Precision mass measurements for nuclear physics

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Currently on sabbatical at the
MPI-K Heidelberg
& EMMI

Hirschegg workshop 2015
January 11-16 2015
TRIUMF is owned & operated by a consortium of 19 universities
Founded 45 years ago in Vancouver

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Canada’s National Laboratory for Particle and Nuclear Physics
TRIUMF’s accelerator complex

**ISAC**
- Highest Power ISOL RIB facility
  - Nuclear Structure
  - Nuclear Astrophysics
  - Fund. Symmetries
  - CMMS ($\beta$NMR)

**ISAC-I**
- 60 keV, 1.7 AMeV

**ISAC-II**
- >10 AMeV

**Cyclotron**
- 500 MeV
- 350 $\mu$A

**e-LINAC**
- 300-500 kW photo-fission driver (2015-2017)

**Advanced Rare Isotope Laboratory (ARIEL)**

**CMMS**
- Centre for Molecular and Material Science ($\mu$SR)

**Particle Physics**
- Pienu (- 2012)
- Ultra Cold Neutrons (2015 -)

**Nordion**
- commercial medical isotope production
- 3 cyclotrons

**40 MV SRF Heavy Ion Linac**

**3 cyclotrons**

**500 MeV**

**350 $\mu$A**
ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV, p)

**ISAC II:**
- 10 AMeV for A<150
- 16AMeV for A<30

**ISAC I:**
- 60 keV & 1.7 AMeV

**Programs in**
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
Future Project: ARIEL

- expand RIB program with:
  - 3 simultaneous beams
  - increased number of hours delivered per year
  - new beam species
  - enable long beam times (nucl. astro, fund. symm.)
  - increased beam development capabilities

- New electron linac driver for photo-fission
- New proton beamline

- staged installation
- started 2012
Cyclotron Vault (exiting)

Target Hall

Electron Hall

RIB front end

ARIEL, Civil construction and eLINAC

October 1\textsuperscript{st}: 22.9 MeV e-beam
ARIEL: e-linac for photo-fission
total power: 0.5 MW

**TIMELINE:**
- 2014 first beam, target R&D
- 2017 new front end (phase II)
- 2017 physics production $^8$Li
- 2018 photo fission
- 2020 proton beam (3 beams)
Mass difference of 2 nuclei gives energy gain in reactions (like in stars) and for beta decay.

\[ \text{binding energy} = N \cdot \bullet + Z \cdot \bullet + Z \cdot \bullet \]

Binding energy includes all effective interactions and reflects the nuclear potential.

Mass difference of 2 nuclei gives energy gain in reactions (like in stars) and for beta decay.

Element Synthesis via r-process (supernova)

The nature of neutrinos and double beta decay

Evolution of Nuclear Shells

\[ 10^{-6} < \frac{\delta m}{m} < 10^{-5} \]

\[ 10^{-8} < \frac{\delta m}{m} < 10^{-6} \]

\[ \frac{\delta m}{m} = 10^{-7} \]

\[ \frac{\delta m}{m} < 10^{-8} \]

Abundance vs. \( A \)

100 120 140 160 180 200 220

10\(^{-1}\) 10\(^{-0}\) 10\(^{0}\) 10\(^{1}\) 10\(^{2}\) 10\(^{3}\) 10\(^{4}\) 10\(^{5}\) 10\(^{6}\) 10\(^{7}\)

Abundance vs. \( A \) graph showing data from Ame2011-preview (G. Audi and W. Meng).

Data from TRIUMF.

Kepler's supernova remnant, SN 1604
500 MeV protons

Mass Separator

Low-energy beam transport

TITAN

500 MeV protons

ISOL facility with highest primary beam intensity (100 μA, 500 MeV p)

TRIUMF’s Ion Trap for Atomic and Nuclear Science

- High-precision mass measurements
- In-trap decay spectroscopy

ISAC RIB Facility

ISAC-I and ISAC-II Facility

TRIUMF
**BNG:** fast $m/q$ selection

**RFQ:** Accumulation, cooling, and bunching

**EBIT:** ms charge breeding

**MPET:** mass measurement via cyclotron frequency determination

Future traps:
- MR-TOF MS after RFQ (w/ U. of Giessen)
- Cooler Penning trap before MPET
- Both set-ups installed off-line
Measurement Penning Trap

- Lorentz steerers
- TOF-ICR technique

→ Fast measurements:
  
  \[ T_{1/2} \geq 9 \text{ ms (}^{11}\text{Li}) \]

\[ 2\pi v_c = \left( \frac{q}{m} \right) \cdot B \]

\[ ^{31}\text{Na}^+ \]

\[ T_{1/2} = 17 \text{ ms} \]

M. Brodeur et al., PRC 80 (2009) 024314; M. Brodeur et al., IJMS 20 (2012) 310
Since PT were developed for ions, they behave the same way for stable or unstable particles! Ideal for systematic test and optimizations.

