Three-body effects in the Hoyle-state decay

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Jonas Refsgaard, KU Leuven
O.S. Kirsebom, H.O.U. Fynbo and K. Riisager, Aarhus University
Introduction to the Hoyle state

- Astrophysics (triple-α process).
- Exotic structure (α-particle clusters).
- Sequential vs. direct decay (SD and DD)

\[ 8\text{Be} + \alpha \rightarrow 12\text{C} + \alpha + \alpha + \alpha \]

\[ \begin{align*}
    0^+ & 7.65 \\
    2^+ & 4.44 \\
    0^+ & 0.00 \\
    \text{12C} & \\
\end{align*} \]

\[ \begin{align*}
    0^+ & 7.37 \\
    0^+ & 7.28 \\
\end{align*} \]
Experiments on the breakup

• 1994: M. Freer et al., PRC 49 R1751: \( \text{BR} < 4\% \)
• 2011: A. Raduta et al., PLB 705 65: \( \text{BR} = 17(5)\% \)
• 2012: J. Manfredi et al., PRC 85 037603: \( \text{BR} < 0.45\% \)
• 2012: O. Kirsebom et al., PRL 108 202501: \( \text{BR} < 0.5\% \)
• 2013: T. Rana et al., PRC 88 021601: \( \text{BR} = 0.91(14)\% \)
• 2014: M. Itoh et al., PRL 113 102501: \( \text{BR} < 0.2\% \)
• 2017: R. Smith et al., PRL 119 132502: \( \text{BR} < 0.047\% \)
• 2017: D. Dell'Aquila et al., PRL 119 132501: \( \text{BR} < 0.042\% \)
Motivation?

- Reaction rate for the resonant triple-\(\alpha\) process.
- Structure of the Hoyle state.
- Reaction rate for the non-resonant triple-\(\alpha\) process.

Ishikawa, S., PRC 90 061604(R) (2014)
The Dalitz plot

- Energy spectrum for three-body decays.
- Six-fold symmetry
Experimental data

O.S. Kirsebom et al., PRL 108 202501 (2012)
Mission

• Improve on the model for sequential decay.
• Predict the spectrum of a direct decay.
• Explore the effect of Coulomb interaction.

How?

• We apply an established R-matrix model.
The model

\[(3\text{-body amplitude}) = \text{(Penetration factor for } \alpha_1^{-8}\text{Be}) \times \text{(Resonant scattering amplitude for } \alpha_2\text{-}\alpha_3 \text{ system)}\]


\[(\text{Penetration factor} = \text{Probability for penetrating the Coulomb barrier, } r \to \infty)\]
Result

Ishikawa, S., PRC 90 061604(R) (2014)
Problem?

Lifetime dependent on $E_{23}$. 

\[ \tilde{r} \]
Variation in length parameter

\[ \tilde{r} = a_1 + \nu_1 \tau_2 \]

\[ \tau_2 = \hbar \frac{d\delta_2}{dE_{23}} + \frac{a_2}{\nu_{23}} \]
Penetration factor

Before: \[(\text{Penetration factor for } {}^8\text{Be}, a_1 \to \infty)\times (\text{Penetration factor for } {}^2\text{Be} - {}^3\text{Be}, a_2 \to \infty)\]

Now: \[(\text{Penetration factor for } {}^8\text{Be}, a_1 \to \tilde{r})\times (\text{Penetration factor for } {}^2\text{Be} - {}^3\text{Be}, \tilde{r} \to \infty)\times (\text{Penetration factor for } {}^2\text{Be} - {}^3\text{Be}, a_2 \to \infty)\]

Result
Prediction for non-resonant decay

\[ 2\delta E \]

<table>
<thead>
<tr>
<th>( \delta E ) (keV)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_\infty )</td>
<td>2.3e-4</td>
<td>1.1e-4</td>
<td>6.0e-5</td>
<td>1.7e-5</td>
</tr>
<tr>
<td>( I_{\text{short}} )</td>
<td>1.1e-2</td>
<td>8.4e-3</td>
<td>6.8e-3</td>
<td>4.0e-3</td>
</tr>
<tr>
<td>( I_F )</td>
<td>5.2e-4</td>
<td>3.1e-4</td>
<td>2.2e-4</td>
<td>1.4e-4</td>
</tr>
</tbody>
</table>

\( I_{\exp} < 4.7e-4 \) (Smith et al.)

\( I_{\exp} < 4.2e-4 \) (Dell’Aquila et al.)

