USING ELECTRON COOLING TO HELP WEIGH EXOTIC NUCLEI - PROGRESS ON TITAN'S COOLER PENNING TRAP (CPET)

BY BRIAN KOOTTE, CORINA ANDREOIU, CARLA BABCOCK, BRADLEY BARQUEST, THOMAS BRUNNER, USMAN CHOWDHURY, JENS DILLING, ANDREW FINLAY, MATTHEW FOSTER, AARON GALLANT, GERALD GWINNER, RENEE KLAWITTER, YANG LAN, DANIEL LASCAR, ERICH LEISTENSCHNEIDER, STEFAN PAUL, MORITZ REITER, AND DEVIN SHORT[1]

The formation of approximately half of the elements in the universe which are heavier than iron is understood to occur in extremely neutron-rich environments in what is called the "rapid neutron capture process" or "*r*-process" [1]. In a matter of seconds, nuclei undergo successive neutron captures to produce heavy, but extremely unstable, neutron-rich isotopes which eventually beta-decay into the higher mass elements that we observe on Earth. The site of this process, however, remains a point of contention. Popular candidate astrophysical sites include core-collapse supernovae and neutron star mergers [2].

The Isotope Separator and ACcelerator (ISAC) facility located at TRIUMF, in Vancouver, BC, Canada is able to synthesize some of the isotopes which directly impact the reaction pathways in these extreme environments, as well as those which can help to constrain our theoretical understanding of the isotopes that are presently unfeasible to produce with current technology.

TITAN AS THE SOLUTION

In order to calculate the nuclear reaction pathways which determine the present day abundances of the heavy elements in the universe, the masses of nuclei need to be known to high precision [2-4]. Masses of short-lived nuclei are also critical inputs for theorists striving to uncover the fundamental structure of the nucleus [4-6]. TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) specializes in determining the masses of these nuclei to high precision (see Fig. 1). Mass uncertainties of less than 10^{-6} are needed to study nuclear structure [4], and uncertainties of 10^{-7} or better are required to constrain r-process models [3,4].

SUMMARY

We are commissioning a new trap for cooling short-lived isotopes relevant to astrophysics in order to quickly perform high-precision mass spectrometry.

MASS MEASUREMENTS AT TITAN

At TITAN we employ Penning Trap Mass Spectrometry (PTMS) to measure the masses of short-lived isotopes produced in nuclear reactions. This involves measuring the cyclotron frequency of a series of trapped ions, as they orbit in the magnetic field of the trap due to the Lorentz force. The mass can be extracted due to the fact that the cyclotron frequency is inversely proportional to the inertial mass of the ion as seen in the expression $f = \frac{qB}{2\pi m}$, where f is the orbital frequency, q is the charge of the ion, B is the magnitude of the magnetic field, and m is the mass. By applying a range of excitation frequencies near the cyclotron frequency, we produce a resonance curve with the maximal energy being transferred to the ion at the resonant frequency. We observe this energy transfer as a reduction in the time-of-flight to a detector when the ion is ejected from the trap.

HIGHLY CHARGED IONS AND THE NEED TO COOL

Since the precision of a Penning trap mass measurement scales linearly with the charge of the ion, charge breeding (stripping additional electrons from the singly-charged ions) can be employed to enhance the precision of these measurements. The gain in precision achieved by charge breeding radioactive ions is given by

Brian Kootte
<bkootte@
triumf.ca>,
University of
Manitoba / TRIUMF,
4004 Wesbrook
Mall, Vancouver,
BC V6T 2A3

Jens Dilling
<jdilling@
triumf.ca>,

Gerald Gwinner
<Gerald.Gwinner@
umanitoba.ca>,

and

Daniel Lascar
<dlascar@
triumf.ca>

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[1] **Corina Andreoiu and Devin Short:** Simon Fraser University.
Carla Babcock, Bradley Barquest, Usman Chowdhury, Jens Dilling, Aaron Gallant, Renee Klawitter, Yang Lan, Daniel Lascar, Erich Leistenschneider, Moritz Reiter and Devin Short: TRIUMF.
Thomas Brunner: McGill University.
Usman Chowdhury and Gerald Gwinner: University of Manitoba.
Jens Dilling, Andrew Finlay, Aaron Gallant, Yang Lan and Erich Leistenschneider: University of British Columbia.
Matthew Foster: University of Surrey.
Renee Klawitter and Stefan Paul: University of Heidelberg.

