively new type of dispenser cathode from the Beijing University of Technology.

TH1WH02 **Performance of ANL EBIS and Radioactive Beam Production**
09:30 30

R.C. Vondrasek, *M.D. Gott, J.P. Greene, J.T. McLain, R.H. Scott (ANL)*

Operation of the Argonne National Laboratory Electron Beam Ion Source was paused in March 2020 due to COVID restrictions. Source operation resumed in early 2022 with a focus on elongating the extracted beam pulse while maintaining high breeding efficiency. Through modification of the trap emptying waveform, a 10 ms pulse of $133Cs^{27+}$ with a breeding efficiency of 21% has been achieved. In addition to the EBIS work, the ECR ion sources have produced radioactive beams of C-14 from gaseous material and Ra-223 using parent material produced at Oak Ridge National Laboratory.

TH1WH03 **The nuCARIBU Upgrade to the ATLAS Reaccelerated Beam Program**
10:00 20

C. Dickerson, *R.V. Gampa, J.A. Nolen, G. Savard, R.C. Vondrasek (ANL)*

Beams of re-accelerated, exotic neutron-rich nuclei allow access to little known regions of the nuclear landscape that are important both structurally and for r-process nucleosynthesis. The nuCARIBU upgrade will increase the consistency, reliability, and intensity of radioactive beam at the ATLAS-CARIBU accelerator facility, and will raise the demands on the CARIBU EBIS charge breeder. nuCARIBU will replace the existing source of ^{252}Cf with a system of neutron induced fission of actinide foils as the RIB production mechanism. The new RIB production scheme will be integrated into the existing collection and separation equipment. Details of the nuCARIBU system and the expected impacts to the re-accelerated beam program will be discussed.

TH2WH — Thursday - Oral Session 2

TH2WH01 10:50 30 **Development of a Double-Sided Electron Beam Loss Detector for Extended EBIS at BNL**

S. Ikeda, *E.N. Beebe, S.A. Kondrashev (BNL)*

The ExtendedEBIS upgrade is being developed at Brookhaven National Laboratory to replace RhicEBIS. ExtendedEBIS consists of two series solenoids to allow increased trap length and to accommodate an internal gas injection system in the upstream solenoid. An insertable electron beam detector is installed between the solenoids. The detector comprises two sets of quadrant plates placed on either side of a base plate. Each set of the quadrants has an (8.5 mm) aperture, larger than the beam diameter (4.5 mm) at that location. By comparing the 4 signals from any intercepted losses on the cathode facing side, the pulsed electron beam position can be monitored. Therefore, one can continuously adjust the electron beam radial position at the axial midplane of Extended EBIS system without stopping the beam. The detector is useful for the beam alignment during commissioning and for checking the transverse beam steering system during operations. The set of the quadrants on the collector facing side is used to measure the electrons back-streaming from the collector or collector suppressor electrodes. During this presentation, the detector design and electron beam test results will be discussed.

TH2WH02 11:20 30 **Status of CANREB EBIS at TRIUMF**

B.E. Schultz, *F. Ames, S.B. Beale, M. Cavenaile, C.R.J. Charles (TRIUMF)*

The Canadian Rare isotope facility with Electron Beam ion source (CANREB) is an essential part of the Advanced Rare Isotope Laboratory (ARIEL) presently under construction. CANREB can accept stable or rare isotope beams from a variety of ion sources, delivering high purity beams of highly charged ions (HCI) to experiments. The injected beams are bunched and using an RFQ cooler/buncher, and energy adjusted using a pulsed drift tube for injection into an EBIS charge state breeder. The EBIS was designed for a maximum electron beam current of 500 mA at a maximum magnetic field of 6 Tesla. The EBIS can accept ion beam energies up to 14 keV and HCI with $3 < A/q < 7$ will be charge bred and extracted. The HCIs are separated using Nier-type spectrometer before being transported to the linac for post-acceleration. Recent results from CANREB EBIS operation will be presented.

