The ISAC facility at TRIUMF and TITAN mass measurements on halo nuclei

Jens Dilling, TRIUMF & UBC

• ISAC at TRIUMF: Present and future plans
• TITAN system, a new Penning trap mass spectrometer
• Mass measurements for halo-nuclei studies
• He and Li on-line experiments
• Conclusions & Outlook
ISAC: Highest power for On-Line facilities, we go up to 100µA @ 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 licence to 5 MeV/U)

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

Yields: \( ^{11}\text{Li} \times 10^4 / \text{s} \), \( ^{74}\text{Rb} \times 2 \times 10^4 / \text{s} \), \( ^{62}\text{Ga} \times 2 \times 10^3 / \text{s} \)
**ISAC: Targets and Sources**

**Ion-sources:**
- Surface
- Resonant-Laser source on-line
- Negative, off-line test
- FEBIAD, on-line
- ECR, on-line tests and checks (changes needed)
- ECR new design (Mystic) to be tested on-line 2008

**Targets:**
- High power target tested on-line and reached 50kW on target
- Actinide target: licence test scheduled in summer schedule 2008
- Targets are typically used for 6 weeks.
- We have 2 target stations
- Change of targets takes ~ 10 days
- Limited by one user facility (science and R&D)
The proposed new facilities for TRIUMF

- A new electron accelerator produces 50 MeV electrons
- Electrons impinge on converter and photons are generated
- Photons hit U-target and photo-fission occurs
- New, very exotic, neutron rich isotopes are produced

- A second proton beam-line from the cyclotron connects to a new target station.
- Main focus actinide targets
- Go to higher power (~100 kW)
- Have three radioactive beams a the same time.
Very important process for the formation of heavy elements is the r-process, BUT is not well understood, in part due to the need of hard physics data from very neutron-rich nuclei.
**The r (apid neutron capture)-process**

Supernovae?

The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

**OPEN QUESTIONS:**
- Where does the r-process occur?
- Are there multiple r-processes and are the individual contributions?
- What can the r-process tell us about the physics of extreme environments?

Neutron star mergers?
Calculate isotopes production from 40 MeV, 10µA.
Need intensities of ~10/s for useful experiments, like masses and half-lives to determine the r-process path and find the limits of existence.

Double peak distribution

Sn-isotopes

Useful information can be gained from beams with ~10ions/s!
We have very sensitive tools.
Using protons or photo-fission

$U(\gamma,f) \text{ vs } U(p,f) \text{ @1 GeV}$

$(p,f) \rightarrow 100 \mu A \text{ on } 30 \text{ g/cm}^2 \rightarrow 5 \times 10^{13} \text{ f/s}$

$(\gamma,f) \rightarrow 10^{13} \text{ f/s (} \sim 50 \text{ kW } 25 \text{ MeV})$

**Sn-isotopes:**

- Clearly higher production via photo-fission.
- Even better at higher photon-flux. (we assume factor 20 more fission in target)
- We can produce comparable, and cleaner beams than p-based. (N-converter?)
E-linac concept for photo-fission

Cornell ERL Injector serves as model for many components of fission driver
**Base-line design for the E-linac**

<table>
<thead>
<tr>
<th><strong>Injector linac</strong></th>
<th><strong>Main linac</strong></th>
<th><strong>Fission driver</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mA, 10 MeV</td>
<td>10 mA, 40 MeV</td>
<td>Fission driver</td>
</tr>
<tr>
<td>100 kW beam pwr</td>
<td>400 kW beam power</td>
<td></td>
</tr>
<tr>
<td>Single 9-cell cavity</td>
<td>4 cavities; 9 cell/cavity</td>
<td>All K.E. dumped in target</td>
</tr>
<tr>
<td>Two 50 kW input coupler; 10 MV/m</td>
<td>Two 50 kW coupler/cavity; 10 MV/m gradient</td>
<td></td>
</tr>
<tr>
<td>Single HOM absorber</td>
<td>1 HOM absorber/cavity</td>
<td>500 kW</td>
</tr>
</tbody>
</table>

Will put proposal forward in 2008 to CFI (funded SNOlab), if funded start building in 2009.
Estimated reach for a mega-watt class photo fission facility at ISAC

Cleaner beams than p-spallation.