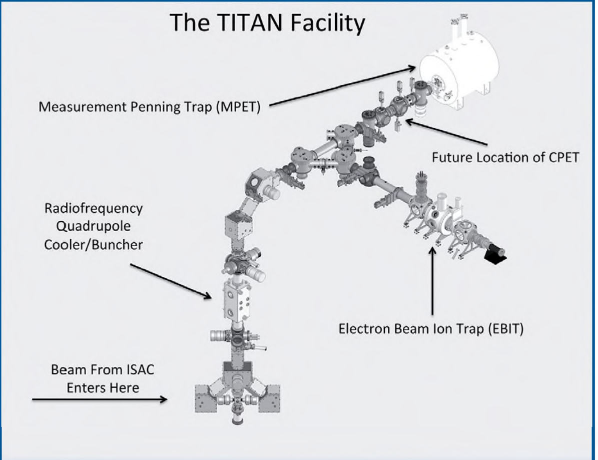

Fig. 1 The TITAN facility specializes in measuring the masses of short-lived isotopes to high precision. Beams of short-lived isotopes enter at the bottom left and are cooled and bunched in a helium-filled radiofrequency quadrupole trap. To enhance the precision, ions can then be charge-bred in the EBIT. When fully operational, the Cooler Penning Trap (CPET) will be installed in front of MPET to cool the charge-bred ions prior to mass measurement.

$$G_{HCI} = q\sqrt{2^{-\frac{t_{CB}}{t_{1/2}}}\eta_{pop}\epsilon},$$

where t_{CB} is the charge breeding time, $t_{1/2}$ is the half-life of the ion, η_{pop} is the fraction of ions bred to the desired charge state, and ϵ is a term relating to the efficiencies of charge breeding [7]. Therefore, prior to mass measurement at TITAN, we use an Electron Beam Ion Trap (EBIT) to strip additional electrons from the singly charged ions delivered to TITAN from ISAC. These charge-bred ions have been used successfully to measure the masses of a variety of nuclei (e.g. [8,9]).

However, the charge breeding process inside the EBIT has been found to increase the energy spread of the ion bunch sent to the measurement Penning trap to ~ 30 eV per charge state. This negatively impacts the precision by reducing the injection efficiency of the valuable radioactive beam into the measurement trap and by spreading out the time-of-flight resonance.

SOLUTION: THE COOLER PENNING TRAP (CPET)

In order to cool the charge-bred ions down to 1 eV per charge state prior to mass measurement, we are commissioning a Cooler PEnning Trap (CPET). If hot charged particles are trapped in the same spatial region as cold charged particles, they will interact via the Coulomb interaction and exchange kinetic energy. In this way, we plan to use a plasma of electrons to sympathetically cool the short-lived, highly charged ions. Although many of the ions of interest at ISAC have half-lives in the range of only tens of milliseconds, it has been predicted that we can sufficiently cool many of these isotopes before they decay. Moreover, the rate of recombination of ions with the electron plasma should be small compared to our cooling times [10].

CPET is composed of a magnetic field aligned along the path of the ions and a series of trapping electrodes. The magnetic field radially confines charged particles to the central axis of the trap, and DC voltages applied to the electrodes confine them in the axial direction. In order to trap both the positively charged ions and the negatively charged electrons in the same region, we plan to employ a "nested potential" configuration. This involves trapping the electrons within a local potential minimum that is located inside the larger ion trapping potential of the ions. Recent work has involved optimizing the trapping of the electron coolant by injecting electrons from a thermionic source located directly on the beam axis.

An elegant feature of cooling with electrons (rather than ions) is that they will self-cool in CPET's 7 Tesla magnetic field via the emission of synchrotron radiation. In principle, one bunch of trapped electrons can be used to cool many consecutive bunches of ions.

