Effects of coupling to breakup channels in reactions induced by weakly bound and halo nuclei.

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LNS
1. Introduction.
2. $^{6,7}\text{Li} + ^{64}\text{Zn}$ reactions.
3. $^{6}\text{He} + ^{64}\text{Zn}$ reaction.
4. Summary and Conclusions
Weakly bound nuclei ($^{6,7}$Li): Low break-up threshold.
$S_\alpha=1.47(2.47)$ MeV
Cluster structure ($^{6,7}$Li $\rightarrow \alpha + d(t)$)
\[\Downarrow \Downarrow\]
Coupling to breakup channels expected to be important.

Halo nuclei ($^6$He): Low break-up threshold.
$S_{2n}=0.98$ MeV
Halo structure ($^6$He $\rightarrow \alpha + n + n$)
\[\Downarrow \Downarrow\]
Coupling to breakup channels expected to be important.
Introduction

Continuum-Discretized Coupled-Channels (CDCC) formalism

- Uses Coupled-Channel (CC) method to solve the scattering problem.
- For weakly bound/halo nuclei it is important to introduce the continuum (unbound) states of the projectile.
- Unbound states of the projectile included by means of a discretization procedure (binning).
- Describes the reaction using an effective 3-body model.
- The breakup process is treated as an inelastic excitation of the projectile.

![Diagram showing the coupling of unbound continuum states with bound states in the CDCC formalism](image)
Experiment $^{6,7}\text{Li} + ^{64}\text{Zn}$ at LNS laboratory, Italy

- $^{6,7}\text{Li} + ^{64}\text{Zn}@E_{c.m.} = 11.7, 12.4, 13.5, 15.0, 16.3$ and $18.1$ MeV.
- 5 Telescopes $\Delta E (10 \, \mu m) + E (200 \, \mu m)$.
- Stable beam. Good data quality.

CDCC calculations - Coupling to the continuum effect

Coupling to breakup channels are more important for $^6\text{Li}$.

$S_\alpha(^6\text{Li})=1.47\text{ MeV}$ $S_\alpha(^7\text{Li})=2.47\text{ MeV}$
Experiment $^6\text{He} + ^{64}\text{Zn}$ at CRC laboratory, Belgium.

New experimental data above the Coulomb barrier - $E_{c.m.} = 13.5$ and $16.5$ MeV.
Angular range between $5$ - $120$ degrees.

<table>
<thead>
<tr>
<th>DSSSDs</th>
<th>LAMP</th>
<th>LEDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$67^\circ - 120^\circ$</td>
<td>$22^\circ - 65^\circ$</td>
<td>$5^\circ - 12^\circ$</td>
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</table>

A $^{64}\text{Zn}$ target of $0.5 \text{ mg/cm}^2$ was used and rotated $45^\circ$. 

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Experiment $^6\text{He} + ^{64}\text{Zn} - E_{\text{c.m.}} = 13.5$ and 16.5 MeV.

New experimental data above the Coulomb barrier
Angular range between 5 -120 degrees.
Experiment $^6\text{He}+^{64}\text{Zn} - E_{c.m.} = 13.5$ and $16.5$ MeV.

Angular range between 5 -120 degrees.

- Deviation from Rutherford.
- Diminution of Fresnel peak.
- Expected important nuclear and/or Coulomb couplings.
Optical model analysis

Describes the interaction projectile-target with an effective average potential $U(R) = V(R) + iW(R)$

The absorption of the elastic channel is represented by an imaginary part in the nuclear potential $U(R)$ phenomenological - Woods-Saxon form.

$U(R) = V_0 f + iW_0 f$

$$f(R, R_x, a_x) = \frac{1}{e^{\frac{R-R_x}{a_x}} + 1}$$
Optical model analysis - $^4\text{He}+^{64}\text{Zn}$

\[ U(R) = U_\alpha(R) + W_L(R) \]

\[ U_\alpha(R) = V(R) + iW(R) \quad \text{— Core potential} \]
\[ W_L(R) = \frac{df(R)}{dR} \quad \text{— Long range effect} \]

<table>
<thead>
<tr>
<th>$E_{lab}$</th>
<th>$V_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a_0$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 MeV $^a$</td>
<td>131.1</td>
<td>1.04</td>
<td>0.594</td>
</tr>
<tr>
<td></td>
<td>$W_0$ (MeV)</td>
<td>$r_i$ (fm)</td>
<td>$a_i$ (fm)</td>
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<tr>
<td>11.53</td>
<td>1.27</td>
<td>0.358</td>
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<thead>
<tr>
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<th>$a_0$ (fm)</th>
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</thead>
<tbody>
<tr>
<td>17.5 MeV</td>
<td>22.38</td>
<td>1.2</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>$W_0$ (MeV)</td>
<td>$r_i$ (fm)</td>
<td>$a_i$ (fm)</td>
</tr>
<tr>
<td>23.86</td>
<td>1.05</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

Optical model analysis - $^6\text{He} + ^{64}\text{Zn}$

\[ U(R) = U_\alpha(R) + W_L(R) \]

\[ U_\alpha(R) = V(R) + iW(R) \quad \text{— Core potential} \]

\[ W_L(R) = \frac{df(R)}{dR} \quad \text{— Long range effect} \]

