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PICOSECOND LASER ABLATION AND ION CLUSTERS FOR EXTERNAL INJECTION INTO THE EXTENDED EBIS*

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Abstract

The Extended Electron Beam Ion Source (EBIS) is currently going through final development and offline testing and will replace Relativistic Heavy Ion Collider (RHIC) EBIS as a main ion injector for both RHIC and National Aeronautics and Space Administration (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. The inclusion of a high efficiency gas injection module will give Extended EBIS an improved capability to generate intense beams of light ions, such as $^4He^{2+}$ and $^3He^{2+}$. With a further upgrade, the Extended EBIS will also produce polarized $^3He^{2+}$ ions for the future Electron-Ion Collider (EIC). Similarly to RHIC EBIS, charge breeding mode will continue to be important for Extended EBIS. Singly charged ions produced in external ion sources will be accumulated in the Extended EBIS, contained until required charge state is reached, and then extracted from the EBIS in intense pulses of highly charged ions. 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. We studied the properties of different element plasmas generated by a ps-laser with 1.27 mJ energy within an 8 ps pulse to investigate feasibility and specify parameters of a laser ion source for Extended EBIS using both accumulation and single pulse injection modes. It is shown that both injection modes are accessible with a single ion source geometry and single injection line. 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. The electrical current required to deliver the same number of atoms into the trap is several magnitudes lower in both single pulse and accumulation injection modes in this case. It is especially advantageous that even single pulse injection mode for hydrogen and helium clusters with cluster size of about 1000 atoms becomes feasible. It is shown that cluster ion beam with the same particle current is easier to transport and inject into the EBIS trap due to less severe space charge effects. A cluster ion source with the required intensity is viable and can be designed, built, optimized, and tested.

EXTENDED EBIS

The Extended EBIS offline testing setup is presented in Fig. 1.

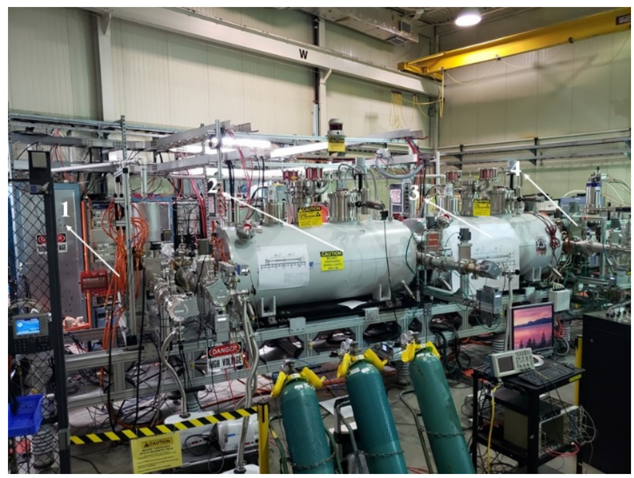

Figure 1: Extended EBIS offline testing setup (1 – electron gun, 2 and 3 – 2 m, 5 T superconducting solenoids, 4 – electron collector).

The main features of Extended EBIS are:

- New oxide electron gun (e-gun) cathode with significantly lower operational temperature compared to previously used IrCe cathode
- Lorenz pulsed gas valve to inject different gasses directly into drift tube structure
- Two custom high capacity ZAO NEG linear modules mounted right in a vicinity of the ion traps [1]
- Advanced vacuum system [2]
- Quadrant electron beam detector for electron beam alignment and measurement of back streaming from the collector electrons placed in between superconducting solenoids [3].

We plan to complete offline testing of Extended EBIS by the end of this summer with following source relocation, installation, and commissioning in the injector area.

"FAST" AND "SLOW" ION INJECTION MODES INTO EBIS

For most of ion species the Extended EBIS will operate as a charge bleeder of 1+ ions injected from external ion sources, although some gaseous species will be injected by

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THE JENA S-EBIT FACILITY

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Abstract

Electron beam ion traps (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. 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 micro-calorimeter maXs30. In addition, the setup was expanded by a testing beamline, to evaluate the potential of S-EBIT I as an ion source. 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 Gesellschaft für Schwerionenforschung (GSI) accelerator infrastructure.

INTRODUCTION

The two Jena S-EBIT traps are based on the cryogenic R- and S-EBIT from the AlbaNova University Centre in Stockholm. R-EBIT was set up in 2005 and used for x-ray studies and measurements with extracted and charge-separated ions. The construction of the S-EBIT upgrade started in 2008, with the aim to increase the maximum electron-beam energy from 30 to 260 keV [1]. In 2013/14 all R- and S-EBIT parts were moved to the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt. Here, they were assembled as two independent EBITs, S-EBIT I & II. While S-EBIT I is already in operation, S-EBIT II is currently in commissioning.

