Fusion and direct reactions around the barrier with light exotic nuclei

Outline

• Exotic nuclei and their properties: influence on reaction process
• How to evaluate: calculations and measurements
  • Problems by calculations
  • Problems by measurements
• Experimental techniques and results (fusion, direct reactions)
• Conclusions

Credits

• Experimental work (at Louvain-la-Neuve)
  Groups Saclay, Catania, Napoli, Louvain-la-Neuve, Leuven
• Discussions with Jean Luc Sida, Nick Keeley, Nicolas Alamanos
Light exotic nuclei

Clusters and Halos

Light exotic nuclei

Matter radius

Light exotic nuclei

Breakup thresholds

- Strong breakup channel
- Coupling to and in the continuum
Effects on reactions

Calculations / Measurements

Calculations
- Evaluate effects separately using model calculations
- Inclusion of continuum effects ??
- Inclusion of structure ?? (many-body projectile)
- Which potential for fusion?
  - Extraction from CDCC is ambiguous
  - Phenomenological (elastic scattering): same potential?
  - Directly calculated

Measurements
- Uncertainties
- Different effects present simultaneously
- Identification of processes

Venezia, March 19-23 2006
**Insert: definitions**

**Compound nucleus vs. Direct ?**

- Complete fusion: all nucleons penetrate inside the barrier
  - breakup + fusion of all fragments (calculations)
- Incomplete (partial) fusion
  - breakup followed by fusion
- Total fusion = complete + incomplete
- Direct breakup (Coulomb and nuclear)
- Transfer to bound states
- Transfer to unbound states (continuum)
  - stripping breakup

**Direct:** $l \sim l_c$

**Fusion:** $l = l_c$

**BUT** light nuclei: $l_c$ and the “window” are small

Experimentally: identify the process (fusion-evaporation vs incomplete fusion)

Calculations: quantities are not easily defined
Effects on reactions: matter distribution

**Fusion: $^6$He**

Density distribution from proton scattering

- halo $R_{\text{rms}} = 2.30$
- no halo $R_{\text{rms}} = 1.95$

Effects on reactions: matter distribution

**Fusion: $^8\text{He}$**

- Halo $R_{rms} = 2.46$
- No halo $R_{rms} = 1.68$

Fusion: $^6,^8$He, $^{11}$Li

- halo $R_{\text{rms}} = 3.62$
- no halo $R_{\text{rms}} = 2.55$

Measurements: radioactive beams

Low-energy

- Technical challenges: intensity, purity, normalisation
- Variable energy
- Detection set-up
- ISOL: Louvain-la-Neuve (\(^6\)He, \(^7\)Be), SPIRAL (\(^6,8\)He), DRIBs (\(^6\)He), REX-ISOLDE (\(^{11}\)Be)
- Fragmentation: RIKEN (\(^{11}\)Be)
- Solenoids: Notre Dame (\(^6\)He), Sao Paulo

Methods

\(\gamma\), X, \(\alpha\)
direct identification
The measurement: Louvain-la-Neuve

$^6\text{He}: \sim 10^6 \text{ pps}$

$^7\text{Be}: \sim 10^7 \text{ pps}$
Fission as signature

EFFE setup

- \(^{238}\text{U}\) target 500 µg/cm\(^2\)
- Detection of back-to-back fission fragments in an array of Si detectors (angular coverage about 70% of 4\(\pi\))

- Fission induced by direct reaction channels: a quasi-projectile particle is produced
$^6\text{He} + ^{238}\text{U}$

- Strong transfer channel
- No enhancement below the barrier

$^7$Be, $^7$Li, $^9$Be + $^{238}$U: no halo, comparison $^7$Be-$^7$Li

Curves:
1-dim barrier penetration model (double folding potential)
$^7$Li density used for $^7$Be

Slight enhancement for $^7$Be...?
Light charged particle – $^7$Be

- Peaked angular distributions $\Rightarrow$ direct processes
- Various processes can produce particles at those energies $\Rightarrow$ need to cross check the shape of E spectra at all energies and angles

Hints:
- few events at $\sim$twice the energy
- very few fission + 2 particle events $\Rightarrow$ no breakup observed
- Inelastic: peak at wrong energy

$\Rightarrow \alpha$ and $^3$He transfer (different Q-values)
Light charged particle – $^7$Li, $^9$Be

$^7$Li

$^9$Be

$\alpha$ and t (and n) transfer

$\alpha$ (and n) transfer
$^7\text{Be}, ^7\text{Li}, ^9\text{Be} + ^{238}\text{U}$

**Fusion – Direct**

- Suppression at $E=V_B$:
  - $^7\text{Be}$ 40%.
  - $^7\text{Li}$ 10%.
  - $^9\text{Be}$ 15%.

