Nuclear Structure of light Halo Nuclei determined from Scattering on heavy targets at ISAC-II

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On behalf of the E1104 & S1202 Collaborations:
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TIGRESS @ TRIUMF
HALO NUCLEI & REACTIONS

Common “Structural” properties
- Rather inert core plus one or two barely unbound extra neutrons
- Extended neutron distribution, large “radius”. → “halo”
- Very few excited states –if any.

Reaction properties at near-barrier energies:
Is the Optical Model able to describe the scattering of the halo systems?
- Strong absorption in elastic channel
- Large cross section for fragmentation
- They are easily polarizable.

Reaction Mechanisms and Nuclear effects of halo nuclei need to be understood!
**Experimental Set up @ ISAC-II TRIUMF**

9-11Li on $^{208}$Pb

### Beam Energy, Target Pb, and Time

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MeV/u)</th>
<th>Target Pb (mg/cm²)</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9Li</td>
<td>2.67 (24.0)</td>
<td>1.45</td>
<td>11.75</td>
</tr>
<tr>
<td></td>
<td>3.27 (29.4)</td>
<td>1.45</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>3.27 (29.4)</td>
<td>1.9</td>
<td>9.95</td>
</tr>
<tr>
<td></td>
<td>3.67 (33.0)</td>
<td>1.9</td>
<td>31.05</td>
</tr>
<tr>
<td>11Li</td>
<td>2.2 (24.2)</td>
<td>1.45</td>
<td>82.2</td>
</tr>
<tr>
<td></td>
<td>2.7 (29.7)</td>
<td>1.45</td>
<td>118.12</td>
</tr>
</tbody>
</table>

### Detector Details

<table>
<thead>
<tr>
<th>Detector</th>
<th>Thickness (µm)</th>
<th>Angular Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: DSSSD+PAD</td>
<td>42 + 500</td>
<td>10° - 40°</td>
</tr>
<tr>
<td>T2: DSSSD+PAD</td>
<td>42 + 500</td>
<td>30° - 60°</td>
</tr>
<tr>
<td>T3: SSSD+DSSSD</td>
<td>20 + 60</td>
<td>50° - 100°</td>
</tr>
<tr>
<td>T4: SSSD+DSSSD</td>
<td>20 + 63</td>
<td>90° - 140°</td>
</tr>
</tbody>
</table>

**11Li ions average 4300 pps on target**
Which is the mechanism responsible of the $^{11}$Li scattering?

What can we learn of the $^{11}$Li structure?

Comparison of the experimental data with theoretical calculations.

Semicalssical Calculations for B(E1) and breakup data:

Include Coulomb coupling at first order

Continuum Discretised Coupled Channel (4b-CDCC):

$V[n-n-^{9}$Li$] + V[n-n-^{208}$Pb$] + V[^{9}$Li$ + ^{208}$Pb$]$ (from $^{9}$Li elastic scattering)

Image the direct breakup of the projectile

Includes Coulomb and multipole nuclear couplings.

Continuum up to 5 MeV considering the binning procedure

Based on M. Rodriguez-Carmona, PRC80 (2009) 051601R

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Elastic scattering of $^9$Li used to tune the potential

Tune THEORY i.e. the potential & the EXPERIMENT i.e. set-up

- Elastic scattering of $^9$Li on $^{208}$Pb @ 2.67 MeV/u follows Rutherford.
- The real part of the potential is from double folding Sao Paolo Potential (SPP) and the imaginary part from a Wood Saxon: $V_{SPP} + iW_{WS}$
- It is possible to describe the data with fixed geometry, $r_i = 1.35$ fm, $a_i = 0.51$ fm
- The contribution of 1st excited state in $^9$Li included in CC calculation
- The OM and CC reproduce similarly well the data.
First determination of Elastic Scattering of $^9\text{Li}$ & $^{11}\text{Li}$ around the Coulomb Barrier

- The $^9\text{Li}$ elastic scattering data follow the OM calculation as any other compact nuclei both below and around the Coulomb Barrier.

- 4body-CDCC calculation uses the OM potential deduced from the $^9\text{Li}$ data for energies above the barrier.

- If no continuum states are included 4body-CDCC is unable to describe the $^{11}\text{Li}$ data.

- The 4b-CDCC calculations fit better the data if a low energy resonance around 0.3 MeV beyond threshold is included.

PRL 109,262701 (2012)

4b-CDCC calculations performed by Manoli Rodriguez-Gallardo
Break-up probabilities

\[ P_{bu} = \frac{N_{bu}}{N_{bu} + N_{el}} \]

Assuming

\[ \sigma_{el} + \sigma_{bu} \approx \sigma_R \]

Good agreement with 4b-CDCC, when a resonance 0.3 MeV above the threshold is considered.

The dashed line is the Equivalent Phonon Method corresponding to \( B(E1) \) deduced from \(^{11}\text{Li}\) 3-body CDCC.

The point-dashed line is the Equivalent Phonon Method corresponding to the \( B(E1) \) measured by Nakamura et al. [PRL96 (2006) 252502]. This calculation follows the trend by underestimate the breakup probability at low angles.