TH2WH03 11:50 20 **Pulse Stretching Out of the CANREB EBIS**

M. Cavenaile, *F. Ames, C.R.J. Charles, O.K. Kester, B.E. Schultz (TRIUMF) R. Kanungo (Saint Mary's University)*

The CANadian Rare isotope facility with Electron-Beam ion source (CANREB) at TRIUMF is set to deliver rare isotope beams in high charge states. In the Electron Beam Ion Source (EBIS) ions are charge-bred by collisions with an electron beam of up to 500 mA. A strong magnetic field (up to 6T) maximizes the overlap between ions and electron beam and increases the breeding efficiency. Ion confinement is maintained by a combination of an electrostatic field and the electron beam space-charge potential. Ions are released by lowering the trapping potential with a step function. The extraction scheme produces pulses shorter than 10 μs with high instantaneous rates that can saturate detectors in experiments. Stretching the pulse can be done using a slowly varying function to release the ions. The ideal function produces a pulse with a flat top distribution and can be calculated by knowing the ion energy distribution inside the trap. Theoretical calculations, diagnostics improvement as well as early measurements will be discussed.

TH2WH04 12:10 20 **Simulations of the CANREB EBIS: Where Might the Issue(s) Be?**

C.R.J. Charles, *F. Ames, M. Cavenaile, B.E. Schultz (TRIUMF)*

The CANREB EBIS at TRIUMF has enjoyed an ongoing issue of high-voltage breakdown in the presence of applied magnetic field. This issue continues to prevent using the system at its maximal specifications. In the latest mitigation attempt, the full 15 kV can be applied to the drift-tubes without magnetic field. However, it is only possible to operate at ~7 kV in a 1 Tesla field before discharge occurs. The discharge appears to occur mostly in the collector-trumpet region near the wiring that delivers high-voltage to the drift tubes (the wiring transitions from room temperature to 4 Kelvin). After two different design changes in this area, this high-voltage breakdown with applied B-field has unfortunately not been solved. Here I present OmniTrak 3D simulations of the CANREB EBIS in an ongoing effort to understand the physics of this chronic problem, and to promote lively discussions on other ways to remedy this problem, so that the EBIS can be restored to rare ion beam charge breeding and beam delivery.

FR1WH — Friday - Oral Session 1

FR1WH01 09:00 30 **An Optical Atomic Clock Based on a Highly Charged Ion**

***P. Micke**, E. Benkler, N. Huntemann, S.A. King, R. Lange, T. Leopold, P.O. Schmidt, L.J. Spieß, A. Surzhykov, A. Wilzewski, V.A. Yerokhin (PTB) J.R. Crespo López-Urrutia, **P. Micke** (MPI-K)*

Highly charged ions (HCI) have many favorable properties*. In particular, they are well-suited for high accuracy optical atomic clocks. However, up to recently HCI were not accessible for such type of instruments. In this talk, I will briefly review how we overcame all previous obstacles by demonstrating Coulomb crystallization of HCI**, the implementation of quantum logic spectroscopy***, and ground-state cooling of weakly-coupled motional modes****. With these prerequisites we realized the first optical atomic clock based on an HCI by stabilizing an ultrastable clock laser to the ground-state fine-structure transition in Ar^{13+} at 441 nm. By comparing this optical frequency to the one of the electric-octupole transition in $171Yb^{+}$, we realized a frequency ratio measurement with a fractional uncertainty of about 1x10-16, limited by statistics. We thereby improved the uncertainty of the absolute transition frequency of Ar^{13+} by about eight orders of magnitude. Furthermore, we compared the transition frequencies of $40Ar^{13+}$ and $36Ar^{13+}$ and improved the isotope shift uncertainty by nine orders of magnitude.

FR1WH02 09:30 30 **Spectroscopy of Co-Like Highly Charged Ions with the NIST EBIT Complementing the Study of QED and Higher Order Effects**

***R. Silwal** (TRIUMF) T. Brage (Lund University) D. Dipti, Yu. Ralchenko (NIST) A. Hosier, S.C. Sanders, E.T. Takacs (Clemson University) R. Hutton (Fudan University)*

Electron Beam Ion Traps (EBIT) can be used to create highly charged ions (HCI) of almost any charged state by simply tuning the energy of the electron beam. Atomic spectroscopy with EBITs, therefore, offers a great platform to identify previously unmeasured transitions, understand atomic processes in laboratory and astrophysical plasmas, and explore the structure of unique electron configurations to benchmark modern atomic theories. An interesting case of the latter is the fine structure 3d9 2D3/2 - 2D5/2 transitions in Co-like ions with suppressed correlations and enhanced relativistic and quantum electrodynamics (QED) effects *, **. These transitions, also labeled as "Layzer quenched" transitions, can be used to accurately test current methods to compute Breit and QED effects. Here, we present direct measurements of the 3d9 2D3/2 - 2D5/2 fine structure of Co-like Yb, Re, Os, and Ir using the National Institute of Standards and Technology (NIST) EBIT facility. Comparisons with the existing theories ***, **** are made in an effort to understand the Briet interaction and the self-energy contribution to QED.