PLASMA OBSERVATION IN CPET

Initial attempts to trap electrons in CPET proved difficult. We discovered that this was due to the fact that the dense electron cloud was exhibiting behaviour characteristic of a non-neutral plasma. We observed that the entire column of electrons in the trap rotated about the trap axis as a result of an $\vec{E} \times \vec{B}$ drift as the plasma interacted with its own image charge on the trap wall. This so-called "diocotron" motion stymied our detection of the electron plasma for some time. Compared to ions, electrons are very light, and consequently follow the magnetic field lines as they exit the magnet. An initially small displacement of the plasma column from the centre of the trap will expand with the diverging magnetic field lines when the electrons are ejected from the trap. By the time electrons reached our detector, they were too far off-axis to be observed.

A TALE OF TWO DETECTORS

Fortunately, we were able to overcome our challenges with electron detection in order to study the electron plasma by employing two different techniques for their detection. At first, a phosphor screen was installed inside our beam line, well within the influence of the magnetic field. This allowed us to observe the radius of the diocotron motion of the extracted electrons before they were steered into the walls of the beam line by the magnetic field. We were able to draw the useful conclusion that the radius of the plasma motion damps over time [11], which is encouraging since we want to spatially overlap the ions with a high density of electrons.

Despite our success with the phosphor screen, any long-term detection of the presence of electrons in CPET needs to also allow ions to enter the trap, but the phosphor screen obstructed the beam line. We therefore designed and built a new detector based on an array of thin wires that TITAN uses for ion deflection, known as a Bradbury-Nielsen gate [12]. This new mesh detector is positioned

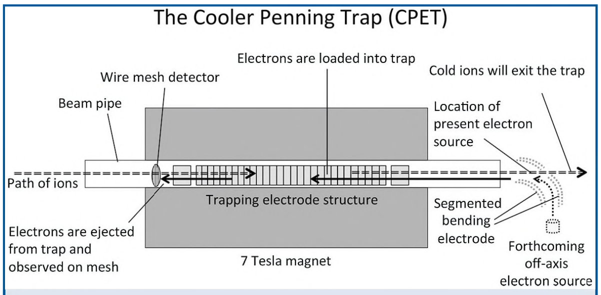

Fig. 2 Overview of CPET. Electrons (solid black line) were injected from the right, trapped for up to 1 minute, and then ejected onto the wire mesh detector. The dotted/dashed lines represent features that have not yet been implemented. A segmented bending electrode (light grey dots) will inject electrons (black dots) from off of the beam axis. This will allow for ions (dashed double line) which are injected from the left and trapped, to be ejected out the right side of the trap.

inside the magnetic field at nearly the same location as where the phosphor screen was located (see Fig. 2). When it is biased to the local drift tube voltage, ions will pass through the mesh essentially unobstructed. However, by grounding the mesh and making it a local potential minimum for the electrons, we can quantify the electron plasma in the trap by measuring the charge of the electron bunch as it hits the mesh. What was lost in not knowing the position of the electron cloud was more than made up for by the fact that we could determine their quantity. By comparing the current on the mesh when the trap is loaded with electrons and undergoes an ejection cycle to the current on the mesh when the empty trap undergoes an ejection cycle, we were able to separate the electron signal from the noise of switching electrodes.

We detected $\sim 10^8$ electrons per bunch for up to 1 minute of time stored in CPET[13]. This quantity of electrons should prove sufficient for cooling the highly charged ions, providing the electrons and ions suitably overlap.

MOVING FORWARD

We are installing a newly designed set of segmented bending electrodes to both inject the electrons from off-axis and provide steering through the magnetic field. When the bending is turned off, ions can continue through the bending electrode to our measurement trap. Having this installed will allow us to better recreate the conditions which CPET will operate under when used to cool ions in TITAN. As a result, we will be able to work towards the cooling of singly charged ions independent from the TITAN facility in order to demonstrate CPET's readiness without interfering with our science program.

The ability to cool singly charged ions will allow us to confidently incorporate CPET into the TITAN beamline so we can work to reduce the energy spread of short-lived highly charged ions in a short time frame. Once fully operational, the time of the cooling cycle will need to be optimized for the lifetime of the species of interest. Realizing electron cooling of highly charged, exotic isotopes will represent a valuable step forward in the Penning trap mass spectrometry of these extreme species.

ACKNOWLEDGEMENTS

This work is supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC). TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada (NRC). B. Kootte acknowledges a University of Manitoba Faculty of Science Studentship.

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