Towards nuclear lifetime measurements of highly charged radioactive ions: Development of a hybrid EBIT-Penning ion trap

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Radioactive decay was discovered more than a century ago, and yet it is not fully understood despite its crucial role in stellar nucleosynthesis, investigations of the neutrino, and fundamental symmetries. Additional questions arise when we consider the non-terrestrial conditions in stars, where the hot and dense conditions can lead to partial or full ionization. This change in charge state can alter the available decay channels. For example, orbital electron capture (EC) is forbidden in bare ions and suppressed in hydrogen-like ions. Thus, radionuclides like ^{7}Be which is part of the *pp*-chain in the sun can become extremely long lived. In the reverse process, bound-state β decay can cause terrestrially stable nuclides to become unstable when highly charged. These two processes alone can alter the course of stellar evolution, which in turn affects the nucleosynthesis of elements heavier than iron and cosmology.

Four principle challenges present themselves in the lifetime measurements of highly charged ions (HCI): the production of the desired – predominantly radioactive – species, charge breeding to the high charge states, storage compatible with the expected half-lives, and a compatible detection scheme. Tape stations and most traditional nuclear decay spectroscopy techniques are unfeasible such measurements since HCI must be stored in vacuum. As such, we propose a hybrid ion trap which combines the charge-breeding capabilities of an electron beam ion trap (EBIT) with the mass-spectrometry techniques of a Penning trap at the Cyclotron Institute.

The upgrades under development at the Cyclotron Institute, namely the light and heavy ion guides, will provide low-energy radioactive (singly charged) ions to the trap. The EBIT is the only means to charge breed low-energy beams to bare, hydrogen-like, and helium-like charge states necessary. These are achieved through successive electron impact of the nuclides by electrons in a high-energy beam. In Penning traps, the Fourier-Transform Ion-Cyclotron-Resonance (FT-ICR) technique is used for ultra-high-precision mass spectroscopy and *g*-factor measurements, will allow for precise identification of both the desired nuclide and the desired charge state, and can be adapted for lifetime measurements. The proposed system will share the beam cooler and buncher of the TAMUTRAP system [1].

A Penning trap relies on a strong, uniform magnetic field for radial confinement and a quadrupolar electrostatic field for axial confinement. An EBIT unites a cylindrical Penning trap with an electron beam. The use of a 7-Tesla superconducting solenoid magnet (JASTEC JMTB-7.0T/96/SS) is under negotiation from TRIUMF (Vancouver, Canada). A cylindrical Penning trap design was chosen based on those of SHIPTRAP [2] (GSI, Darmstadt, Germany) and TAMUTRAP [1]. It was then adapted to be an EBIT with the addition of cylindrical electrodes similar to the designs of the FLASH [3] and TITAN [4] (sister) EBITs. The field and ion trajectories were simulated in SIMION 8.1 [5]. These simulations indicate that switching between EBIT and Penning trap modes, i.e. turning off the electron beam and changing the trapping potential, acts as evaporative cooling. To reduce these losses we are investigating different trap geometries and trapping potentials.

Charge-breeding simulations were performed with CBSIM [6] and CHASER [7] with electron beam energies up to 100 keV. The maximum beam energy is limited by the available space in the experimental hall. Due to the *Z* (proton number) dependence in charge breeding, the heaviest element which could be fully ionized is mercury [8], which is beyond the lanthanides which are the heaviest nuclides of interest. The simulations indicate 1% of heavy beams will populate the bare charge state when the product of the electron current density *J* and the charge breeding time *t*, *Jt* equals 80000 $A \cdot s/cm^2$. The ratio will allow other charge states to be cleaned with standard Penning-trap-mass-spectrometry techniques [9] with an allowance to clean the ionized background gas as well. The *Jt* is feasible with standard cathodes and the expected beam compression due to the 7 T magnetic field and the terrestrial and expected half-lives of the radionuclides of interest.

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