FR1WH03 10:00 20 **Collinear Laser Spectroscopy of $12C^{4+}$: First Results Towards an All-Optical Nuclear Charge Radius Determination at COALA/TU Darmstadt**

***P. Imgram**, K. König, W. Nörtershäuser (TU Darmstadt) B. Maaß (ANL)*

For the determination of nuclear charge radii different measurement techniques have been developed over time such as elastic electron scattering or muonic spectroscopy. Atomic spectroscopy has so far been limited to H and He or to the differential nuclear charge radii of short-lived isotopes accessed by collinear laser spectroscopy (CLS). In an all-optical approach we want to determine the absolute charge radii of further He-like ions by exciting them from the metastable 2 3S1 state, which has a lifetime of a few 10-100 ms, to the 2 3PJ states. This experimental value is to be compared with nonrelativistic QED calculations* that are currently being performed. The results will compliment and improve existing measurements of nuclear charge radii. The first high-precision collinear laser spectroscopy measurements of $12C^{4+}$ have been carried out at the Collinear Apparatus for Laser Spectroscopy and Applied Physics (COALA) at TU Darmstadt which has recently been upgraded with an electron beam ion source to produce the highly charged ions. This contribution will summarize the current status of the project and present first results which will serve to benchmark the QED calculations.

FR2WH — Friday - Oral Session 2

FR2WH01 10:50 30 **Hyperfine-Structure-Resolved Laser Spectroscopy of Highly Charged Ions in a Compact EBIT**

N. Kimura *(RIKEN, Atomic, Molecular and Optical Physics Laboratory)*

Hyperfine-structure is a small energy splitting in an atomic or molecular level system. This mainly originates from magnetic interaction between the nucleus and electrons, and its spectroscopic research provides rich information for studying nuclear properties and atomic structures. Highly charged ions (HCIs) are excellent targets for such spectroscopic research because the contracted electron cloud enhances the splitting energy of its hyperfine-structure and gives advantages to searching for fundamental physics. Additionally, recent proposals for a new type of atomic clock using heavy HCIs with many electrons enhance the importance of understanding the hyperfine-structures. However, there have been no established spectroscopic methods for observing the hyperfine-structures of such moderate charge state HCIs. In this talk, we present a recent experimental demonstration for hyperfine-structure-resolved laser spectroscopy of HCIs stored in a compact electron beam ion trap at the University of Electro-Communications.

FR2WH02 11:20 30 **Excitation and Recombination Studies with Astrophysically Relevant Ions at S-EBIT**

R.H. Schuch *(Stockholm University, Department of Physics)*

We measured electron-impact excitation and recombination rate coefficients at the Stockholm Electron Beam Ion Trap (S-EBIT) with Highly Charged Ions (HCI) such as Siq+ and Sq+ that are of astrophysical interest. The experimental method was a combination of photon detection from the trapped ions and subsequently extraction and time-of-flight analysis of these ions. This allows to obtain recombination rate coefficients separately for every charge state, and together with the photon spectra of these ions also the excitation rate coefficients. Particularly electron-impact excitation measurements are rare, although important for astrophysics, and their description are challenging for theory. Here we compare the experimental results* ** with calculations of recombination and excitation rates for Si10±Si13+ and S12±S15+ ions*** **** using relativistic distorted-wave approach*** ****. The direct and resonant excitation (EIE) cross sections associated with 1s nl core excitations are calculated for the ground states of Si10±Si13+ and S12±S15+ions3*** ****. The different recombination and excitation channels and differences between experiment and theory are discussed.

FR2WH03 11:50 20 **Charge-Exchange Factor in EBIT Spectral Analysis**

Y. Yang*, A. Hosier, E.T. Takacs (Clemson University) N.S. Brickhouse, A.R. Foster, A.G. Gall, R.K. Smith (CfA) D. Dipti, A. Naing, G. O'Neil, Yu. Ralchenko, P. Szypryt, J.N. Tan (NIST) D. Schultz (Northern Arizona University)*

Spectral analysis of an EBIT plasma requires an understanding of the ionization balance. Simulations require accurate atomic data (excitation, ionization, and recombination cross sections) and known operating conditions (electron beam density and energy, and trapped ion temperature). For highly charged ions in an EBIT, charge exchange (CX) recombination is significant despite the relatively low density of neutral ions. Uncertainties of the CX cross sections combined with the limited knowledge of the experimental parameters (neutral density, relative ion velocity) constrain the models of spectral emission. To combine the unknown factors into one free parameter, we introduce a charge exchange factor that can be accurately determined experimentally using measured line intensity ratios and theoretical cross sections. Using measured Fe spectra at multiple electron beam energies (9.21 kV x 18 kV), the charge exchange factor was determined in a measurement at NIST. The factor was used in our collisional-radiative (CR) model* to produce simulated spectra and line intensity ratios. The agreement demonstrates the usefulness of this approach for spectral modeling.