THE FACILITY

The design of both EBITs is based on the Super EBIT from the Lawrence Livermore National Laboratory [2], with a difference that cooling of the super conducting magnet of each EBIT is achieved by means of a cold head and therefore both setups are liquid helium free. The operating parameters of both EBITs are listed in Table 1.

Table 1: S-EBIT Operating Parameters Comparison

Parameter	S-EBIT I	S-EBIT II
Type	Cryogenic (liquid helium free)	
Magnetic field	3 T	4 T
Electron-beam energy	40 keV	260 keV
Electron-beam current	180 mA	250 mA
Electron-beam radius (80%)	37 μm	
Trap length	2 cm	
Ions per pulse	10^7	
Maximum charge state	U^{72+}	U^{92+}
Status	Operating	Commissioning

S-EBIT I

S-EBIT I is at the moment in operation as part of the Jena S-EBIT facility. It is used as tool for x-ray spectroscopy studies, with electron-beam energies of up to 40 keV. This is realised by having the drifttubes operating at positive high voltages while the cathode is kept at ground potential. A section view of the setup is shown in Figure 1.

S-EBIT I is a reliable x-ray source, providing fluorescence from several different ion species, including heavy highly charged ions. This enables the ability of testing newly de-

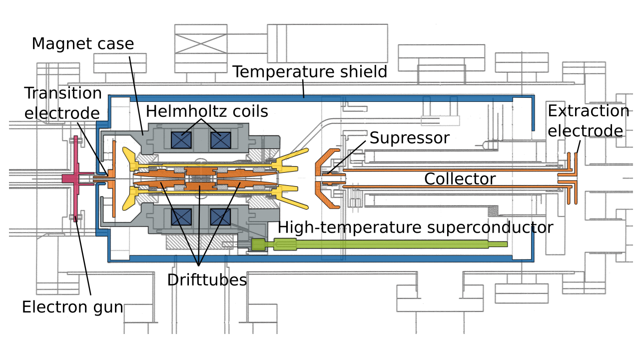

Figure 1: Technical sketch of S-EBIT I.

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NUCLEAR DECAY STUDIES OF HIGHLY CHARGED RADIOACTIVE IONS AT TITAN

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Abstract

Interactions between the atomic nucleus and its surrounding electrons can have a large impact on the decay modes of rare-isotopes. Partial or complete ionization of radioactive nuclei can open new exotic decay modes, such as nuclear excitation via electron capture, or selectively block decay modes to expose second order processes, such as double-gamma decay. The TITAN Electron Beam Ion Trap (EBIT) at TRIUMF has successfully been used to generate and store highly charged radioactive ions, while also providing a controlled, low-background environment for decay spectroscopy.

INTRODUCTION

When investigating the decay of radioactive nuclei, interactions between the nucleus and bound electrons in the constituent atom are typically ignored. However, in common modes of electroweak decay such as electron capture and internal conversion, the probability of decay is significantly affected by the spatial distribution of the atom's electron cloud. For nuclear beta decay, the energy and momentum distributions of the emitted positron or electron are modified by the surrounding orbital electrons. Understanding the nature of these decay modes requires not only knowledge of the nuclear structure of the initial and final states, but also the effects of the atomic charge state on the decay itself.

Studies of the electroweak decay modes of highly charged ions (HCIs) offer an experimental challenge due to the significant technical obstacles of creating and storing radioactive nuclei at high charge states. The Experimental Storage Ring at GSI in Darmstadt, Germany, has been used to study the effects of charge state on electron capture [1] for over 30 years. The work presented in this article represents the only other attempt to study radioactive HCI decays, and the world's only low-energy ion trap decay station.

DECAY SPECTROSCOPY WITH THE TITAN EBIT

The Isotope Separator and Accelerator (ISAC) [2] facility at TRIUMF in Vancouver, Canada, provides a broad array of rare-isotope beams (RIBs) using the isotope separation on-line (ISOL) technique [3]. The TRIUMF cyclotron produces a 500-MeV proton beam at up to 100 µA. The high-intensity proton beam impinges on a production target, yielding radioactive ions from spallation and fission reactions. The RIB of interest is separated according to mass to charge ratio and delivered to one of TRIUMF's experimental facilities.

TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) utilizes multiple traps and instruments in conjunction to study short-lived nuclei [4]. As shown in Figure 1, a radio-frequency quadrupole (RFQ) linear Paul trap is used for cooling via buffer gas and bunching the single-charge ion (SCI) beam. The Measurement Penning Trap (MPET) and Multi-reflection Time of Flight Mass Spectrometer (MR-TOF-MS) are primarily used for precision mass measurements. Lastly, the Electron Beam Ion Trap (EBIT) generates and traps HCIs, both for delivery to the MPET and for decay spectroscopy.

