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Improvements to TITAN's mass measurement and decay spectroscopy capabilities

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ABSTRACT

The study of nuclei farther from the valley of β-stability than ever before goes hand-in-hand with shorter-lived nuclei produced in smaller abundances than their less exotic counterparts. The measurement, to high precision, of nuclear masses therefore requires innovations in technique in order to keep up. TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility deploys three ion traps, with a fourth in the commissioning phase, to perform and support Penning trap mass spectrometry and in-trap decay spectroscopy on some of the shortest-lived nuclei ever studied. We report on recent advances and updates to the TITAN facility since the 2012 EMIS conference.

TITAN's charge breeding capabilities have been improved and in-trap decay spectroscopy can be performed in TITAN's Electron Beam Ion Trap (EBIT). Higher charge states can improve the precision of mass measurements, reduce the beam-time requirements for a given measurement, improve beam purity, and open the door to access isotopes not available from the ISOL method via in-trap decay and recapture. This was recently demonstrated during TITAN's mass measurement of ^{30}Al. The EBIT's decay spectroscopy setup was commissioned with a successful branching ratio and half-life measurement of ^{124}Cs. Charge breeding in the EBIT increases the energy spread of the ion bunch sent to the Penning trap for mass measurement, so a new Cooler PEnning Trap (CPET), which aims to cool highly charged ions with an electron plasma, is undergoing offline commissioning. Already CPET has demonstrated the trapping and self-cooling of a room-temperature electron plasma that was stored for several minutes. A new detector has been installed inside the CPET magnetic field which will allow for in-magnet charged particle detection.

Precision mass measurements provide critical input data for nuclear astrophysics models [35], nuclear structure calculations [30], and tests of fundamental symmetries [17]. The precision requirements for each field varies from $\frac{\delta m}{m} \leqslant 10^{-7}$ for nuclear astrophysics to $\frac{\delta m}{m} \leqslant 10^{-10}$ for tests of Charge, Parity and Time (CPT) invariance. Penning traps are the tool of choice for online precision mass determinations [2] and have demonstrated the ability to quickly and precisely measure masses at a variety of different facilities with differing means of production [43,44,20,31,12]. As newer facilities as well as upgrades to older facilities are coming online and providing access to nuclei farther from the valley of

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β-stability than ever before, the need to make precise mass measurements using shorter measurement cycles than before is ever present.

TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility [10], coupled to TRIUMF's Isotope Separator and ACcelerator (ISAC) in Vancouver, Canada, is one such facility capable of performing high precision mass measurements. At TITAN, three ion traps are used to perform and support high precision mass measurements or perform in-trap decay spectroscopy. Since the last EMIS conference in 2012 [23], TITAN has made advances in the service of high-precision mass measurements and in-trap decay spectroscopy.

1. The TITAN system

Ions produced at ISAC are selected by a magnetic dipole mass separator ($R \approx 2500$ [11]) and delivered to the TITAN facility at a typical energy of 20 keV. The ions are thermalized and bunched in TITAN's He-filled radiofrequency quadrupole (RFQ) cooler-buncher [6].

After ejection the cooled ion bunch passes through an electrostatic beam switchyard where the ions can be sent either to TITAN's Electron Beam Ion Trap (EBIT) or directly into TITAN's Measurement PEnning Trap (MPET) for precision mass measurement. Before entering MPET, all ions pass through TITAN's Bradbury Nielsen Gate (BNG), which performs a mass selective deflection with $R \sim 100$ based on the ions' times of flight [5]. In the EBIT, ions can be charge-bred and then sent to MPET for mass measurement (see Section 2.1), or remain in the EBIT to perform in-trap decay spectroscopy (see Section 2.2).

Precision mass measurements are carried out in MPET [3,4] where a 3.7 T magnetic field confines ions radially and a harmonic electrostatic potential confines ions axially. Masses, m, are measured using the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) method which measures an ion's cyclotron frequency,

$$\omega_c = \frac{qeB}{m}, \tag{1}$$

where B is the magnetic field in the Penning trap, q is the ion's charge state and e is the elemental charge of 1.6×10^{-19} C. Through an optimization of both ion injection optics into MPET as well as an efficient measurement cycle using a Lorentz-steerer technique [33], TITAN has specialized in measuring the masses of the shortest-lived nuclides ever measured. Among the shortest-lived species successfully measured are ^{31}Na ($t_{1/2} = 17$ ms) [8], ^{32}Na ($t_{1/2} = 13.2$ ms) [*paper in process*], and ^{11}Li ($t_{1/2} = 8.75$ ms) [41]. A measurement cycle time of 6.7 ms with a 6 ms quadrupolar excitation time has been shown to be the shortest measurement cycle time so far [7].