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<tr>
<th>$E_{lab}$ (MeV)</th>
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<th>$r_L$ (fm)</th>
<th>$a_L$ (fm)</th>
</tr>
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<tbody>
<tr>
<td>15</td>
<td>2.62</td>
<td>1.2</td>
<td>0.71</td>
</tr>
<tr>
<td>18</td>
<td>2.28</td>
<td>1.2</td>
<td>0.94</td>
</tr>
</tbody>
</table>

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Optical model analysis - $^6\text{He}+^{64}\text{Zn}$

\[ U(R) = U_\alpha(R) + U_{CDP}(R) \]

\[ U_{CDP} = -\frac{4\pi Z_t^2 e^2}{9 \hbar \cdot v} \frac{1}{(r - a_0)^2} \int_{\varepsilon_b}^{\infty} d\varepsilon \frac{dB(E1, \varepsilon)}{d\varepsilon} F(r, \varepsilon) \]

\[ F(r, \varepsilon) = g \left( \frac{r}{a_0} - 1, \xi \right) + if \left( \frac{r}{a_0} - 1, \xi \right) \]

Optical model analysis - $^6$He+$^{64}$Zn

$$U(R) = U_\alpha(R) + W_L(R) + U_{CDP}(R)$$

$$U_{CDP} = -\frac{4\pi Z_t^2 e^2}{9} \frac{1}{h \cdot v} \left( r - a_0 \right)^2 r \int_{\epsilon_b}^{\infty} d\epsilon \frac{d\mathcal{B}(E_1, \epsilon)}{d\epsilon} F(r, \epsilon)$$

$$F(r, \epsilon) = g \left( \frac{r}{a_0} - 1, \xi \right) + i f \left( \frac{r}{a_0} - 1, \xi \right)$$


<table>
<thead>
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<th>$a_L$</th>
<th>Change</th>
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<tr>
<td>15 MeV</td>
<td>0.71 fm</td>
<td>0.69 fm</td>
</tr>
<tr>
<td>18 MeV</td>
<td>0.94 fm</td>
<td>0.90 fm</td>
</tr>
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Small effects of the dipole Coulomb couplings.
Optical model analysis - $^6\text{He} + ^{64}\text{Zn}$

\[ U(R) = U_\alpha(R) + U_{CDP}(R) \]

\[ U_{CDP} = -\frac{4\pi}{9} \frac{Z_t^2 e^2}{\hbar \cdot v} \frac{1}{(r - a_0)^2 r} \int_{\varepsilon_b}^{\infty} d\varepsilon \frac{dB(E1, \varepsilon)}{d\varepsilon} F(r, \varepsilon) \]

\[ F(r, \varepsilon) = g \left( \frac{r}{a_0} - 1, \xi \right) + if \left( \frac{r}{a_0} - 1, \xi \right) \]


Optical model analysis - $^6$He+$^{64}$Zn

$$U(R) = U_\alpha(R) + U_{CDP}(R)$$

$$U_{CDP} = -\frac{4\pi Z_t^2 e^2}{9} \frac{1}{\hbar \cdot \nu} \frac{1}{(r-a_0)^2} r \int_{\varepsilon_b}^{\infty} d\varepsilon \frac{dB(E1, \varepsilon)}{d\varepsilon} F(r, \varepsilon)$$

$$F(r, \varepsilon) = g \left( \frac{r}{a_0} - 1, \xi \right) + if \left( \frac{r}{a_0} - 1, \xi \right)$$

Optical model analysis - $^{6}\text{He}+^{64}\text{Zn}$

$$U(R) = U_\alpha(R) + W_L(R) + U_{CDP}(R)$$

$a_L = 1.9 \text{ fm} \rightarrow 1.0 \text{ fm}$

$a_L = 0.94 \text{ fm} \rightarrow 0.90 \text{ fm}$
CDCC calculations - Coupling to the continuum effect

- Effective 3-body model \((^4\text{He}+2n+^{64}\text{Zn})\)
- The breakup process is treated as an inelastic excitation of the projectile.
- CDCC calculations underestimate the experimental data.

The couplings to breakup channels are important.
Break-up mechanism - $^{6}\text{He} + ^{64}\text{Zn}$
Break-up mechanism - $^6\text{He} + ^{64}\text{Zn}$

CDCC(DBU)  
CRC(2n-TC)  
CRC(1n-TC)

CRC calculations, based on 1n-transfer mechanism, reproduce the experimental data.
Break-up mechanism - $^{6}\text{He} + ^{64}\text{Zn}$

CRC calculations, based on 1n-transfer mechanism, are in reasonable agreement with the experimental data.
Conclusions

The reactions $^6,^7\text{Li} + ^{64}\text{Zn}$ were measured at energies around the Coulomb barrier at LNS, Italy.

CDCC calculations suggest more important effects of the coupling to the continuum states of the projectile in the reactions induced by $^6\text{Li}$ compared with the ones induced by $^7\text{Li}$. 
Conclusions

New measurements of $^6$He+$^{64}$Zn at energies above the Coulomb barrier have been presented.

Optical Model calculations have been performed, showing long range effects.

Small effect of the dipole Coulomb potential has been observed.

Calculations including couplings to the continuum have been performed within different breakup mechanism.

We have shown that the CRC method, based on one-neutron transfer mechanism, provides a more suitable approach.
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