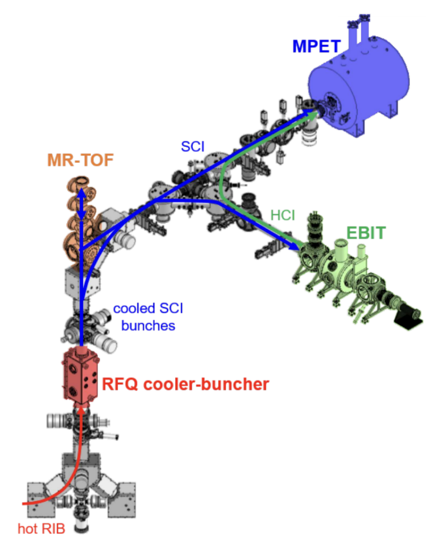

Figure 1: A diagram of the TITAN facility. The ISAC beam (red) is injected into the RFQ cooler-buncher, and the resulting singly-charged ion beam (blue) is delivered to one of several ion traps that comprise TITAN. In the Electron Beam Ion Trap (EBIT), ions are charge bred to higher charge states and either sent to the Measurement Penning Trap (MPET) or trapped in the EBIT for decay spectroscopy, as in this work.

After successfully being used for the charge breeding of stable ions at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany, the FLASH-EBIT design was repurposed for RIBs at TRIUMF in the form of the TITAN EBIT (Figure 2) [5]. Axial confinement in the trap itself is provided by an electrostatic quadrupole potential well created by nine copper drift tubes. The drift tubes are held at specific voltages to create the potential profile of the trap, which is

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ABSOLUTE NUCLEAR CHARGE RADIUS MEASUREMENTS WITH EUV SPECTROSCOPY AT TITAN EBIT *

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Abstract

Nuclear charge radii, a quantity crucial in many nuclear physics studies, can be extracted from Li-like electronic transitions, even in heavy ions, when combined with atomic theory [1,2]. This has progressed to permit such calculations from transitions in Na-like ions [3,4]. 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 [5] will be presented. The first measurement candidates are ^{211}Fr and a suitable spin-0 isotope of Ra. These two elements are relevant for atomic parity violation (APV) experiments and searches for time-reversal violating permanent electric dipole moments (EDM).

INTRODUCTION

The nuclear charge radius is a fundamental property of the nucleus, and it plays a key role in understanding nuclear and atomic phenomena. Accurate measurement of nuclear charge radii is vital to understand nucleon-nucleon interactions, the appearance of non-traditional magic numbers, the onset of deformation, and the structure of exotic halo nuclei [6, 7]. Precision atomic tests of fundamental symmetries, such as atomic parity violation (APV) or searches for permanent electric dipole moments (EDM) as a signature of time reversal violation, require knowledge of nuclear charge distributions to extract the weak interaction physics from the measurement.

Some standard methods available to measure the absolute charge radius include elastic electron scattering [8] and muonic atom spectroscopy [9]. However, these techniques require macroscopic samples, exceeding by orders of magnitude the amount of short-lived radioactive isotopes that can be accumulated at radioactive beam facilities.

The critical ingredients to measure the absolute nuclear charge radius of short-lived heavy isotopes are access to intense radioactive ion beams (RIB), charge breeding to Na-like or higher charge states, optical access to the stored highly charged ions, and finally a spectrometer matched to the EUV light. All of these ingredients are united at TITAN [10], making it presently the only facility in the world capable of such measurements. Our first candidates are ^{211}Fr and a suitable spin-0 isotope of Ra. These two elements are of interest for APV experiments and the searches for EDM. We plan to probe the light emitted from the $3s\ ^2S_{1/2} - 3p\ ^2P_{1/2}$ $(D1)$ transition of Na-like Fr and Ra isotopes to measure the energy emitted from this electronic transition. This specific transition is chosen as it offers the strongest optical signal, which is in the EUV regime, hence the necessity for a spectrometer that is highly sensitive to the EUV light. We will also probe the same transition from several isotopes of elements with well-known charge radii charge bred to the same charge state, which are used as references. We will then compare the energy shift with the expected theoretical energy difference, and obtain the charge radius of the isotope being measured by adjusting it in the theoretical calculation to match the measured transition energy shift.

In this proceeding, we describe the status and outlook of this nascent program.

