Pionic fusion study of the halo nucleus $^6$He in the reaction $d+^4$He $\rightarrow ^6$He+$\pi^+$ at Celsius

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Idea of experiment

Cluster Structure of $^6\text{He}$
- Measure total and differential cross-section of $d + ^4\text{He} \rightarrow ^6\text{He} + \pi^+$ close to threshold
- Large momentum transfer
- Cross-section sensitive to cluster structure in the $^6\text{He}$ wave function
Mass 6 nuclei

This experiment: \( d + ^4\text{He} \rightarrow ^6\text{He} + \pi^+ \)

Earlier experiment: \( \alpha + d \rightarrow ^6\text{Li}^* + \pi^0 \) where \(^6\text{Li}^*\) at 3.56 MeV is the isobaric analogue state of the ground state of \(^6\text{He}\)

\[
\begin{array}{c|c|c|c|c|c|c}
\text{Level} & \text{Energy} & \text{Spin} \\
\hline
^6\text{He} & [4.05 \text{ MeV}] & 0^+ \\
\hline
^6\text{Li} & 3.56 \text{ MeV} & 0^+ \\
\hline
^6\text{Be} & [3.09 \text{ MeV}] & 0^+ \\
\end{array}
\]
TSL at Uppsala
Celsius

- Combined accelerator and storage ring
- Electron cooled beam
- Stored beams: p - Ne
- Circumference 81.8 meter
- Internal gas jet target (H - Xe)
Detection of $^6$He

Gas jet target

$^4$He $^6$He

Focusing & steering magnets

Zero-degree spectrometer $\Delta E, E$

In c.m. system

$d$ $\theta$

$^4$He $^6$He

Detector area

$0^\circ$ $90^\circ$ $180^\circ$
Zero-degree spectrometer

- Consists of two detectors:
  - $\Delta E$: Si 1.0 mm
  - $E$: Ge 1.7 mm

$E$ detector is position sensitive:
- 18 horizontal strips
- 66 vertical strips
$E - \Delta E$ plot

d + $^4$He

<table>
<thead>
<tr>
<th>d-beam energy (MeV)</th>
<th>above threshold for $^6$He + $\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>215</td>
<td>below</td>
</tr>
<tr>
<td>217.2</td>
<td>0.6</td>
</tr>
<tr>
<td>218.2</td>
<td>1.2</td>
</tr>
<tr>
<td>224</td>
<td>5</td>
</tr>
</tbody>
</table>

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$^6\text{He}$ energy distribution

- Peak at higher energy - $^6\text{He}$ emitted in forward direction (0° in c.m.)
- Peak at lower energy - $^6\text{He}$ at 180° c.m.
- Energy difference between peaks is measure of beam energy
Simulated energy distribution

- Monte-Carlo simulations with ray-trace
- Isotropic angular distribution
- d-beam 217.2 MeV, 0.6 MeV above threshold
$^6$He events

- Beam energy 217.2 MeV, 0.6 MeV above threshold, 941 events
- Beam energy 218.2 MeV, 1.2 MeV above threshold, 921 events
Experimental x-y distribution of $^6$He

0.6 MeV above threshold

Some x- and y-strips are missing
Simulated x-y distribution of $^6$He

0.6 MeV above threshold
Fits

- Maximum-Likelihood method

- Simulated data were fitted to experimental using
  \[ f(E,x,y) = a f_1(E,x,y) + b f_2(E,x,y) + c f_3(E,x,y) \]
  where
  - \( f_1(E,x,y) \) is number of simulated events with energy \( E \),
    and coordinates \((x,y)\) on the detector.
  - \( f_2(E,x,y) \) represents \( \cos \theta \) distribution
  - \( f_3(E,x,y) \) represents \( \cos^2 \theta \) distribution

- \( \frac{d\sigma}{d\Omega} = k(a + b \cos \theta + c \cos^2 \theta) \)
Preliminary results using energy-information
Black line is experimental data, red is fit
Acceptance 78 %

\[ \frac{d\sigma}{d\Omega} = k(a + b \cos\theta + c \cos^2\theta) \]

The coefficients are:

- \( a = 2.7 \pm 0.2 \)
- \( b = 0.8 \pm 0.2 \)
- \( c = 2.5 \pm 0.5 \)
$^6$He at 1.2 MeV above threshold

- Preliminary results using energy-information
- Black line is experimental data, red is fit
- Acceptance 49%
- In $d\sigma/d\Omega = k(a + b \cos\theta + c \cos^2\theta)$ the coeff. are $a = 4.6 \pm 0.4$, $b = 0.9 \pm 0.3$, $c = 3.2 \pm 0.7$

$\frac{b}{a} = 0.2$
Results from $\alpha + d \rightarrow {}^6\text{Li}^* + \pi^0$

Beam energy (MeV) $a_0$ (nb/sr) $a_1$ (nb/sr) $a_2$ (nb/sr) $\sigma$ (nb) $a_1/a_0$

417.95 $\pm$ 0.07 18.2 $\pm$ 0.8 -2.1 $\pm$ 0.8 0.2 $\pm$ 1.2 228 $\pm$ 10 -0.1

420.30 $\pm$ 0.07 11.4 $\pm$ 1.3 -4.6 $\pm$ 1.0 -1.2 $\pm$ 1.5 144 $\pm$ 18 -0.4

**Comparison**

<table>
<thead>
<tr>
<th>Q (MeV)</th>
<th>Asymmetry (b/a)</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This experiment:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d + (^4\text{He}) → (^6\text{He}) + π(^+)</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Earlier experiment:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha + d \rightarrow (^6\text{Li})* + π(^0)</td>
<td>1.2</td>
<td>-0.1</td>
</tr>
</tbody>
</table>
Summary

- We have measured pion production in two experiments.
- Cross sections:
  \[ d + ^4\text{He} \rightarrow ^6\text{He} + \pi^+ \quad \Rightarrow \quad \sigma \text{ increases with energy} \]
  \[ \alpha + d \rightarrow ^6\text{Li}^* + \pi^0 \quad \Rightarrow \quad \sigma \text{ decreases with energy} \]
- Asymmetry with respect to the heavier particle in initial system has the same sign.
- Different energy dependences of asymmetry.