FR3WH — Friday - Oral Session 3

FR3WH01 13:40 30 **Polarimetry of Hard X-Rays from Highly Charged Ions Using a Si/CdTe Compton Camera**

Y. Tsuzuki, *T. Takahashi (Kavli IPMU) N. Nakamura, N. Numadate, S. Oishi (University of Electro-communications) H. Odaka (The University of Tokyo, Graduate School of Science) Y. Uchida (Hiroshima University, Faculty of Science) S. Watanabe (ISAS/JAXA) H. Yoneda (RIKEN)*

Polarimetry of hard X-rays emitted through interactions between highly charged heavy ions and electrons is important. In particular, polarized hard X-rays emitted from high-Z ions are of significant importance in evaluating relativistic and quantum-electrodynamics interactions such as the Breit interaction. A new polarimetric method has been needed so far to achieve high sensitivity and accuracy for hard X-ray polarimetry. Recently, novel Compton polarimeters, called silicon (Si) / cadmium telluride (CdTe) Compton cameras, have proven powerful for observations of celestial X-ray and gamma-ray objects. We applied a Si/CdTe Compton camera for the polarimetry of hard X-rays from highly charged ions and evaluated its polarimetric performance. A series of experiments were conducted to measure the degree of polarization of X-rays emitted through radiative recombination of highly charged krypton ions. The uncertainty of the result is sufficiently small to probe effect of the Breit interaction on X-ray polarization.

FR3WH02 14:10 30 **Progress and Status of RAON EBIS Charge Breeder**

Y.H. Park, *S. Heo, J.H. Lee, T.S. Shin (IBS) S.A. Kondrashev (BNL) C. Lim (Korea University Sejong Campus) H.J. Son (FRIB) K.H. Yoo (UNIST)*

An electron beam ion source (EBIS) was considered as a charge breeder for rare isotopes produced from isotope separation on-line (ISOL) system of the heavy ion accelerator RAON in Korea. The off-line installation of the RAON EBIS was conducted at the Korea University, Sejong from 2017 to 2020. A lot of effort went into getting very low vacuum pressure of around 10^{-10} torr at the breeding region adopting cryopumps and getter pumps as well as vacuum-firing the chambers. In order to find and align the central magnetic field lines of the solenoids, we used a gimbal mount for a hall probe with rotation, tilt, and translation functions. With the help of four sets of steering coils around the drift tube chamber, we successfully transport electron beam of 2 A at a magnetic field of 6 T producing charge bred ions from the residual gas. After confirming the performance of our EBIS system at the off-line site, we moved it to RAON accelerator site at Shindong and started the on-line installation from 2021. Cesium test ion beam was used for the first charge breeding experiment showing a relative abundance of Cs^{27+} ions more than 20 % with electron beam current of 1 A in breeding time of 40 ms.

FR3WH03 14:40 20 **PolarX-EBIT – A Versatile Tool for X-Ray Resonant Spectroscopy**

R. Steinbrügge *(HIT) S. Bernitt (HIJ) J.R. Crespo López-Urrutia, S.K. Kühn, M. Togawa (MPI-K) M.A. Leutenegger, C. Shah (NASA Goddard Space Flight Center)*

Resonant photo-excitation provides a direct tool for investigating electronic transitions in atoms and ions. By combining EBITs and ultrabrilliant x-ray sources this kind of spectroscopy became also available for highly charged ions. Here we present the PolarX-EBIT, a compact permanent magnet EBIT* built by the Max-Planck-Institute for Nuclear Physics and University Jena specifically for operation at synchrotron radiation light source facilities. It employs a novel off-axis electron gun, allowing the photon beam to pass through the trap and be made available for downstream setups. Additionally, it features fast-switching power supplies for charge breeding and background reduction schemes, a time-of-flight ion extraction beamline and large area SDD detectors. Multiple successful experiments have been performed in the soft and hard x-ray regimes at the light sources BESSY II and PETRA III, measuring transition energies, oscillator strengths, natural line widths, photoionization and population balance**. Furthermore, narrow lines of He-like ions have also been used as a diagnostic tool for the spectral performance of the photon beamlines.