Approx. boundary for (d,p) reactions to probe neutron capture rates (during r-process freezeout)

Half-lives: EMMA + TIGRESS
Neutron emission probability: DESCANT + EMMA
Masses: TITAN
(d,p) reactions: EMMA + SHARC Si-barrel (York) & TIGRESS
**New proton beam line and 3 simultaneous RIBs**

New proton beam: mostly actinide targets for production of heavy elements (Fr, Ra) for fundamental symmetries and light neutron rich fragments ($^{21}$C etc…)

- **Cyclotron**
- **BL4N**
- **BL2A**
- **50MeV e-linac**
- **Medium Energy Experiments**
  - **DTL1**
  - **Med β SCRF**
- **Low Energy Experiments**
  - **Low β SCRF**
  - **S0**
- **High Energy Experiments**
  - **High β SCRF**
  - **S1**
  - **GS**
A new accelerator leg will take advantage of the new targets and provide two simultaneous accelerated beams.
3 RIBs to ISAC and ISACII

Proposal will be part of next TRIUMF 5 year plan for 2010-2015 (submission Aug 2008).
TITAN and halo nuclei
TITAN
Triumf’s Ion Trap
for Atomic and Nuclear science

- Mass measurements on isotopes with short half-life $T_{1/2} \approx 10$ ms and low production yields ($\approx 100$ ions/s) with high precision $\delta m/m \approx 10^{-8}$.

- Ideally, uniquely matched to isol-type production mode, only system in the world to use HCIs

- TITAN started April 2003 (NSERC), first on-line mass measurements on singly charged ions carried out in 2007.

- TITAN has also a program for other experiments (x-ray spectroscopy, laser spectroscopy, double-beta decay)

McGill, UBC
U Manitoba
TRIUMF
York
Windsor
Calgary.
MPI-HD
TU Munich,
Muenster
Col. School of Mines,
York,
GANIL
RCNP Osaka
TITAN RFCT

- 400 V<sub>pp</sub> applied RF at up to 3 Mhz
- 68% DC efficiency for $^{133}$Cs$^+$ in He
- 15% DC efficiency for $^{6,7}$Li$^+$ in He
- 60% DC efficiency for $^6$Li$^+$ in H$_2$
- Pulses as short as 50 ns FWHM @ up to 1 kHz
- Reversed extraction successfully demonstrated with $^{136}$Xe from OLIS
Off-line mass measurements

<table>
<thead>
<tr>
<th></th>
<th>Mass Excess (keV)</th>
<th>$\delta m/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AME03</td>
<td>14908.14(79)</td>
<td>1.1$x10^{-8}$</td>
</tr>
<tr>
<td>SMILETRAP</td>
<td>14907.0951(42)</td>
<td>6.4$x10^{-10}$</td>
</tr>
<tr>
<td>TITAN</td>
<td>14907.053(44)</td>
<td>3.2$x10^{-9}$</td>
</tr>
</tbody>
</table>

- Confirmation of recent SMILETRAP measurement and agreement with $^6,^7\text{Li}$
- Systematic tests confirm system at the level of $\sim10^{-9}$
- Systematic tests with C-12 as reference.
HALO-nuclei:

- In 1985 Tanihata et al. fired light nuclei at Beryllium, Carbon and Aluminum targets
- They found the radius of $^{11}\text{Li}$ to be much larger than its neighboring nuclei

HALO-nuclei: $^{11}\text{Li}$

$T_{1/2} \approx 8.6 \text{ ms}$

Borromean three body halo nuclei.

- One-proton halo
- Two-proton halo
- Binary system
- One-neutron halo
- Two-neutron halo
- Four-neutron halo
ToPLiS collaboration @ ISAC measured laser frequency shifts for the Lithium isotopes.