EUV SPECTROSCOPY WITH TITAN EBIT

The TITAN EBIT [11] permits electron beams with currents up to 5 A and energies up to 66 keV. The Helmholtz style magnet allows optical access through seven radial ports. On one of these ports an EUV spectrometer will be installed. We have designed our spectroscopy setup, as illustrated in Figure 1. It will contain three major components: the EUV focusing optics, the EUV monochromator, and the charge coupled device (CCD) camera, where two key optical elements in the EUV monochromator will be an entrance slit and a grating substrate.

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PERFORMANCE OF ANL EBIS AND RADIOACTIVE BEAM PRODUCTION*

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Abstract

Operation of the Argonne National Laboratory Electron Beam Ion Source (EBIS) was paused in March 2020 due to COVID restrictions. Source operation resumed in March 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 $^{133}Cs^{27+}$ with a single charge state breeding efficiency of 22.2% has been achieved.

EBIS

Description

The EBIS charge breeder was designed in collaboration with Brookhaven National Laboratory and is based upon the RHIC TestEBIS [1]. Several parameters such as the electron gun, potential distribution in the ion trap region, electron collector, and injection/extraction systems were modified from those used for the TestEBIS with the goals of a shortened breeding time, higher transverse ion acceptance, and higher breeding efficiency [2, 3].

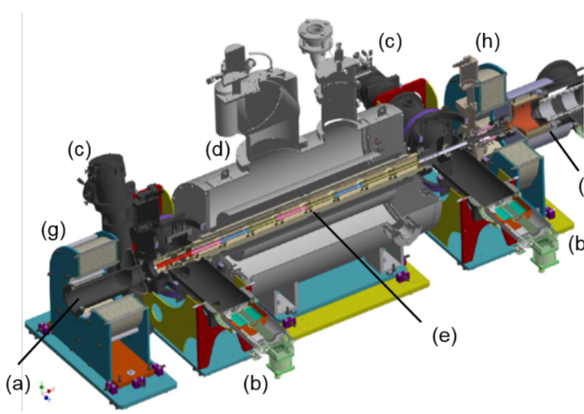

Figure 1: Overview of the EBIS charge breeder showing: a) electron gun, b) cryogenic pumps, c) turbomolecular pumps, d) 6 T superconducting solenoid, e) drift tube structure, f) electron collector, g) electron gun solenoid coil, h) collector solenoid coil.

The EBIS has turbomolecular and cryogenic pumps installed at either end of the trap and non-evaporable getter (NEG) strips installed along the length of the trap (Fig. 1). The trap operating pressure is < 1×10^{-10} Torr with the beamline operating at 1×10^{-9} Torr. A surface ionization source provides beams of $^{133}Cs^{+}$ for device tuning and charge breeding studies. A pulsed electric steerer after the surface source produces a beam pulse of 50 µs [4]. The electron beam is normally operated at 1.2 A, but for this series of measurements operation was reduced to 0.35 A, together with an increase in duty cycle to 60%. While trap capacity was reduced, measurements showed a relatively low electron beam neutralization factor of 2.5% during the breeding cycle. Source operating parameters are shown in Table 1.

Table 1: EBIS Parameters Used for Pulse Lengthening Series of Measurements

Magnetic field in trap	5.5 T
Magnetic field on cathode	0.15 T
IrCe cathode diameter	4.2 mm
Electron beam current	0.35 A
Electron beam diameter in trap	0.692 mm
Electron beam density in trap	92 A/cm2
Electron beam energy in trap	8951 eV
Drift tube diameter	20 mm
Trap length	0.532 m
Trap capacity	3.5 nC
Injection time	50 µs
Repetition rate	10 Hz
Duty cycle	60 %
EBIS high voltage bias	20 kV
Pressure (in trap)	<1x10-10 Torr

Beam Production

The EBIS started delivering radioactive beams for the ATLAS physics program in 2018. Beams produced to date have had an A/Q < 6, breeding times between 30-60 ms at 10 Hz repetition rate, and an average single charge state (SCS) breeding efficiency of 15.4% with a maximum of 24.6% (Table 2). The source has a substantially reduced beam contaminant level when compared to the ECR charge breeder it replaced [5]. The radioactive species (RIB Content) typically account for > 70% of the beam incident on target, whereas with the ECR the fraction was < 3%. Beam contaminants are volatile species such as fluorine or potassium with additional constituents arising from the 316L stainless steel components and the copper electron collector [6]. The charge state selected for beam delivery can typically be adjusted to avoid these known contaminants.