FR4WH — Friday - Oral Session 4

FR4WH01 **Miniature Electron Beam Ion Trap and Penning Trap for Highly Charged Ions with Low Ionization Thresholds**
15:30 30
A.S. Naing, *D.S. La Mantia, J.N. Tan (NIST)*

The development of electron beam ion sources/traps (EBIS/T) has advanced the study of highly charged ions (HCI). The original EBIT employed superconducting magnets to intensify the electron beam. In recent years, the use of rare-earth magnets, e.g. neodymium iron boron (NdFeB), has made it possible to construct small EBIS/T(s) and other ion traps* At NIST, a room-temperature miniature EBIT (mini-EBIT with a field of 0.29 T) using a pair of axial NdFeB rings was built as a source of ions with ionization thresholds up to 900 eV, offering a simpler setup and easy operation. Ease of construction should enable more applications. To recapture and isolate ions, we discuss the design and construction of a compact Penning trap** with a magnetic field of 0.755 T, in which three pairs of radial NdFeB rings are used to generate a trap volume of 230 mm^3 with good homogeneity. Based on the prototype mini-EBIT and the 0.755 T unitary Penning trap, another permanent magnet EBIT is being built at NIST to attain an axial field of about 0.676 T. Potential applications include the production of HCIs such as Pr X, Nd XI for HCI-based atomic clocks*** and the calibration of quantum sensors.

FR4WH02 **Highly Charged Argon Ion Spectroscopy Experiment at PAL-XFEL with the UNIST-EBIT**
16:00 20
P. Park, *M. Chung, B.K. Shin (UNIST)*

Visible matters exist mostly in highly charged states. To analyze those, CHEA (Centre for High Energy Astrophysics) built an Electron Beam Ion Trap (EBIT) to acquire spectral data of individual elements in their highly charged states. Preliminary experiments on connecting the EBIT with the PAL-XFEL have been conducted over the two R&D beam times. During these shifts, we study the highly charged argon with the aid of a monochromatic photon beam from the PAL-XFEL (Pohang Accelerator Laboratory X-ray Free Electron Laser). In this work, we demonstrate argon spectroscopic measurements as well as preparation for our final target experiments with iron.

FR4WH03 **Offline Test of EBIS Charge Breeder for RAON Facility Using Cs^{1+} Ion Beam**
16:20 20
K.H. Yoo, *M. Chung (UNIST) S. Heo, J.H. Lee, Y.H. Park (IBS) C. Lim (Korea University Sejong Campus)*

The heavy-ion accelerator RAON is being developed by the Rare Isotope Science Project (RISP) in the Institute for Basic Science (IBS) of Korea for basic science research through experiments with rare-isotope (RI) beams. Various RI beams are transported from the Isotope Separation On-Line (ISOL) beamline, and they are accelerated in the superconducting post-accelerator. The energy requirement of the RI beams for the post-accelerator is 10 keV/ u, and their charge state must be adjusted to facilitate the acceleration. The Electron Beam Ion Source (EBIS) charge breeder is installed before the post-accelerator to match the mass-to-charge ratio (A/q) of the RI beams to the accelerator condition. A singly charged ion beam is trapped in the EBIS and interacts with the compressed electron beam in a strong magnetic field. The electron beam removes electrons of the ion beam by collision and produces highly charged ions. A Cs test ion source is used for the offline test of the EBIS charge breeder, and the results will be described in this presentation.

FR4WH04 **Momentum Resolved Charge Exchange Cross Section Measurements and X-Ray Spectroscopy**
16:40 20
P.R. Johnson *(Clemson University)*

Highly charged ions are ubiquitous in the Universe and consequently understanding the X-ray spectra resulting from charge exchange with these species is critical to fully interpreting X-ray spectra of astrophysical origins. Measuring the X-ray spectra in coincidence with momentum-resolved cross sections in a beam line using extracted ions will yield n,l state-selective cross sections as a function of collision energy. We will also compute theoretical n,l state-selective cross sections using a variety of state of the art methods. This combined experimental and theoretical effort will provide a powerful benchmark for ions and collision energies of astrophysical interest. Progress towards the laboratory based investigation of these rates will be presented.

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Authors