G. W. Drake et al. did the calculations for the mass shifts, and extracted the charge radius.

A source of error in the calculations is the mass of $^{11}$Li.

Five Previous measurements of the mass of $^{11}$Li:

- Need precision of $\delta m \leq 1 \text{ keV}/c^2$ for charge radius calculations.
- Need precision of $\delta m \leq 5 \text{ keV}/c^2$ to confirm accuracy of MISTRAL 2003 experiment.
- A value of $S_{2n}$ with 1\% error, $\delta m \leq 3 \text{ keV}/c^2$, would provide a solid test for nuclear theory.

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**Halo-nuclei**

R. Sanchez et al., PRL (2006)
Two Neutron separation

\[ S_n \text{ (keV)} \]

\[ A \]

- **Be**
  - \( ^{6}\text{Be} \):
    - \( 2p=100\% \)
    - EC=100\%
  - \( ^{7}\text{Be} \):
    - \( \alpha=100\% \)
    - Abundance=7.99\%
  - \( ^{8}\text{Be} \):
    - \( \beta^-=100\% \)
    - Abundance=92.41\%
  - \( ^{9}\text{Be} \):
    - \( \beta^-=100\% \)
  - \( ^{10}\text{Be} \):
    - \( \beta^-=100\% \)
  - \( ^{11}\text{Be} \):
    - \( \beta^-=100\% \)
  - \( ^{12}\text{Be} \):
    - \( \beta^-=100\% \)
  - \( ^{13}\text{Be} \):
    - \( n=100\% \)
  - \( ^{14}\text{Be} \):
    - \( \beta^-=100\% \)

- **Li**
  - \( ^{5}\text{Li} \):
    - \( p=100\% \)
    - Abundance=99.99653\%
  - \( ^{6}\text{Li} \):
    - \( \beta^-=100\% \)
    - Abundance=7.96\%
  - \( ^{7}\text{Li} \):
    - \( \beta^-=100\% \)
    - Abundance=92.41\%
  - \( ^{8}\text{Li} \):
    - \( \beta^-=100\% \)
  - \( ^{9}\text{Li} \):
    - \( \beta^-=100\% \)
    - n=100\%
  - \( ^{10}\text{Li} \):
    - \( \beta^-=100\% \)
  - \( ^{11}\text{Li} \):
    - \( \beta^-=100\% \)
    - n=100\%
  - \( ^{12}\text{Li} \):
    - \( \beta^-=100\% \)
    - n=100\%
$S_{2n}$ of all bound nuclides

- Number of occurrences
- $S_{2n}$ (MeV) in 0.5 MeV bins
Halo-nuclei: theory

PHYSICAL REVIEW C 76, 051602(R) (2007)

Geometry of Borromean halo nuclei

C. A. Bertulani¹,² and M. S. Hussein³,⁴

<table>
<thead>
<tr>
<th></th>
<th>$r_{NN}$ (fm)</th>
<th>$r_{c-2N}$ (fm)</th>
<th>$R_{rms}$ (fm)</th>
<th>$\delta_{NN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$He</td>
<td>5.9±1.2 [4]</td>
<td>3.36 (39) [16]</td>
<td>2.67 (2.48)</td>
<td>83⁺²⁰⁻¹⁰</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.71 (07) [21]</td>
<td>2.78</td>
<td>78⁺¹³⁻₁⁸</td>
</tr>
<tr>
<td>$^{11}$Li</td>
<td>6.6±1.5 [4]</td>
<td>5.01 (32) [2]</td>
<td>3.17 (3.12)</td>
<td>66⁺²⁺²²⁻¹₈</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.97 (22) [20]</td>
<td>3.4</td>
<td>58⁺¹⁺¹₀⁻₁⁴</td>
</tr>
<tr>
<td>$^{14}$Be</td>
<td>5.60±1.0 [5]</td>
<td>4.50 [17]</td>
<td>3.10 (3.16)</td>
<td>64⁺⁴⁺⁹⁻₁⁰</td>
</tr>
<tr>
<td>$^{17}$Ne</td>
<td>4.45 [9]</td>
<td>1.55 [9]</td>
<td>2.70 (2.75)</td>
<td>110°</td>
</tr>
</tbody>
</table>