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STATUS OF THE CANREB EBIS AT TRIUMF

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Abstract

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 at TRIUMF. 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 cooled using a radiofrequency quadrupole (RFQ) cooler-buncher, and energy adjusted using a pulsed drift tube for injection into an electron beam ion source (EBIS) charge breeder. The EBIS was designed for a maximum electron beam current of 500 mA at a maximum magnetic field of 6 T. The EBIS can accept ion beam energies up to 14 keV and HCI with $3 < A/q < 7$ can be charge bred and extracted. The HCIs are separated using a Nier-type spectrometer before being transported to the linac for post acceleration. The status of the CANREB EBIS and recent results will be presented.

INTRODUCTION

TRIUMF houses a cyclotron which can produce proton beams at energies up to 520 MeV and currents up to 120 μA (> 300 μA total for all beamlines). For production of rare isotope beams (RIB), protons with energy 480 MeV (and currents up to 100 μA) impinge on targets comprised of U, Ta, Si, Th, Nb, or C [1]. Reaction products are formed through fission and spalation reactions and ionized using surface, laser, or plasma discharge ion sources. Ions are extracted at energies up to 60 keV and can be transported directly to low energy experiments in the Isotope Separator and ACcelerator (ISAC) facility. Ions can also be transported to high energy experiments (up to 15 MeV/nucleon for low A/q) following post-acceleration through a multi-stage (room temperature and superconducting) linac. The linac has an energy acceptance of 2.04 keV/nucleon, limiting the mass-to-charge ratio to $A/q = 30$ for 60 keV. Post-acceleration of heavier ions requires charge breeding to $3 < A/q < 7$. Currently, highly charged ions (HCI) are created using an electron cyclotron resonance ion source (ECRIS) installed in ISAC [2]. The ECRIS is limited to efficiencies of a few percent, and also generates high background currents due to high residual gas pressure and plasma chamber sputtering. The resulting isobaric currents can be several orders of magnitude more intense than the species of interest. The maximum achievable charge state from the ECRIS is also limited, and secondary stripping in the linac is often required to reach the necessary energy which further limits the efficiency.

The Advanced Rare IsotopE Laboratory (ARIEL) project is currently under construction at TRIUMF. In addition to adding two new target stations for RIB production, ARIEL also includes the CANadian Rare isotope facility with Electron Beam ion source (CANREB) for charge breeding of ions. CANREB utilizes an electron beam ion source (EBIS) to generate HCI. The EBIS is designed for ultrahigh vacuum operation, which greatly reduces the background contamination relative to the ECRIS. The EBIS can also reach higher charges states, mitigating the need for a second stripping and permitting the delivery of clean and intense post-accelerated beams to ISAC.

CANREB OVERVIEW

CANREB is located in the ARIEL building adjacent to ISAC (Fig. 1). The lower level of the ARIEL building contains the future mass separator room, which houses the CANREB high resolution separator (HRS). The HRS has a dual magnetic dipole which is designed to reach resolving powers up to 20000 [3]. The HRS can accept beam from the future ARIEL target stations, which is then transported upstairs through a vertical beamlime. If additional mass separation is not required, the HRS can be bypassed. The HRS is currently being commissioned off-line. The mass separator room also contains the ARIEL test ion source (TIS) [4], a small surface source used for stable beam tests in CANREB.

The CANREB charge breeding systems are located on the ground floor of the ARIEL building. Stable ion beams can be injected from the TIS or from the off-line ion source (OLIS) in ISAC. RIB can currently be injected from the ISAC target stations and from ARIEL in the future. Ions can be injected at energies up to 60 keV into the radiofrequency quadrupole (RFQ) cooler-buncher [5] with intensities up to a few 100 pA. The ions are confined using a combination of DC electric and RF fields ($f_{RF} = 3 - 6$ MHz) for up to 10 ms (at a nominal rep rate of 100 Hz). A helium buffer gas ($P \approx 30$ mTorr) cools the trapped ions. The extracted ions have a nominal FWHM width of ≈ 1 μs. The extracted ions must be reduced in energy for coupling into the charge breeder, which is accomplished using a pulsed drift tube (PDT). The PDT is rapidly switched between high voltage and ground using a push-pull Behlke switch (fall time < 500 ns).

The EBIS was designed and constructed at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany [6]. The system is designed to accept ions with energies up to 14 keV (set by the desired A/q and the energy acceptance of the linac) and intensities up to $\sim 10^7$ particles per bunch at 100 Hz. The ions are confined electrostatically in the center of a split-bore, semi-Helmholtz superconducting (4 K) magnet with a maximum field strength of 6 T. A barium dispenser cathode generates an electron beam with an energy

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COLLINEAR LASER SPECTROSCOPY OF $^{12}C^{4+}$: TOWARDS AN ALL-OPTICAL NUCLEAR CHARGE RADIUS DETERMINATION

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Abstract

Recent progress in non-relativistic QED calculations for He-like atomic systems opens up the possibility of all-optical nuclear charge radius determinations beyond He. Therefore, $1s2s\,^3S_1 \rightarrow 1s2p\,^3P_J$ transitions in $^{12}C^{4+}$ are investigated as a proof-of-principle experiment. Here, first collinear laser spectroscopy resonance spectra of $^{12}C^{4+}$ from an electron beam ion source (EBIS) are presented and peak shapes are studied for different EBIS production modes.