**Accuracy**

- exact theoretical description
  - M. König et al., Int. J. Mass Spect. 142, 95 (1995)
- even for non-ideal traps
- off-line tests with stables

\[ v_c = \frac{1}{2\pi} \frac{q}{m} B \]
Verification of performance using stable masses (or standard $^{12}$C)

K. Blaum et al., EPJ A 15, 245 (2002)
ISOLTRAP: Carbon Cluster tests
$(dm/m)_{res} = 8 \cdot 10^{-9}$

B. Brodeur et al., INJM 310, 20 (2012)
TITAN: Global compensation method
$\Delta R/R_{total} = -4(6) \times 10^{-12} \cdot \Delta (m/q) \cdot V_0$

V.-V. Elomaa et al., NIM A 612, 97 (2009)
JYFLTRAP: Carbon Cluster tests
$\sigma_{res,lim}(r)/r = 7.9 \times 10^{-9}$

C. Droese et al., NIM A 632, 157 (2011)
SHIPTRAP: Temperature stability
$\sigma_o = 1.3(3) \times 10^{-9}/h$

Reached high accuracy and precision: Excellent reliability

Other on-line trap systems do this as well…CPT, LEBIT…
Fast and efficient (but keeping the precision)

\[ n = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B \]

\( \delta m \approx \frac{1}{\nu_c} \cdot \infty \cdot \frac{1}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}} \)

- Improve precision using different excitation modes in the Ramsey (gain factor \( \sim 2 \))
- Precision depends on \( \nu_c \), boosting the frequency key.
  - Can be done with higher excitation modes:
    - Octupole excitation: JYFLTRAP, LEBIT, SHIPTRAP: S. Eliseev et al., PRL. 107, 152501 (2011)
    - Using highly charged ions: developed at SMILETRAP, now also for radioactive beams: TITAN: S. Ettenauer et al., PRL 107, 272501 (2011), IJMS 349 (2013) 79
Developed very fast preparation: (needed to ensure reproducibility of initial conditions)

For ex.: Lorentz-steerer developed at LEBIT: able to reach short half-lives below 100ms:

**ISOLTRAP:**

$^{32}$Ar (98 ms) K. Blaum et al.,

$^{74}$Rb (65ms): A. Kellerbauer et al.,
PRL 93, 072502 (2004)

**TITAN:** $^{11}$Li (9ms) M. Smith et al.,
PRL 101, 202501 (2008)

But we have also done other short-lived species:

$^{12}$Be (21 ms)

$^{34}$Mg (20 ms)

$^{31}$Na (17 ms)

Demonstrated off-line that 5 ms cycle are possible:

Some examples:
A=20,21 Mg & Island of Inversion

- Mg (p-rich, light)
- N-deficient Mg isotopes
- N-rich Na, Al, Mg isotopes (lol)
Mass measurements of Mg masses

Technical difficulty: ISOL production is not selective:
- isobars are co-produced with the isotopes of interest!
- Na, closer to stability, and longer-lived
- much more extracted and delivered to experiment (1,000,000:1 ratio)
- cleaning system required!
Tricks for clean beams:
Go to the source! Ion Guide Laser Ion Source (IG-LIS)

- Suppress normal surface ions (Na).
- Only allow neutral atoms to drift into the laser ionization region.
- Selective ionization of species (Mg).
- Laser ion source still has significant contribution of surface ions.
Performance of the source: IG-LIS

Background reduction of 6 orders of magnitude!
Penning trap mass measurements

Measured Na contamination at MPET < 1%
Isospin-symmetry breaking in $A = 20, 21$ multiplets with TITAN

$$M(A, T, T_z) = a(A, T) + b(A, T) T_z + c(A, T) T_z^2$$

- G.S. binding energy

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Exp.</th>
<th>USDA</th>
<th>USDB</th>
<th>NN + 3N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Mg}$</td>
<td>-6.94</td>
<td>-6.71</td>
<td>-6.83</td>
<td>-6.89</td>
</tr>
<tr>
<td>$^{21}\text{Mg}$</td>
<td>-21.59</td>
<td>-21.79</td>
<td>-21.81</td>
<td>-23.18</td>
</tr>
</tbody>
</table>

