Reaching ppb Mass Determination using Highly Charged Ions at TITAN

M. Brodeur1,2, T. Brunner1,3, S. Ettenauer1,2, A. Gallant1,2, A. Lapierre1, R. Ringle1, V.L. Ryjkov1, P. Delheij1, G. Gwinner4, D. Lunney5 & J. Dilling1,2

1. TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada.
2. Department of Physics & Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada.
3. Physik Department, E17, Technische Universität München, Garching, Germany.
4. S. Department of Physics & Astronomy, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada.
5. CSNSM-IPNO-CMS, F-91405 Orsay-Campus, France.

Why doing mass measurements?

- Halo physics: the atomic mass, through the binding energy and charge radii, put tighter constrain on nuclear theory models [1-3].
- Nuclear Astrophysics: the nuclear synthesis processes time scale is mass-dependent [4,5].
- Nuclear structure: the appearance of new magic numbers can be seen from sudden jumps in separation energies [6].
- Nuclear Physics: very precise QEC of superallowed β 0 → 0 transitions are important to put tighter constrain on the different models used to calculate structure numbers can be seen from sudden jumps in separation processes' time scale is mass-dependent [4,5].

Why using Highly Charged Ions?

The two ways to improve the δm/m for low yield RIB:

- Route taken by TITAN: uses of HCI produced by an Electron Beam Ion Trap (see A. Lapierre’s poster)
- Linear Magnetic Field + Harmonic Electrostatic Potential
- Three Harmonic Eigen-motions: one axial of frequency ωc, two radial called magnetron (ωm) and reduced cyclotron (ω) such that the ions have similar average velocities in the trap, hence minimizing shifts in the frequency ratio (see left figure).

The TITAN facility, located in ISAC at TRIUMF, is dedicated to the mass measurement and laser spectroscopy of RIB as well as EC branching ratio measurements (see T. Brunner poster)

Penning Trap Mass Spectrometry in a Nutshell

- The mass measurement is made by finding the true cyclotron frequency ωC of the ion in the trap
- Extraction through magnetic field converts radial energy to longitudinal energy
- Measurement of TOF gives cyclotron frequency and hence the mass

Relativistic mass increase for low m/q

For mass determination at the ppb level using HCI, the relativistic mass increase (RMI) is non-negligible.

With the relativistic mass increase the cyclotron frequency becomes:

$$\omega_C = \frac{eB}{m_{\text{rel}} c} \sqrt{1 - \beta^2}$$

where $\beta = c \frac{\omega_C}{\omega_{\text{un}}} = \frac{s - \Delta V_{LS}}{\Delta V_{LS}}$ is the mass-dep, steering strength.

Hence, the decrease in $\omega_C$ due to RMI can be obtained by measuring $\omega_C$ for different $\Delta V_{LS}$ and by subsequently fitting:

$$\Delta V_{LS} = \frac{\omega_C}{\omega_{\text{un}}} \frac{1}{\sqrt{1 - \left(\frac{s - \Delta V_{LS}}{\Delta V_{LS}}\right)^2}}$$

Knowing the values of $a$ of the calibrant and the ion of interest, one can then chose $\Delta V_{LS}$ such that the ions have similar average velocities in the trap, hence minimizing shifts in the frequency ratio (see left figure):

$$\frac{\Delta V_{LS}}{\Delta V_{LS,\text{meas}}} = \frac{\omega_C}{\omega_{\text{un}}} \frac{1}{\sqrt{1 - \left(\frac{s - \Delta V_{LS}}{\Delta V_{LS}}\right)^2}}$$

Penning trap electric field compensation

The non-harmonicities in the trapping potential introduced by the hole in the end-caps and the truncation of the hyperbolic electrodes induce shifts in the cyclotron frequency of the ion such as [11]:

$$\omega_{\text{measured}} = \omega_{\text{ideal}} + \Delta \omega_{\text{(C)}} + \Delta \omega_{\text{(C)}} + \ldots$$

depends on RF amplitude

$$\Delta \omega_{\text{(C)}} = \frac{3C_4 V}{4B^2} (\frac{P_2}{\omega_c} - 2)$$

$$\Delta \omega_{\text{(C)}} = \frac{15C_6 V}{8B^4} (\frac{P_2}{\omega_c} - 2) (\frac{P_2}{\omega_c} + 2) - 8$$

For optimal compensation, $C_4 & C_6 \rightarrow 0$ and the difference in $\omega_C$ for different RF amplitude $V_{RF}$ should be minimal.

Conclusion

- Sys. error due to rel. effect < 1 ppb ($^6\text{Li}$ vs $^7\text{Li}$)
- Rel. effects studies on HCI underway
- Mass dependent shift due to electric field anharmonicities < 0.5 ppb/u.
- First mass determination on HCI (R. Ringle talk)
- Ready to radioactive HCI (see A. Lapierre’s poster)

References