INTRODUCTION

The investigation of the nuclear size plays an important role in the unraveling of the nuclear structure since its discovery by Rutherford. Different techniques have been developed over time to measure the nuclear mean square charge radius $\langle r^2 \rangle$ [1]. For stable nuclei, the nuclear charge distribution can directly be probed through elastic electron scattering [2]. Also myonic atom spectroscopy has been proven a valuable tool for the extraction of nuclear size information [3]. For radioactive nuclei, one had to come up with a procedure which takes only few ms from the production of the unstable nuclei to the measurement. Therefore, Collinear Laser Spectroscopy (CLS) has been developed [4] and since then established as a workhorse in this field [5, 6]. It unites high resolution with a fast measurement cycle through in-flight spectroscopy on fast ions (10 - 60 keV) in a collinear geometry. However, laser spectroscopy of radioactive nuclei only yields changes $\delta\langle r_c^2 \rangle$ of the nuclear ms charge radii along an isotopic chain. In order to obtain the nuclear size $\langle r^2 \rangle$ also for short-lived isotopes, a combined analysis of all available measurements is used [1]. Due to major advances in non-relativistic QED (NRQED) calculations in one- and two-electron-systems in the past years they are now chiefly limited by the finite nuclear-size effect. This means that the nuclear size can be determined in an all-optical way through a comparison between a measured transition frequency ν_0 and the calculated frequency ν_{point} in the respective transition under assumption of a point-like nucleus. This has been demonstrated in H [7, 8], μH [9] and μHe so far [10] and also led to the famous proton radius puzzle [11]. The recent agreement between theory and experiment in the $2\,^3S_1 \rightarrow 2\,^3P_J$ in He reported in [12] opens up the possibility to expand this approach of all-optical nuclear charge radii also to He-like ions of heavier species. Unfortunately, the lifetime of the metastable $2\,^3S_1$ state decreases quickly with increasing nuclear charge Z as shown in Table. 1. Similar to short-lived nuclei, CLS is the best-suited method to investigate the corresponding transitions in He-like Be, B and C ions. Beginning with N the wavelength is not accessible with commercial laser systems anymore but might be available at some point. Furthermore, the determination of the stable nuclei ^{10,11}B with this all-optical approach is of special interest since it promises much better accuracy compared to elastic electron scattering which is hindered by the interference of the two form factor components C0 and C2 in these nuclei [13]. A precise charge radius measurement in these stable nuclei is crucial to deduce the possible proton-halo from ^{8}B [14, 15].

From all available candidates besides He, the nuclear charge radius of ^{12}C is known to highest precision from myonic atom spectroscopy [16] and elastic electron scattering [17] making $^{12}C^{4+}$ a perfect proof-of-principle candidate. Furthermore, ^{12}C is the only nucleus in this region without nuclear spin which simplifies the NRQED calculations as well as the experiment. In the following, the experimental setup will be explained and first resonance spectra of the $2\,^3S_1 \rightarrow 2\,^3P_2$ transition in $^{12}C^{4+}$ for different measurement parameters are shown and compared.

Table 1: Lifetime τ and Transition Wavelength λ of the Metastable $2^3\,S_1$ State in He-like Ions

Ion species	$\tau\,(2\,^3S_1)$	$\lambda\,(2\,^3S \rightarrow 2\,^3P)$
He	2.2 h	1082 nm
Li^+	50 s	548 nm
Be^{2+}	1.8 s	372 nm
B^{3+}	150 ms	282 nm
C^{4+}	21 ms	227 nm
N^{5+}	3.9 ms	190 nm

EXPERIMENTAL SETUP

The experiment is performed at the COllinear Apparatus for Laser spectroscopy and Applied science (COALA) situated at the Institute for Nuclear Physics of the Technical University of Darmstadt. The technique of (quasi-)simultaneous collinear and anti-collinear laser spectroscopy [18] has been established and improved at COALA in previous experiments [19–21]. Although a few improvements and changes of the setup have been carried out over the past years, the measurement principle and main parts of the beamline are are still as detailed in [22]. Therefore, only a brief sum-