- non-zero $d$ coefficients in all three multiplets, $A=20,0^+, A=21,1/2^+, 5/2^+$

- $d_{\text{exp}}$ cannot be explained by USDA/B models

- uncertainties in $\chi$EFT calculations too large to be definitive

$^{20}\text{Mg}^+$: 45$\sigma$ deviation from AME12 & 15x improved precision

$^{21}\text{Mg}$: 14$\sigma$ deviation & 22x improved precision

Compared to USDA/B & $\chi$EFT $NN+3N$ predictions

Excellent collaboration of target/ion source group, experiment and theory
Mass measurements with TITAN:

- Fast (short half-lives !)
- Precise
- Accurate

- Many with very short $T_{1/2}$:
  - $^{32}\text{Na}$: 12.9 ms
  - $^{31}\text{Na}$: 17 ms
  - $^{34}\text{Mg}$: 20 ms

<table>
<thead>
<tr>
<th>Z</th>
<th>N</th>
<th>Isotope</th>
<th>Half-life (ms)</th>
<th>Quantum State</th>
<th>$\beta^+$</th>
<th>$\beta^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>12</td>
<td>$^{19}\text{Mg}$</td>
<td>130</td>
<td>$3/2^+$</td>
<td>100%</td>
<td>99%</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>$^{19}\text{Na}$</td>
<td>30.5</td>
<td>$1^+$</td>
<td>100%</td>
<td>58%</td>
</tr>
<tr>
<td>?</td>
<td>22</td>
<td>$^{23}\text{Na}$</td>
<td>3.60</td>
<td>$3^+$</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>21</td>
<td>13</td>
<td>$^{23}\text{Al}$</td>
<td>644</td>
<td>$5/2^+$</td>
<td>100%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

ISLAND OF INVERSION MASS CARTOGRAPHY (Himpe et al., PLB 658 (2008) 203)
Island-Of-Inversion Mass Cartography

- Island-of-inversion behavior due to correlation energy
- Isomer would have a smaller effect
  - Decay losses excluded 26 ms state

1Rotaru et al. PRL 109 (2012) 092503
**BNG**: fast $m/q$ selection

**RFQ**: Accumulation, cooling, and bunching

**MPET**: mass measurement via cyclotron frequency determination

**EBIT**: ms charge breeding

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J. Dilling *et al.*, NIMB 204 (2003) 492
Enhanced mass measurements: Electron Beam Ion Trap

- Superconducting magnet, Helmholtz configuration
- Design specs up to an electron beam 70 keV & 5 A
- 7 radial ports with recessed Be windows

A. Lapierre et al., NIMA 624 (2010) 54
\[ \frac{\delta m}{m} \approx \frac{m}{qB T_{RF} \sqrt{N}} \]

- \( N \): limited by yield/beam time
- \( T_{RF} \): limited by \( T_{1/2} \)
- \( B \): limited by \( \delta B/B \)
- \( q \): up to \( Z+ \)

Boost precision
or
Reduce experimental requirements for the same precision
Increased Resolving Power

\[ T_{RF} = 197 \text{ ms} \]
To measure $^{71}$Ge $Q$-value, needed to separate small amount of $^{71}$Ge from overwhelming $^{71}$Ga contamination

Exploited Z dependence of charge-state distribution & large increase in $I_e$ at closed shells

Ne-like ions could be achieved for $E_e \sim 2$ keV & $Jt \geq 20$ A cm$^{-2}$ s $\rightarrow$ predominantly $^{71}$Ga$^{21+}$ and $^{71}$Ge$^{22+}$ (CBSIM simulations allow for a systematic approach)

Threshold Charge Breeding

- Charge bred to $^{71}\text{Ga}^{21+}$, $^{71}\text{Ge}^{22+}$

- Select desired q/m by TOF

- Captured isobarically and isolectronically pure ion bunches in MPET

<table>
<thead>
<tr>
<th>Laser:</th>
<th>OFF</th>
<th>ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = 21+$</td>
<td>$^{71}\text{Ga}$</td>
<td>$^{71}\text{Ga}$, $^{71}\text{Ge}$</td>
</tr>
<tr>
<td>$Q = 22+$</td>
<td>–</td>
<td>$^{71}\text{Ge}$</td>
</tr>
</tbody>
</table>

