Reaching ppb Mass Determination using Highly Charged Ions at TITAN

TRIUMF

M. Brodeur[1,2], T. Brunner[1,3], S. Ettenauer[1,2], A. Gallant[1,2], M. Smith[1,2], A. Lapierre[1], R. Ringle[1], V.L. Ryjkov[1], P. Delheij[1], G. Gwinner[4], D. Lunney[5] & J. Dilling[1,2]

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, E12, Technische Universität München, Garching, Germany.
4. 6. Department of Physics & Astronomy, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada.
5. CSNSM-IN2P3-CNRS, F-91405 Orsay-Campus, France

TITAN
ISAC-TRIUMF

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 Q_{EC} of superallowed β 0^+ -> 0^+ transitions are important to put tighter constrain on the different models used to calculate structure dependent correction to the ft values [7-8].

Why using Highly Charged Ions?

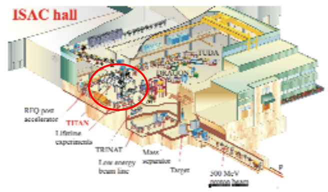
The two ways to improve the $\delta m/m$ for low yield RIB:

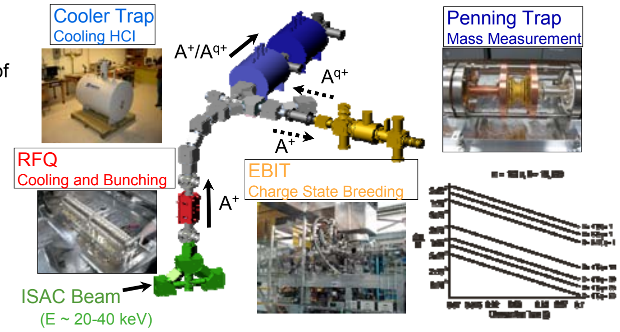
$$\frac{\delta m}{m} = \frac{m}{qTB\sqrt{N}}$$

Route taken by TITAN: uses of HCI produced by an Electron Beam Ion Trap (see A. Lapierre's poster)

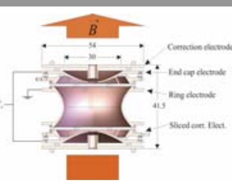
The TITAN facility at ISAC

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)

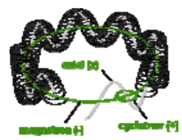




Penning Trap Mass Spectrometry in a Nutshell



Linear Magnetic Field + Harmonic Electrostatic Potential



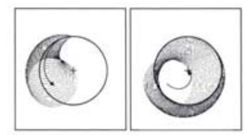
Three Harmonic Eigen-motions: one axial of frequency ω_z, two radial called magnetron (ω_-) and reduced cyclotron (ω_+)

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2 \quad [9]$$

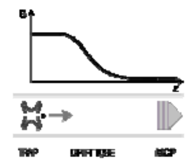
$$\omega_c = \frac{q}{m}B$$

$$\omega_+ >> \omega_-$$

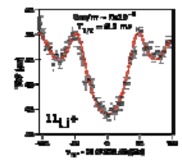
The mass measurement is made by finding the true cyclotron frequency ω_c of the ion in the trap



Application of quadrupolar field converts magnetron motion into cyclotron motion.



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

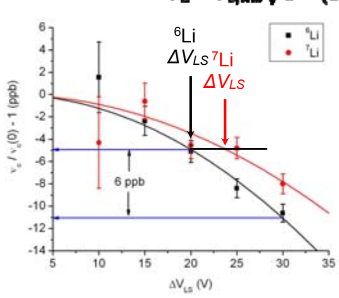
For mass determination at the ppb level using HCI, the relativistic mass increase (RMI) is non-negligible.

