TITAN Mass Measurement of $^{11}\text{Li}$ (and other halo nuclei)

Ryan Ringle, TRIUMF
The weather in Vancouver
(according to the tourist board)
The weather in Vancouver
(the other 364 days of the year)
Outline

- ISAC @ TRIUMF
- The TITAN experiment
- Penning trap mass spectrometry
- Towards shorter half lives
- Results of $^{11}$Li measurement
- Results of other halo nuclei mass measurements
ISAC at TRIUMF

**ISAC:**
Highest power for On-Line facilities, we go up to 100\(\mu\)A @ 500MeV DC proton

**ISAC has 3 exper. areas:**
- Low energy (60keV)
- ISAC I (cont. up 1.8 MeV/u)
- ISAC II (up to 10 MeV/u, present license to 5 MeV/u)

**Many experimental stations:**
- TRINAT, Beta-NMR, 8pi, tape-station, TITAN, Co-linear laser spec, polarized beam line, etc
- DRAGON, TUDA, TACTIC, GPS (Leuven)
- TIGRESS, EMMA (2010), GPS (Maya)

Yields:
- \(^{11}\text{Li} - 4\times10^4 / s\)
- \(^{74}\text{Rb} - 2\times10^4 / s\)
- \(^{62}\text{Ga} - 2\times10^3 / s\)
The TITAN Experiment

Penning Trap
Mass Measurement

RFQ
Cooling and Bunching

EBIT
Charge State Breeding
(talk by T. Brunner)

ISAC Beam
(E ~ 20-60 keV)
Penning Trap Mass Spectrometry

3D ion confinement: linear magnetic field + quadrupolar electric field

Resulting ion motion: 3 independent eigenmotions $\omega_+, \omega_-, \omega_z$

True cyclotron frequency is the sum of radial eigenmotions

$$\omega_- < \omega_z < \omega_+$$

$$\omega_c = \omega_+ + \omega_- = \frac{q}{m}B$$

Application of quadrupolar RF field causes beating between reduced cyclotron and magnetron motions

Extraction through magnetic field converts radial energy to longitudinal energy

Measure TOF to determine the center frequency

$$R \approx v_c \cdot T_{rf}$$
Towards Shorter Half Lives

Measurement time scales:

initial magnetron preparation
dipolar RF excitation ~ 10 ms
Lorentz steerer FREE

Principle: generate electric dipole field in strong magnetic field region to move ions off axis

\[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \]

net offset in ExB direction

\[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \]

R. Ringle et al., IJMS 263, 38 (2007)

- cyclotron motion excitation (limited by half life)

\[ R \approx v_c \cdot T_{rf} = (q/m) \cdot B \cdot T_{rf} \]

buy a bigger magnet (increase B)
charge breeding (increase q)
different RF excitation scheme (reduce FWHM)
Ramsey excitation - S. George et al., PRL 98, 162501 (2007)
Octupolar excitation - R. Ringle et al., IJMS 262, 33 (2007)
S. Eliseev et al., IJMS 262, 45 (2007)
Penning trap benchmarks

6,7\text{Li} mass comparison

Compare to SMILETRAP* values

*14σ deviation of \( m(\text{7Li}) \) from AME03


\( 7\text{Li} \delta m/m \sim 5 \times 10^{-10} \)

Agreement is observed on the 2(7)x10^{-9} level

Mass dependent frequency shifts

\[ M_{\text{TITAN}} - M_{\text{SMILE}} = 13(39) \text{ eV} \]

\( ^{12}\text{C} \) vs. \( ^{6}\text{Li} \)

mass shift insignificant on the 3(4)x10^{-8} level over six mass units
Halo Nuclei

- one-proton halo
- two-proton halo
- binary system
- one-neutron halo
- two-neutron halo
- four-neutron halo

measured with TITAN
proposed
$S_{2n}$ of All Bound Nuclei

Slide from D. Lunney
Li Isotope Shifts

altered charge radius, $r_c$, of $^{11}$Li could indicate a perturbed $^9$Li core

Isotopic Shift

$$\delta \nu_{exp}^{A,A'} - \delta \nu_{MS}^{A,A'} = F \delta <r_c^2>^{A,A'}$$

- optical isotope shift measurements provide relative shift
- $6,7$Li $r_c$ determined via elastic electron scattering
  C.W. de Jager et al., At. Data Nucl. Data Tables 14, 479 (1974)
- mass shift terms calculated by Z.-C. Yan and G.W.F. Drake
- $^{11}$Li mass measurement with $\delta m \leq 1$ keV$/c^2$ required to remove it as a source of significant uncertainty

R. Sánchez et al., PRL 96, 033002 (2006)
$^{11}$Li $S_{2n}$ Value

Five previous measurements of $S_{2n}(^{11}$Li$)$

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>$S_{2n}$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thibault et al.</td>
<td>Mass Spec.</td>
<td>170 ± 80</td>
</tr>
<tr>
<td>J.M. Wouters et al.</td>
<td>TOF</td>
<td>320 ± 120</td>
</tr>
<tr>
<td>T. Kobayashi et al.</td>
<td>$^{11}$B($\pi^-$,$\pi^+$)$^{11}$Li</td>
<td>340 ± 50</td>
</tr>
<tr>
<td>B.M. Young et al.</td>
<td>$^{14}$C($^{11}$B,$^{11}$Li)$^{14}$O</td>
<td>295 ± 35</td>
</tr>
<tr>
<td>Bachelet et al.</td>
<td>Mass Spec.</td>
<td>376 ± 5</td>
</tr>
</tbody>
</table>

