$^{10}$Be + d as a test of three-body theories

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Overview

- Halo nuclei
- What is known about $^{11}$Be
  - Spectroscopic factors
- The (d,p) reaction in inverse kinematics
- Experiments with a $^{10}$Be beam
  - Elastic and inelastic scattering on protons and deuterons
  - Transfer to the bound halo states
  - Comparisons of spectroscopic factors
  - Transfer to first resonance
- Faddeev-type calculations by Deltuva
- Future: experiment proposal
Reactions with halo nuclei

H. Simon (2013), Phys. Scr., 014024
A. Bonaccorso (2013), Phys. Scr., 014019
Previous measurements of $^{11}$Be

- a) Auton (1970)
- b) Zwieginski (1979)
- c) Timofeyuk (1999)
- d) and e) Deltuva (2009)
- f) Lima (2007)
- g) Winfield (2001)
- h) Aumann (2000)
- k) Nunes (1996)
- l) Forseen (2005)
- m) Otsuka (1993)

Previous measurements of $^{11}\text{Be}$

From where do the discrepancies arise?
- Experimental problems?
- Optical model potentials?
- Approximations made in reaction calculations?
  - break-up effects

So what can we do?
- Measure elastic scattering
- Make measurements at different energies
(d,p) in inverse kinematics

**Entrance channel**

$^{10}\text{Be beam}$

$E_{\text{beam}}$

$\text{deuteron target}$

**Exit channel**

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

$E_p$

$\text{proton ejectile}$
First full implementation of ORRUBA. SIDAR at back angles. Proton measurements used SuperORRUBA. CD\textsubscript{2} and CH\textsubscript{2} (90 – 230 µg/cm\textsuperscript{2}) targets with \textsuperscript{10}Be beam energies of 60, 75, 90, and 107 MeV. At HRIBF (ORNL).

Thesis of Kyle Schmitt (UTK)
Detector coverage

![Graph showing detector coverage with different regions labeled: Front ORRUBA, Shadow from Target Ladder, Back ORRUBA, and SIDAR. The graph plots dσ/dΩ (mb/sr) against Lab Angle (degrees).]
Proton elastic scattering

Proton elastic scattering for optical potentials required in ADWA. None of the potentials work well at all energies. Konig and Delaroche (K-D) works best at high beam energies. Need data beyond 60 deg to fit a potential well.
Deuteron elastic and inelastic scattering

Elastic

Inelastic

New potentials fitted by Filomena Nunes to both elastic and inelastic data.

Neutron transfer

High statistics, high resolution with primary tandem beam.
Calculations are with ADWA-FR.
Comparison of spectroscopic factors

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>DWBA</th>
<th>Adiabatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS</td>
<td>0.32 MeV</td>
<td>0.32 MeV</td>
</tr>
<tr>
<td>0.32 MeV</td>
<td>0.32 MeV</td>
<td>0.32 MeV</td>
</tr>
</tbody>
</table>

Comparison of spectroscopic factors

Ground state

0.32 MeV state

Auton (1970)
Zwieglinski (1979)
Aumann (2000)
Palit (2003)
Fukuda (2004)
Lima (2007)
Vinh Mau (1995)
Nunes (1996)

Transfer to the first resonance in $^{11}$Be

FR-ADWA calculations by Anissa Bey and Filomena Nunes with energy bin placed at resonance energy in the continuum.

Faddeev-type calculations: exact 3-body calculations with core excitations

Deuteron elastic scattering.

CX calculations allow core excitation in n-\(^{10}\)Be and p-\(^{10}\)Be channels.
Deltuva: (d,p) to ground state

**CX calculations allow core excitation in n-\(^{10}\)Be and p-\(^{10}\)Be channels.**

Uses a SF of 0.855

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**A. Deltuva PRC 88, 011601(R) (2013)**
Faddeev-type calculations: (d,p) to first excited state

CX calculations allow core excitation in n-\(^{10}\)Be and p-\(^{10}\)Be channels. Uses a SF of 0.786
Faddeev-type calculations: beam energy dependence of XS

For transfer to $1/2^+$ state, ratio of XS to single-particle XS decreases. Due to increase effect of core excitation at higher energies.

$$R_X = \frac{d\sigma_{\text{exp}} / d\Omega}{d\sigma_{\text{DWBA}} / d\Omega}$$
Comparison with Deltuva

\[ \text{gs: } S = 0.71 \]

\[ \text{gs: } S = 0.855 \]
Comparison with Deltuva

\[ gs: S = 0.855 \]

\[ gs: S = 0.71 \]
Comparison with Deltuva

1st ex: $S = 0.62$

1st ex: $S = 0.786$
Future work: Proposal

- September 2016 submitted proposal to ATLAS PAC.
- Repeat $^{10}\text{Be}(d,p)^{11}\text{Be} @ E_d = 20, 28, \text{and} 32 \text{ MeV}$.
- Check agreement with HRIBF measurement, and extend to energy range where effects are more significant.
Future work: Proposal

gs: $S = 0.855$

gs: $S = 0.71$
Future work: Proposal HELIOS
Future work: Proposal

- Need to make direct comparisons of differential cross-sections with exact three-body calculations.
- May need to discuss the S used in the calculations for future comparisons.
Experimental Limitations

- Original work was with primary $^{10}\text{Be}$, which gave great statistics and resolution. Not available with ECR sources.
- Maximum energy with tandem gives the $E_d = 21.4$ MeV point.
- Maximum energy with ATLAS LINAC gives $E_d = 32$ MeV point. Need to use inflight beam.
Summary

- Data set contains
  - elastic scattering of $^{10}\text{Be}$ on p and d,
  - inelastic scattering on d,
  - transfer to the lowest three states in $^{11}\text{Be}$
- SFs extracted using ADWA more consistent than those from DWBA
- Faddeev-type calculations by Deltuva show that $^{11}\text{Be}$ SFs extracted using DWBA or ADWA are energy dependent.
- ATLAS proposal would extend into region where effects are more pronounced.
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Comparison of spectroscopic factors

Current (ADWA) + literature values

Deltuva used
SF(gs) = 0.855
SF (1\textsuperscript{st}) = 0.786

We extracted
SF(gs) = 0.715(5)
SF (1\textsuperscript{st}) = 0.62(4)