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CHARGE-EXCHANGE FACTOR IN EBIT SPECTRAL ANALYSIS*

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Abstract

Detailed modeling of the plasma in an electron beam ion trap (EBIT) not only requires cross section data of electron impact ionization, excitation, and recombination, but also requires knowledge of operating conditions, such as electron beam energy, density, number of neutral atoms, and relative velocities. In the EBIT, charge exchange recombination from the neutral background has a significant effect on the ionization balance despite the relatively low density of neutral ions. However, it becomes the key issue in modeling because experimental conditions are not well-known, and the uncertainties for the charge exchange cross section are difficult to estimate. In this work, we introduced a single charge exchange factor that includes the necessary experimental parameters (neutral density, relative ion velocity) and charge exchange cross section. An experimental method for determining the charge exchange factor is discussed and applied to a collisional-radiative model NOMAD [1]. Comparison between measured and simulated spectra of highly charged Fe ions, produced at the NIST EBIT, show excellent agreement, demonstrating the usefulness of the method.

INTRODUCTION

Electron Beam Ion traps (EBITs) are small scale laboratory devices that create and trap highly charged ions for spectroscopic studies [2]. The combination of a highly controllable EBIT, with plasma modeling (e.g. [1], [3]), allows for the production of important atomic data such as wavelengths, relative line intensities, and cross sections [4–6], needed to benchmark, test, and improve plasma codes. However, modeling of the EBIT plasma requires an understanding of underlying atomic processes and a reliable knowledge of the charge state distribution.

The charge state balance between ions is determined by a set of rate equations that connects the number density of ions via charge changing interactions. These atomic processes decrease (recombination) or increase (ionization) the charge state of the ions through elementary collisional interactions with free electrons in the electron beam and with other ions or neutral atoms in the trap region. Double or multiple ionization and recombination may also occur, changing the ion charge by more than one in a single event. Conditions in the trap region determine the relative importance of these processes. For our application the rate equation (see e.g. [7, 8]) takes the form:

$$\begin{aligned}\frac{dN_i}{dt} &= J_e(N_{i-1}\sigma^I_{i-1} - N_i\sigma^I_i + N_{i+1}\sigma^R_{i+1} - N_i\sigma^R_i) \\ &\quad + N_{i+1}N_0\langle\sigma^{CX}v_r\rangle_{i+1} - N_iN_0\langle\sigma^{CX}v_r\rangle_i\end{aligned} \tag{1}$$

Where only single charge changing processes are assumed, and neighboring charge states are connected with number densities of N_{i+1}, N_i, and N_{i-1}. In Eq. 1, $J_e = n_e v$ denotes the electron current density, σ^I and σ^R are the cross sections corresponding to the sum of different ionization processes including electron impact ionization (EI), excitation followed by autoionization (EA), and recombination processes (R), including radiative recombination (RR) and dielectronic recombination (DR). Charge exchange (CX) recombination occurs between ions and neutral atoms within the EBIT plasma and is a critical component of the charge state balance. As shown in the last two terms of the equation, the number density of neutral atoms, N_0, and the relative velocity of the ions and neutral atoms, v_r, are not easily measured or estimated, and the cross section, σ^{CX}, is difficult to calculate with high accuracy [9–12].

To this end, we will describe how we have combined these unknown factors into a free parameter, termed charge exchange factor, and discuss a technique utilizing measured line intensities and well known theoretical cross sections to determine this factor. Finally we will demonstrate the results of applying this factor by comparing measured and simulated spectra.

CHARGE EXCHANGE FACTOR

The intensity I of a measured spectral line, produced from charge state i, is proportional to the number of ions of that charge state, N_i (determined by the rate equation, Eq. 1). It also depends on the fraction P of these ions in the particular upper level of the atomic transition (upper level population fraction) and A the transition probability to the lower level. The unidirectional electron beam within the EBIT produces anisotropic and polarized emission [13, 14]. Therefore, transition dependent correction factors, like the angular distribution and polarization of the line are included in the term C_t. Detector specific factors, such as spectrometer transmission function, detector efficiency, and solid angle are included in C_d.

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PROGRESS AND STATUS OF RAON EBIS CHARGE BREEDER*

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Abstract

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 of 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 atef 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.

INTRODUCTION

For the post-acceleration of the rare isotope beams, an electron beam ion source (EBIS) had been selected to be a charge breeder for RAON heavy ion accelerator in Korea [1-3]. Its design and development were accomplished by the help of experts from ANL, BNL, and CERN. The CARIBU-EBIS at ANL was the benchmark for the RAON EBIS [4-5] to meet the requirements of beam capacity and breeding efficiencies for various nuclear species. The electron gun and cathodes with maximum current of 3 A were purchased from the Budker Institute of Nuclear Physics. The Tesla Engineering Ltd won the contract of supplying the 6-T superconducting (SC) magnet which arrived at the off-line site, i.e., Korea University Sejong in 2017. Based on the electron beam transmission simulation, the collector was designed and manufactured. Most of the chambers and electrodes were produced by various Korean manufacturers. Parts were tested after their production and the whole system was assembled after confirming their performances. Figure 1 shows the off-line installation of RAON EBIS charge breeder at Korea University Sejong.