AME '03: $S_{2n}(^{11}$Li$)$ = 300 ± 20 keV


- Need a precision of $\delta m \leq 5$ keV/$c^2$ to confirm accuracy of Bachelet et al.
- An $S_{2n}(^{11}$Li$)$ value with 1% uncertainty, $\delta m \leq 3$ keV/$c^2$, would provide a solid test for nuclear theory.
- Need a precision of $\delta m \leq 1$ keV/$c^2$ for charge radius calculations.
TITAN Mass Measurement of $^{9,11}$Li

(preliminary)

$^{9}$Li$^+$

$\delta m/m \sim 8 \times 10^{-9}$

$T_{1/2} = 177$ ms

$\delta m/m \sim 3 \times 10^{-9}$

$\delta m \sim 50$ eV

$^{11}$Li$^+$

$\delta m/m \sim 7 \times 10^{-8}$

$T_{1/2} = 8.5$ ms

$\delta m/m \sim 3 \times 10^{-8}$

$\delta m \sim 550$ eV
TITAN Mass Measurement of $^9,^{11}\text{Li}$

(preliminary)

$^9\text{Li}^+$

$\delta m/m \sim 8 \times 10^{-9}$

$T_{1/2} = 177 \text{ ms}$

$^9\text{Li}^+$

$\delta m/m \sim 7 \times 10^{-8}$

$T_{1/2} = 8.5 \text{ ms}$

$S_{2n}$ [keV]

AME '03

$^9\text{Li}$

$^11\text{Li}$

$T\text{RF} = 6,297,542 \text{ [Hz]}$

$T\text{RF} = 5147353.46 \text{ [Hz]}$
TITAN Mass Measurement of $^{9,11}$Li
(preliminary)

$^{9}$Li$^+$

$\delta m/m \sim 8 \times 10^{-9}$

$T_{1/2} = 177 \text{ ms}$

$^{11}$Li$^+$

$\delta m/m \sim 7 \times 10^{-8}$

$T_{1/2} = 8.5 \text{ ms}$

$S_{2n}$ [keV]

$(\Delta S_{2n})_{\text{AME03}} \sim 3.5 \sigma$

$(\Delta S_{2n})_{\text{Bachelet}} \sim 1.4 \sigma$
How Big is $^8$He?

How Big is $^8$He?

How Big is $^8$He?


<table>
<thead>
<tr>
<th></th>
<th>$^6$He value</th>
<th>$^6$He error</th>
<th>$^8$He value</th>
<th>$^8$He error</th>
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</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
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<tr>
<td>Photon counting</td>
<td>0.008</td>
<td>0.032</td>
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<tr>
<td>Probing laser alignment</td>
<td>0.002</td>
<td>0.012</td>
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<tr>
<td>Reference laser drift</td>
<td>0.002</td>
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<td><strong>Systematic</strong></td>
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<td>Probing power shift</td>
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<td>Zeeman shift</td>
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<tr>
<td><strong>Nuclear mass</strong></td>
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<td>0.074</td>
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<td><strong>Corrections</strong></td>
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<tr>
<td>Recoil effect</td>
<td>0.110</td>
<td>0.000</td>
<td>0.165</td>
<td>0.000</td>
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<tr>
<td>Nuclear polarization</td>
<td>-0.014</td>
<td>0.003</td>
<td>-0.002</td>
<td>0.001</td>
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<tr>
<td>$\delta_{V_{A,4}}$ combined</td>
<td>-1.478</td>
<td>0.035</td>
<td>-0.918</td>
<td>0.097</td>
</tr>
</tbody>
</table>
TITAN Mass Measurement of $^8$He

(preliminary)

- First direct mass measurement of $^8$He
- $^2$H used as buffer gas in RFQ
- Produced with “broken” FEBIAD ion source
- $\delta m \sim 300$ eV
- $\Delta m \sim 1.9\sigma$

$\delta m/m \sim 4 \times 10^{-8}$

$^8$He$^+$

$T_{1/2} = 117$ ms

$\nu_{rf} \sim 7075868$ [Hz]

$^8$He mass excess (MeV)

$^{18}$O($^4$He,$^8$He)$^{14}$O
1975

$^{26}$Mg($^4$He,$^8$He)$^{22}$Mg
1966

$^{64}$Ni($^4$He,$^8$He)$^{60}$Ni
1975

TITAN 2007

AME 2003

Measurements
TITAN Mass Measurement of $^{11}\text{Be}$

(preliminary)

$\delta m/m \sim 1 \times 10^{-8}$

$T_{1/2} = 11 \text{ s}$

$^{11}\text{Be}^+$

$^{9}\text{Be}(t,p)^{11}\text{Be}$

$^{10}\text{Be}(d,p)^{11}\text{Be}$

$\delta m/m \sim 7 \times 10^{-9}$ (reduced by a factor of $\sim 50$)
The TITAN mass spectrometer has been commissioned and is capable of making high-precision mass measurements of very short lived nuclei.

TITAN has performed precision mass measurements of He, Li and Be halo nuclei (final analysis pending).

New halo mass measurements allow a refined charge radius determination and shed new light on the structure of halo nuclei.

More mass measurements to come this year (halo, CKM, structure, HCI, etc.)

Neutrinoless $\beta\beta$-decay measurements using EBIT (T. Brunner on Friday)
The TITANs