With the relativistic mass increase the cyclotron frequency becomes: $\omega_c = \frac{qB}{\gamma m_0} \simeq \omega_{c,ini}\sqrt{1-\bar{\beta}^2}$

Since $\omega_+ >> \omega_-$, we can assume that on average the ions have: $\bar{\beta} \simeq \bar{\rho}_+ \cdot \omega_+ / c = \rho_{-,ini} \cdot k \cdot \omega_+ / c$

k can be obtained by integrating ρ_+ over the measurement period. At TITAN, the $\rho_{-,ini}$ is set by off-axis trap injection using a Lorentz Steerer (LS) [10]: $\rho_{-,ini} = s \cdot \Delta V_{LS}$ where s is the mass-dep. steering strength.

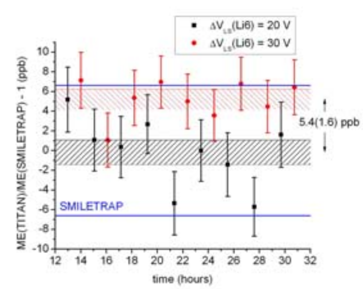
Hence, the decrease in ω_c due to RMI can be obtained by measuring ω_c for different ΔV_{LS} and by subsequently fitting: $\nu_c = \nu_{c,ini}\sqrt{1-(a \cdot \Delta V_{LS})^2}$ where $\nu_{c,ini}$ and a are fitting constants.



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

$$R_{corr} = \frac{\nu_{c,cal}}{\nu_c} = R_{meas}\sqrt{\frac{1-(a_{cal} \cdot \Delta V_{LS,cal})^2}{1-(a \cdot \Delta V_{LS})^2}}$$

With ΔV_{LS} = 22 V for Li7, the mass of Li6 was measured using ΔV_{LS} = 20 and 30 V. The obtained masses showed a 5.4(1.6) ppb difference as expected from the relativistic mass increase (**see right figure**).



Relativistic frequency shifts in the Penning trap for small m/q can be reduced by:

- Reducing the Lorentz steering
- Not fully converting the initial magnetron motion

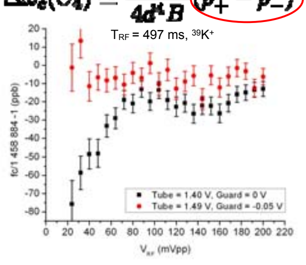
Penning trap electric field compensation

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

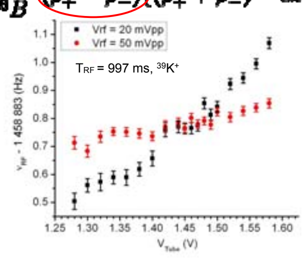
$$\omega_c(measured) = \omega_c(ideal) + \Delta\omega_c(C_4) + \Delta\omega_c(C_6) + \ldots$$

$$\Delta\omega_c(C_4) \simeq \frac{3C_4V_0}{4d^4B}(\rho_+^2 - \rho_-^2) \qquad \Delta\omega_c(C_6) \simeq \frac{15C_6V_0}{8d^6B}(\rho_+^2 - \rho_-^2)\{(\rho_+^2 + \rho_-^2) - 3z^2\}$$

$(\rho_+^2 - \rho_-^2)$ depends on RF amplitude



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



Conclusion

- Sys. error due to rel. effect < 1 ppb (^{6}Li vs ^{7}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

[1] R. Ringle et al. PLB **675**, 170 (2009)
[2] M. Smith et al. PRL **101**, 202501 (2008)
[3] V.L. Ryjkov et al. PRL **101**, 012501 (2008)
[4] J. Savory et al. PRL **102**, 132501 (2009)
[5] J. A. Clark et al. PRL **92**, 192501 (2004)
[6] C. Guenaut et al. JPG: Nucl. Part. Phys **31** S1765 (2005)
[7] T. Eronen et al. PRL **100**, 132502 (2008)
[8] G. Savard et al. PRL **95**, 102501 (2005)
[9] G. Gabrielse et al. PRL **102**, 172501 (2009)
[10] R. Ringle et al. Inter. J Mass Spec. **263**, 38 (2006)
[11] G. Bollen et al. J. Appl. Phys. **68**, 4355 (1990)