The test results of the electron gun and collector are described in the Ref. [6] in detail. Cryopumps, getter pumps, and turbo molecular pumps (TMPs) with high compression ratio were employed to maintain very low vacuum pressure around 10^{-10} Torr. Almost all chambers and stainless-steel structures inside vacuum were vacuum-fired to minimize the hydrogen outgassing. Vacuum test results are described in the Ref. [7] in detail. In the following sections, we describe the issues on magnetic field alignment, and the charge breeding results of the residual gas at the off-line site and cesium test ion beam at the on-line site.

Figure 1: RAON EBIS charge breeder installed at Korea University Sejong.

ISSUES ON MAGNETIC FIELD

We considered making iron shields for TMPs and cryopumps because the ambient magnetic field from the SC magnet could cause the pumps to fail. A calculation of the magnetic field under asymmetric locations of the shields revealed that the magnetic line starting from the cathode ended around 10 mm away from the beam axis at the entrance of the collector. Therefore, we abandoned the plan for making the shields and decided to place the TMPs in a location where the surrounding field affects weaker to the TMPs. After placing the TMPs further from the SC magnet, where the magnetic line was parallel to the pump's rotation axis, we tested the robustness of the pump operation during the SC magnet was energized for several days. Only a TMP with magnetic bearing stopped with a roar when the SC magnet was ramping down, which we replaced with one with hybrid bearing afterwards.

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PolarX-EBIT – A VERSATILE TOOL FOR RESONANT X-RAY SPECTROSCOPY

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Abstract

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.

INTRODUCTION

Electronic transitions in highly charged ions are of great importance for astronomy and astrophysics, as most matter in the universe is in an ionized form. Observed in x rays, their transitions are often the only spectroscopic features. Furthermore the strong electric field involved makes transitions in highly charged ions much more sensitive to relativistic and QED effects. Consequently, extensive spectroscopy measurements have been performed in EBITs and other plasma sources using electron impact as excitation mechanism.

As shown with laser spectroscopy in the optical region, more precise measurements can be performed when the excitation is induced by a photon. This resonant process allows selective excitation of states and thus more control over the atomic system.

Resonant Spectroscopy

By overlapping an ion cloud with a monochromatized photon beam, electronic transitions in highly charged ions can be selectively excited. The subsequent radiative decay of the excited state is observed by x-ray detectors mounted perpendicular to the photon beam. Spectra are recorded by scanning the incoming photon beam energy. The spectral resolving power is determined by the monochromator and other elements of the beamline. With the brightness of current generation synchrotron radiation sources, measurement times can be significantly reduced compared to conventional grating spectrometers.

This principle was developed and successfully applied during multiple campaigns with the FLASH-EBIT of the Max Planck Institute for Nuclear Physics [1–5].

PolarX-EBIT

Based on these campaigns with the FLASH-EBIT an EBIT permanently installed at a synchrotron radiation source was proposed and funded by a BMBF project, named PolarX-EBIT. In a joint development with the PTB-EBIT, a new type of compact permanent-magnet EBITs was designed and built. The main parameters of these EBITs are described in [6]. The modifications made for operation as part of an x-ray beamline are described in the following.

Off-axis Gun

To facilitate a permanent installation at a synchrotron radiation beamline, it is essential that the EBIT does not block the beam, so that other experiments can be performed when the EBIT is not in use or simultaneously to an EBIT measurement. For this reason an off-axis electron gun was designed, leaving the central axis of the EBIT free to pass the x-ray beam through the apparatus. The cathode is mounted below the axis under a 22° angle (see. Fig. 1). To bend the electron beam back onto the axis the anode and focus electrodes are split in two parts each. This design is more susceptible to the applied voltages, but with careful tuning beam transmission rates larger than 95% and electron currents up to 30 mA can be obtained.

X-ray Detectors

The PolarX-EBIT can be equipped with two large area (80 mm^2 and 150 mm^2) silicon drift detectors. The design of the trap allows to mount the detectors close to the trap, so that they cover a large solid angle up to 1 sr. 500 nm thick aluminum foil is mounted in front of them to block visible and VUV light. The detectors are mounted perpendicular to the photon beam and to each other. The two orientations allow investigation of the angular distribution of the emitted

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