PRL 110,142701 (2013)
The 1n halo $^{11}\text{Be}$

**Dipole polarizability**

- $^{11}\text{Be}$ has a 2-body continuum: Simpler reaction mechanism.
- But more complicated exp.
- $\Delta m < (\text{ejectile vs projectile})$
- Bound excited state

**Bound dipole state**

- $^{10}\text{Be} + n$: $503\text{ keV}$
- $^{12}\text{Be}$: $320\text{ keV}$
- $^{11}\text{Be}$: $503\text{ keV}$

New Compilation for $A = 11$
Kelley et al., NPA880 (2012) 88-195

**NS2014 TRIUMF**

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Setup adapted to TIGRESS → PCB² – array

Printed Circuit Board Based Charged Particle Array

11Be: ISAC II & TIGRESS @ TRIUMF
July 2012 on 208Pb & June 2013 on 197Au

2012 on 208Pb (1.45mg/cm²)
- 11Be @ 3.6 MeV/u.
- 108Be @ 3.6 MeV/u.
- 11Be @ 3.1 MeV/u.
- 11Be @ 2.9 MeV/u.

2013 on 197Au (1.9mg/cm²):
- 12C @ 5.0 MeV/u.
- 11Be @ 3.5 MeV/u.
- 11Be @ 2.9 MeV/u.

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**Detector fine positioning**

**Used a $^{12}\text{C}$ beam (high statistics) for fine tuning the electronics & to obtain the angular position of each detector-pixel.**

**Change the position of each detector in X Y Z in relation to the beam-spot**

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**Graphs and data**

- **Tot_per_pixel**
- **El_per_pixel**
- **ratio_breakup_per_pixel**
- **ratio_inel_per_pixel**
**Charged particles and gamma radiation detection**

b) Inelastic scattering at $\theta_{\text{lab}} = 28^\circ$

- $^{11}\text{Be}$ on $^{197}\text{Au}$ @ 2.9MeV/u

- $320 \text{ keV}$
  - $\varepsilon_\gamma = 0.128$

- $501.6 \text{ keV}$

- $^{11}\text{Be}$ on $^{197}\text{Au}$ @ 2.9MeV/u
$^{11}$Be $\rightarrow$ $^{197}$Au @ 31.9 MeV

WELL BELOW THE COULOMB BARRIER @ 40 MeV

Below the break up energy (40 MeV) good separation of $^{11}$Be and $^{10}$Be
$^{11}\text{Be} \rightarrow ^{197}\text{Au} @ 31.9 \text{ MeV}$

well below the Coulomb barrier @ 40 MeV
**11 Be on 197 Au @ 2.9 MeV/u**

- Semiclassical calculation includes Coulomb excitation (E1) at first order, EPM
  
  \[ P_{\text{nu}}(\Omega) = \left( \frac{Ze}{a_0 \hbar v} \right)^2 4 \sin^4(\theta/2) \int_{E_B}^{\infty} dB(E1) \frac{df_{E1}}{d\Omega} \]  
  [Alder & Winther]

- The CDCC includes both Coulomb and nuclear couplings at all orders.

V\(^{(10}\text{Be}-\text{n})\) from P. Capel et al, PRC70 (2004) 064605

V\(^{(10}\text{Be}-197\text{Au})\) from [10Be-208Pb, J. J. Kolata et al, PRC69 (2004) 047601]

V\(^{(197}\text{Au}-\text{n})\) A. J. Koning & J. P. Delaroche NPA713 (2003) 231

- The XCDCC includes a non-spherical 10 Be with deformation reproducing the B(E2) value.

\[ I^{11}\text{Be(gs)}> = a I^{10}\text{Be(gs)}x 2s_{1/2}> + b I^{10}\text{Be}(2^+)x 1d_{5/2}> + c I^{10}\text{Be}(2^+)x 1d_{3/2}> \]

Excited states of 11 Be in the continuum with \(Jp = \frac{1}{2}\pm, 3/2\pm, 5/2\pm\)

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**Elastic Scattering**

**Break-up**

**Inelastic Scattering**
\[^{11}\text{Be} \rightarrow ^{197}\text{Au} @ 3.627 \text{ MeV/u} \ (39.9 \text{ MeV})\]

ON THE COULOMB BARRIER = 40 MEV

**Good separation of \(^{11}\text{Be} \) and \(^{10}\text{Be}\) up to tel3**

Higher energy \(\rightarrow\) fragments more forward \(\rightarrow\) less
Statistics at backward angles
$^{11}\text{Be}$ on $^{197}\text{Au}$ @ 3.627 MeV/u

Preliminary

- Standard CDCC
- XCDCC: no continuum
- XCDCC: full

EPM (only E1)
- Standard CDCC
- XCDCC

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Summary & Outlook

- Elastic and break-up cross section data for $^9$Li & $^{11}$Li on $^{208}$Pb at energies near the Coulomb barrier were obtained for first time.

- The experimental system is able to separate the elastic ejectiles from fragments even at low energy and statistics.

- The $^{11}$Li elastic cross section depart strongly from Rutherford behaviour at energies well below the barrier. The behaviour is well described by 4b-CDCC when Coulomb and continuum couplings are taken into account.

- Break-up cross sections are very large, even larger than predicted by CDCC calculations. Direct breakup dominates up to 50°.

- For the breakup at forward angles, the semiclassic and 4b-CDCC calculations indicate that the dissociation of the projectile is mainly due to the dipolar Coulomb interaction.

- The analysis of $^{11}$Be on $^{197}$Au and $^{208}$Pb @ TRIUMF
  The case of $^{11}$Be is not only more complex experimentally but also theoretically contributing to continues new developments,
  See Lay et al., PRC85 (2012) 054618:
  R. de Diego et al, PRC submitted, ArXiv: 1312.5684
PhD work:

$^{11}$Li Break-up

Juan Pablo Fernandez-Garcia U. Sevilla

$^{11}$Li Elastic

Mario Cubero IEM-CSIC

$^{11}$Be

Vicente Pesudo IEM-CSIC

Theory

J.A. Lay U. Sevilla

Thank you for your attention!