TABLE I. The average distance between the two nucleons in the halo and the core-2N average distance shown in the first and second columns, respectively. The values of $r_{c-2N}$ and the rms radii for $^6$He and $^{11}$Li are obtained both from the $B(E1)$’s values, [16] and [2], and from [20,21] with
Nuclear charge radius of $^8$He

P. Mueller,1,* I. A. Sulai,1,2 A. C. C. Villari,3 J. A. Alcántara-Núñez,3 R. Alves-Condé,3 K. Bailey,1 G. W. F. Drake,4 M. Dubois,5 C. Eléon,5 G. Gaubert,3 R. J. Holt,1 R. V. F. Janssens,1 N. Levesque,3 Z.-T. Lu,1,5 T. P. O’Connor,1 M.-G. Saint-Laurent,3 J. P. Schiffer,1 J.-C. Thomas,3 and L.-B. Wang5

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5Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
(Dated: November 21, 2007)

**accepted PRL (Dec. 21, 2007)**

<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>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon counting</td>
<td>0.008</td>
<td></td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>Probing laser alignment</td>
<td>0.002</td>
<td></td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Reference laser drift</td>
<td>0.002</td>
<td></td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probing power shift</td>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
</tr>
<tr>
<td>Zeeman shift</td>
<td>0.030</td>
<td></td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear mass</strong></td>
<td>0.015</td>
<td></td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td><strong>Corrections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoil effect</td>
<td>0.110 0.000 0.165 0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear polarization</td>
<td>-0.014 0.003 -0.002 0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta r_{A4}$ combined</td>
<td>-1.478 0.035 -0.918 0.097</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Corresponding author.
On-line mass measurements (Nov. run He)

- Measurements of the mass of $^8$He
- First direct mass measurement
- Used H2 in RFQ
- Carried out with 3100/ions sec beam
- Final uncertainty ~ 300eV.
- Used stable Li as reference
On-line mass measurements (Nov. run He)
On-line mass measurements (Dec. run Li)

- Measurements of the mass of Li isotopes
- First direct Penning trap mass measurement
- Used H2 in RFQ
- Carried out at three different beam times/targets+ion source
- Final uncertainty ~ 100eV.
- Used Li stable Li as reference
On-line mass measurements (Dec. run Li)

- TITAN direct mass measurement of $^{11}$Li
- Shortest-lived isotope ever trapped!
- Run @ 50 Hz and 20ms excitation
- ISAC yield of 1200 ions/s.
- Preliminary analysis shows $\delta m = 0.555$ keV + systematic needed for final analysis.
- Reference measurement done with $^{6,7}$Li and $^{12}$C.
- Best precision achieved.
Conclusion:

- ISAC has a very strong science program with state-of-the-art experimental facilities.
- By adding a photo-fission facility a unique niche of physics for nuclear structure and nuclear astro-physics is accessible in the near term (~ 3 years).
- Additional p-beam line will benefit the fundamental symmetries program and n-rich nuclear structure.
- TITAN is a powerful mass spectrometer, well suited for light halo nuclei mass measurements with low production rates.
- TITAN performed precision mass measurements of He, Li, and Be halo nuclei, final analysis pending.
- Will allow refined charge radius determinations and shed new light on the structure of halo nuclei.
- There is more to come from TITAN (halo, CKM, structure…) incl. mass measurements on HCIs.
The TITANs:
Coupled-cluster model \((j\)-scheme\) with 3-body forces for open systems – on a laptop!

- \(V_{\text{low}-k}\) from N3LO with \(\Lambda = 1.9\text{fm}^{-1}\).

First \textit{ab-initio} calculation of decay widths!
- CCM unique method for dripline nuclei.
- \(\sim 1000\) active orbitals
- Underbinding hints at missing 3NF