Electron beam: 70 mA / 2.0 kV

TOF [μs]

Mean TOF [μs]

EBIT background (no injection of $A=71$ beam)
Investigating the $^{71}$Ga Anomaly

- SAGE & GALLEX measured solar $v_e$ flux
- Deficit in measured-to-predicted $^{71}$Ge event rates of 13% or 2.5σ
- Need to verify underlying nuclear-physics assumptions
  - C.E. experiment verified contributions from lowest-lying $^{71}$Ge states
  - Remaining uncertainties from Confirmation of $^{71}$Ga and $^{51}$Cr nuclear structure.
  The discrepancy persists.

Getting new isotopes: In-trap Feeding

- Original question: How to populate $^{34m}\text{Al}$ (1+, 26 ms)?
- Produce isomers or nuclides unavailable via ISOL production through in-trap decay
- Proof of principle with $^{30}\text{Al}$
  - $^{30}\text{Mg}^+$ parent yield $\approx 10^6$ pps
  - Good separation of $T_{1/2}$
  - Expected observables:
    - x-rays & $\gamma$-rays
    - HCl spectra on MCP
    - Resonances in MPET

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In-trap Feeding: $^{30}\text{Mg}^{8+}$ Mother

$\text{t}_{CB} = 500 \text{ ms}$
$\text{t}_{BG} = 300 \text{ ms}$

Mean Time of Flight [ms]

$\nu_{RF} - 15\,154\,066$ [Hz]

$30\text{Mg}^{8+}$

In-trap Feeding: $^{30}\text{Al}^{11+}$ Daughter

Preliminary

$t_{\text{CB}} = 500 \text{ ms}$

$t_{\text{BG}} = 300 \text{ ms}$

$^{30}\text{Al}^{11+}$

$t_{\text{CB}} = 4 \text{ s}$

A.A. Kwiatkowski, R. Klawitter, A. Lennarz, et al., in preparation
In-trap Decay Spectroscopy

- **Advantages:**
  - No backing material
  - High purity sample
  - Background material \(\rightarrow\) precision and sensitivity

- **Objective:** determine 2ν2EC NME by measuring branching ratios of intermediate nuclei

- Up to 7 SiLi detectors w/ CuPb shields

- 1 HPGe detector for normalization

- Electrons are guided away from SiLi detectors and can be detected on a PIPS detector

  OR

- Electron beam can be used to improve confinement

D. Frekers *et al.*, CJP 85(2007)57; K.G. Leach *et al.*, arXiv 1405.7209
In-trap Decay Spectroscopy

- Commissioning of SiLi array with $^{124}$Cs$^{Q+}$
- Trap is completely emptied between runs
- No positron-annihilation radiation

• RFQ space-charge limit 10,000× smaller than EBIT

• Inject multiple ion bunches:
  • Open trap for singly charged ions
  • Close trap for singly charged ions (ΔV)
  • After charge breeding, ions experience deep potential well (ΔV·Q)
Multi-Reflection Time-of-Flight Mass Separator:
- Tested in Giessen to $M/\Delta M \approx 50\,000$
- Will improve beam-purity capability from 1:200 to $1:10^4$ desired ion to contamination ratio
- Arrived at TRIUMF 10th of September
- Off-line commissioning Spring 2015, on-line December 2015
Summary & Outlook

- Penning-trap mass measurements of very short-lived species
  - Measurements in the $N = 20$ island of inversion
  - IMME Mg isotopes at $A=20$
- Charge breeding
  - Systematic approach w/ simulations
  - To boost precision
  - To increase resolving power
  - To improve beam purity (threshold charge breeding)
- In-trap feeding demonstrated
  - Populate a specific ground state or a nuclide not produced with ISOL technique
- In-trap decay spectroscopy
  - Electron beam to improve observation time and confinement
  - SiLi array commissioned with $^{124}$Cs
  - Ion stacking demonstrated
  - Exploring HCl effects

- ISAC offers excellent experimental opportunities
- New developments with the e-linac and photo-fission and extra proton beam line

TITAN technical developments:
- MR-TOF
  - For isobaric contaminant removal & fast mass measurements
  - Tested off-line at Giessen
  - Delivered to TRIUMF in September
  - Off-line commissioning on-going
  - On-line planned for Dec 2015
Thank you!


Thanks to my theory colleagues for the collaboration and help

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