R. Smith et al., PRL 119 132502 (2017)
D. Dell'Aquila et al., PRL 119 132501 (2017)
Mission

• Improve on the model for sequential decay.
• Explore the effect of Coulomb interaction.
• Predict the spectrum of a direct decay.
Mock-up of a direct decay

- Direct processes can be treated in R-matrix formalism.
- Infinitely many levels are approximated by a single background pole.
- $E_{BG} = 20\text{MeV}, \quad \Gamma_{BG} = 200\text{MeV}$
- NOT a physical level.
Result
However...

- Amplitudes must be added coherently
Interference between the channels

• Mixing ratio: \( \delta = \nu_{bg} / \nu_{gs} \)
Summary

• If 100% SD, observation of non-resonant decays are within experimental reach (an order of magnitude).

• The off-resonant strength is sensitive to 3body Coulomb interactions.

• Mock-up of direct decay, i.e. decay with no strong 2α-interaction.

• If direct decay is present, it will un-avoidably mix with the sequential decay channel, and it becomes even harder to connect the observed spectrum to any inner structure.
Thanks

• To my collaborators: Oliver S. Kirsebom, Hans O.U. Fynbo and Karsten Riisager.
• To professor Ishikawa.
• To you.
Sequential R-matrix model 2

- Model is so far successful.
- Parameters of 8Be levels are well known.

Data

Simulation

\[ 12.7\text{MeV} \]

12C

\[ 1^+ \]

\[ 0^+ \]

\[ 2^+ \]

\[ 0^+ \]
Travel of primary fragments

\[ \tilde{r} = a_1 + v_1 \tau_2 \]

\[ \tau_2 = \frac{d \delta_2}{dE_{23}} + \frac{a_2}{v_{23}} \]
Predictions for the Hoyle state

- Strength outside the peak related to the ‘ghost’.
\[ f_{c}^{m_{a}}(123) = \sum_{m_{b}} \langle J_{b}l_{1}m_{b}(m_{a} - m_{b})|J_{a}m_{a}\rangle \times \left[ i^{l_{1}} Y^{m_{a}-m_{b}}_{l_{1}}(\Omega_{1}) \right]\left[ i^{l_{2}} Y^{m_{b}}_{l_{2}}(\Omega_{23}) \right] \times \gamma_{c}(2P_{l_{1}}/\rho_{1})^{\frac{1}{2}} \exp[i(\omega_{l_{1}} - \phi_{l_{1}})] F_{c}(E_{23}), \]

\[ F_{c}(E_{23}) = \frac{\gamma_{\lambda_{b}l_{2}}(2P_{l_{2}}/\rho_{23})^{\frac{1}{2}} \exp[i(\omega_{l_{2}} - \phi_{l_{2}})]}{E_{\lambda_{b}} - E_{23} - \left[ S_{l_{2}} - B_{l_{2}} + iP_{l_{2}} \right]\gamma_{\lambda_{b}l_{2}}^{2}} \]

\[ W = \sum_{m_{a}} \sum_{c} \left| f_{c}^{m_{a}}(123) + f_{c}^{m_{a}}(231) + f_{c}^{m_{a}}(312) \right|^{2} \]
Coulomb interactions?

\[ \frac{p_{l_1}}{\rho_1} \rightarrow \frac{p_{l_1}}{\rho_1} \left[ \frac{\tilde{\rho}_1}{\tilde{p}_{l_1}} \frac{\tilde{p}_{l_2}(E_{12})}{\tilde{\rho}_{12}} \frac{\tilde{p}_{l_2}(E_{13})}{\tilde{\rho}_{13}} \right] \]

• How far apart are the primary fragments when second breakup happens?
Effect of direct channel

- 2013: Ihikawa, PRC 86, 055804
Effect on the Hoyle-state decay

- Enhancement of ‘ghost’.
- Reduction of Coulomb barrier off-resonance.
How about direct channels?

- We mock up a ‘direct’ channel using a ‘background pole’
Interference between the channels

• Mixing ratio: \( \delta = \frac{\gamma_{bg}}{\gamma_{gs}} \)
Problems

• Model predicts too large branching ratio for direct decay.
• Comparison to 3-body calculations using Faddeev-equations suggests $r \sim 35\text{fm}$ (not 5-10fm).
• Effect related to tunnelling.
Conclusions

• Prediction of direct decay spectrum.
• Even a sequential process can show features resembling a direct decay.
• Quantitative predictions influenced by tunnelling effects.
• Measurement of the Hoyle decay could provide information of three-body Coulomb interactions.