Precision Mass Measurements and In-Trap Decay Spectroscopy with TITAN

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Motivation

TRIUMF’s world leading TITAN ion-trap facility is dedicated to high-precision mass measurements in order to provide experimental data for various physics fields:

- Nuclear structure: shell closures, island of inversion, shape coexistence, halo nuclei, etc.
- Astrophysics: abundance of stable elements, r-processes, etc.
- Particle physics: Standard Model \( \Rightarrow \) unitarity of CKM matrix, Q-values in context with \( \nu \) physics, double-beta decay, etc.

TITAN is the fastest Penning trap in the world, with the ability to measure isotopes with lifetimes less than 10 ms by applying the ion-cyclotron resonance time-of-flight (TOF-ICR) method, which is ideal for short-lived nuclei.

Further, TITAN offers the opportunity to perform in-trap X-ray and \( \gamma \)-ray spectroscopy on radioactive isotopes stored in the center of the spectroscopy ion trap (also used as EBIT).

One particular project (TITAN-EC) develops this novel technique to measure the electron-capture branching ratios (ECBRs) of the Intermediate nuclides in \( \beta \)-decays. The ECBRs are important for evaluating the nuclear matrix elements (NMEs) involved in the \( \beta \)-decay for the two-neutrino (2\( \nu \beta \beta \)) and the neutrinoless (0\( \nu \beta \beta \)) decay.

In-trap decay spectroscopy - TITAN-EC

Left: Schematic of the EBIT. Ions are stored backing-free in a strong B-field (up to 6T). X-rays and \( \gamma \)-rays from the radioactive trapped ions are detected by Si(Li) detectors. Right: X-ray detectors mounted around the spectroscopy Penning trap.

First results:

Above: Spectrum of the \( ^{124}\text{Cs} \), \( ^{136}\text{Cs} \) decay. The inset shows the energy region between 400 keV and 600 keV, indicating the complete lack of the 511 keV \( \gamma \)-ray.

Right: Trapping-time dependent X-ray spectrum showing X-rays from three different isotopes.

Penning-Trap Mass Measurement

Ions are confined by a strong, homogeneous magnetic field and a harmonic electrostatic potential trap. The ion motion inside the trap is a superposition of 3 independent eigenmodes:

- Reduced cyclotron frequency
- Magnetron frequency
- Axial frequency

Left: Extraction through the B-field gradient converts the reduced cyclotron motion into an axial motion, reducing the TOF to a detector. The frequency at the minimum TOF is the cyclotron frequency.

Mass Measurement Results

Above: Neutron-separation energy in dependence of the neutron number. The mass values measured by TITAN agree with the theoretical models.

- The island of inversion shows the break-down of the standard “magic-numbers”
- TITAN’s measurements in Mg isotopes show the smallest “shell gap” for a magic nuclide
- Measurements in Na hint at stronger deformations

Right: Neutron-separation energy of \( ^{31}\text{Al} \), \( ^{30}\text{Mg} \) and \( ^{29}\text{Na} \) in dependence of the neutron number.

Above: Example of a double resonance for the Q-value determination with 2 species inside of the trap.

The neutrino remains a mystery in nuclear and particle physics. It may be possible that the \( \nu \) is its own anti-particle. By searching for the O(\( \nu \beta \beta \)) decay one wants to determine the \( \nu \)’s nature. To look for these very rare events we need to know the Q-value of the decay. TITAN measured the masses of \( ^{46}\text{Ca} \) and \( ^{48}\text{Ti} \), and found deviations to the literature values, but is in agreement with other Penning-trap facilities.

Acknowledgments

We thank the TRIUMF staff, esp. the TITAN group, the ISAC beam development group, the TRIILS team, and the operators.

This work is supported by National Science and Engineering Research Council of Canada and the Deutsche Forschungsgemeinschaft (DFG) under grant-number no. FR 6013-1.