1.1. Improving mass measurement precision

A typical Penning trap mass measurement has a fractional statistical precision,

$$\frac{\delta m}{m} \propto \frac{m}{qeBt_{rf}\sqrt{N_{ion}}}, \tag{2}$$

where m is the mass of the ion of interest and t_{rf} is the quadrupole excitation time for the ion in the Penning trap. For more stable isotopes, increasing the quadrupole excitation time is a trivial means of improving the precision, but for short-lived isotopes that method is limited since the ion of interest may decay in the trap. In practice, the maximum applicable $t_{rf} \approx 2t_{1/2}$, so for short-lived isotopes improvements in precision must come from other parameters.

The precision in Eq. 2 improves as the charge state increases with an obvious limit of $q = Z$. For example, an ion in a +2 charge state will resonate in the Penning trap at a frequency twice that of the singly charged ion (SCI) but the uncertainty of the frequency measurement, $\delta\omega$, is (all things being equal) unchanged. Since $\frac{\delta\omega}{\omega} = \frac{\delta m}{m}$, the precision of the mass measurement should improve by a factor of 2 by measuring a frequency that is twice as large.

2. The TITAN EBIT

TITAN's EBIT [25] was designed to charge-breed ions in preparation for their mass measurement in MPET. Since the first HCI mass measurement of $^{44}K^{4+}$ [25] and the first short-lived HCI mass measurement of $^{74}Rb^{8+}$ [13], TITAN has measured and published the masses of 22 exotic ground-state nuclei [31,13,15,24,18,40] and the long-lived isomeric state of ^{78}Rb [18]. The EBIT consists of a superconducting magnet in a Helmholtz configuration capable of generating a magnetic field of up to 6 T. An electron gun typically produces electron beam energies of 1.5–7 keV and currents as high as 500 mA[1]. The EBIT is surrounded by seven radial ports with recessed Beryllium windows that can accommodate either Lithium-drifted Silicon (Si(Li)) or high-purity Germanium (HPGe) detectors [26]. With these detectors in place, in-trap decay spectroscopy and half-life measurements such as those of ^{124}Cs and ^{124}In [29] have been performed. The ability to capture multiple ion bunches inside the EBIT up to the trap's space charge limit of 10^9e was also demonstrated during the ^{124}Cs and ^{124}In measurements [28,22].

When charge-breeding for mass measurements in MPET, the EBIT's electron beam imparts an estimated energy spread of 10–100 eV/charge on the highly charged ion (HCI) bunch [21]. An increased energy spread increases the emittance of the ion cloud, adversely affects the trapping potential in MPET, decreases the trapping efficiency in MPET, and has the overall effect of reducing the precision of mass measurements. We are currently commissioning a new Cooler PEnning Trap (CPET) [21] whose purpose is to cool HCI bunches to ~1 eV/charge using a plasma of trapped, self-cooled electrons while avoiding charge exchange with the cooling medium (see Section 3).

2.1. EBIT for mass measurement support

The EBIT has been used successfully to enhance the mass measurements of, for example, ^{74}Rb where the higher charge state of 8^+ was used to improve the mass measurement precision [13], or ^{71}Ge and ^{71}Ga where charge breeding was used to aid in mass selection [15]. While Eq. (2) demonstrates the statistical improvement in precision from using HCI ($\delta m/m \propto q^{-1}$), that relation only dominates as long as ion production is high enough that 1–5 ions can be sent into MPET for a given measurement cycle. If less than an ion/shot is produced the statistical gains from working with HCI can be outweighed by the $\sqrt{N_{ion}}$ dependence in Eq. (2). The effective gain in precision from using HCI, G_{HCI}, is therefore given by,

$$G_{HCI} = q\sqrt{2^{-t_{cb}/t_{1/2}}\eta_{pop}\epsilon}, \tag{3}$$

where $t_{cb}/t_{1/2}$ is the ratio of the charge-breeding time to the nuclear half-life of the isotope undergoing charge-breeding in the EBIT, η_{pop} is the fraction of the ion's population in the bunch with charge state q, and ϵ is the combined efficiencies related to the use of HCI including (but not limited to) transport, capture in EBIT, capture in MPET, losses in EBIT due to charge-breeding and loss of charge state due to

[1] Though the gun was designed to provide a 70 keV beam at 5 A.