- Direct reactions become dominant below the Coulomb barrier.

- Difference $^7\text{Be}$ and $^7\text{Li}$?
  - No visible enhancement of fusion implies no strong effect of couplings?

- NO for fusion;
  - YES for direct reaction cross sections?

- $^7\text{Be}$ and $^7\text{Li}$

M. Dasgupta et al., PRC 66 (2002) 41602

$\Rightarrow$ competing effects?
\( ^6\text{He} + ^{64}\text{Zn} \)

**Activation**


- Strong direct channels
- No enhancement below the barrier

![Activation diagram](image_url)
$^6\text{He} + ^{209}\text{Bi}$

**Delayed $\alpha$-particles**

J. Kolata et al., PRL 81 (1998) 4580

- Enhancement below the barrier?

Further measurements:
- Strong direct channels

E.F. Aguilera et al., PRL 84 (2000) 5058

Alamanos et al., PRC 65 (2002) 54606
• Little difference between $^9, ^{10,11}$Be
• Direct channels for $^{11}$Be?

Which direct processes?

\[ {\text{Which direct processes?}} \]

### 6,7Li

\[ \text{6Li}^+\text{208Pb} \]

<table>
<thead>
<tr>
<th>( E ) (MeV)</th>
<th>( \sigma_0 ) (mb)</th>
<th>( \sigma_d ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>52 ± 1.5%</td>
<td>18 ± 40%</td>
</tr>
<tr>
<td>24</td>
<td>20 ± 1.9%</td>
<td>11 ± 40%</td>
</tr>
<tr>
<td>22</td>
<td>5.0 ± 40%</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>4 ± 30%</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3.2 ± 40%</td>
<td>2.2 ± 40%</td>
</tr>
<tr>
<td>16</td>
<td>0.0 ± 40%</td>
<td>0.58 ± 40%</td>
</tr>
</tbody>
</table>

R. Ost et al., PRC 5 (1972) 1835

### 6Li\(^{+197}\)Au 75 MeV

<table>
<thead>
<tr>
<th>Reaction mechanism</th>
<th>( \frac{d\sigma}{d\Omega} ) (mb/ster) ( ^a )</th>
<th>( \frac{d\sigma}{d\Omega} ) (mb/ster) ( ^a )</th>
<th>( \frac{d\sigma}{d\Omega} ) (mb/ster) ( ^a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha + d ) breakup</td>
<td>143 ± 10</td>
<td>88 ± 44 ( ^d )</td>
<td>0</td>
</tr>
<tr>
<td>Sequential + nonsequential</td>
<td>156 ± 50</td>
<td>78 ± 30 ( ^* )</td>
<td>0</td>
</tr>
<tr>
<td>( 6\text{Li}, \alpha \rightarrow \alpha + p )</td>
<td>72 ± 16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( 6\text{Li}, \alpha \rightarrow \alpha + \gamma )</td>
<td>0</td>
<td>&gt;15 ± 13</td>
<td>0</td>
</tr>
<tr>
<td>( 6\text{Li}, d \rightarrow \alpha + n )</td>
<td>0</td>
<td>0</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>( 6\text{Li}, [\alpha] \rightarrow \alpha + \alpha )</td>
<td>(150 ± 50) ( ^b )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>371 ± 57</td>
<td>103 ± 44</td>
<td>86 ± 30</td>
</tr>
</tbody>
</table>

C.M. Castaneda et al., PRC 21 (1980) 179

- Detection of alphas in excess of deuterons (tritons for \( ^7\)Li)
  \( \Rightarrow \) various transfer processes

- Transfer is strongly dependent on the projectile
Conclusions

- **Radioactive nuclei**: measurements are difficult, data are sparse and of rather poor quality if compared to stable
- Calculations present lots of challenges too (continuum, structure)
- Direct processes become more important at energies around the barrier
  Transfer beside breakup
  Transfer more important? ⇒ Couplings (fusion) different for each system
- Effects on fusion:
  - Suppression above the barrier
    Related to breakup threshold
  - No visible enhancement below the barrier
- No visible effect of halos

**What we need**

- Exclusive reaction cross sections
- Elastic scattering
(Near) future

**REX-ISOLDE**

$^{11}\text{Be}$ fusion + ...

**LLN: elastic scattering**

$^{6}\text{He} + ^{238}\text{U}$

**SPIRAL**

$^{8}\text{He}$ fusion + ...