Study of Excited States of $^{12}$C in Full Kinematics

Martin Alcorta

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OUTLINE

- Introduction
  - Motivation
- Experiment
  - How to populate excited states in $^{12}$C
  - Reaction at the CMAM
- Analysis
  - How to reconstruct the energy in $^{12}$C
  - Identification of particles
- Results
  - Decay mechanism of the resonances in $^{12}$C
    - Sequential/Direct
- Conclusions/Outlook
MOTIVATION

- **Nuclear Astrophysics**
  - The triple-\(\alpha\) process is crucial to overcome the mass gaps at \(A=5\) and \(A=8\).
  - Above \(T_q > 2\) K, other excited states in 12C influence the reaction rate.

- **Nuclear Structure**
  - Three body break-up
    - Sequential
    - Direct
  - Cluster Model

- **Exact calculations for \(A\leq12\)**
The $3\alpha$ process

$\alpha + \alpha \leftrightarrow ^8\text{Be}$

$^8\text{Be} + \alpha \rightarrow ^{12}\text{C} + \gamma$
Sequential vs. Direct Decay

$^{12}\text{C}^* \rightarrow ^8\text{Be} + \alpha$

Sequential

Direct

$\text{E}, \Gamma$

$X$

$Y$

$E_1 \leq \Gamma_1$?
• Introduction

• **Experiment**
  – How to populate excited states in $^{12}$C
  – Reaction at the CMAM

• Analysis

• Results

• Conclusions
How to populate excited states in $^{12}$C

- Through $\beta$-decay
  - $^{12}$N or $^{12}$B
- Through a reaction
  - $A+a \rightarrow C^* \rightarrow B^*+b$
Experimental Setup

- 2 telescopes
  - DSSSD(60 μm)+1500 μm
  - DSSSD(69 μm)+1500 μm+1000 μm
- \( \Omega = \frac{1}{9^{\text{th}} 4\pi} \)
- \( \varepsilon_{1p} = 11\% \)
- \( \varepsilon_{3p} = 0.1\% \)

\[ \varepsilon_{2p} = \sum_{i=1, j=1 \atop i \neq j}^{256} (\varepsilon_{1i} \cdot \varepsilon_{2j})^2 \]
• Introduction
• Experiment
• **Analysis**
  • How to reconstruct the $^{12}$C energy
  • Particle Identification
• Results
• Conclusions
Identification of protons and alphas

Plot of $\Delta E - E$

<table>
<thead>
<tr>
<th>Detector</th>
<th>Thickness</th>
<th>Max $E_p$</th>
<th>Max $E_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSSD</td>
<td>$\sim 60 , \mu m$</td>
<td>$\sim 2.4 , MeV$</td>
<td>$\sim 9.5 , MeV$</td>
</tr>
<tr>
<td>Si-PAD</td>
<td>$\sim 1500 , \mu m$</td>
<td>$\sim 15 , MeV$</td>
<td>$\sim 50 , MeV$</td>
</tr>
</tbody>
</table>
Particle Identification

$\Delta E$-$E$ plot

$\alpha + ^9B^*(g.s.)$

d + $^{11}C$

$p + ^{12}C^*$

Available energy $p + ^{12}C = 21.6$ MeV

Protons up to 19.9 MeV
Identification of excited states in $^{12}\text{C}$

We select the protons and calculate the excitation energy of $^{12}\text{C}$
Detecting alpha particles in coincidence

- multiplicity 1
  1p

- multiplicity 2
  1p & 1α

- multiplicity 3
  1p & 2α

- multiplicity 4
  1p & 3α

12C Excitation Energy (MeV)
- Introduction
- Experiment
- Analysis
- **Results**
  - Sequential/Direct
    - $^8$Be Energy
  - Decay mechanism of the resonances in $^{12}$C
- Conclusions
How do we differentiate between break-up through the $^8\text{Be} (0^+)$ and $^8\text{Be} (2^+)$?

$^12\text{C}^*$ → $\alpha_1 + ^8\text{Be}(2^+) + ^8\text{Be}(0^+)$

$E_{\text{sum}} = \frac{3}{2}E_1 + 0.092 \text{ MeV}$
Selection rules prohibit some decays through the $^8\text{Be} \ (0^+)$

$$| J_{12\text{C}} - J_{^8\text{Be}} | < l < J_{12\text{C}} + J_{^8\text{Be}} $$

$$\pi(^{12}\text{C}) = \pi_1(^8\text{Be}) \pi_2(\alpha)^*(-1)^l$$
Calculate the $^8\text{Be}$ energy using alpha pairs

**$^8\text{Be}$ Energy (MeV)**

- $11.83$ MeV
- $^8\text{Be}(\text{g.s.}) (0.09$ MeV)
- $^8\text{Be}(2^+) (3.05+0.09$ MeV)

\[
E(^8\text{Be}) = \frac{|P_1|^2 + |P_2|^2 - 2 \cdot |P_1| \cdot |P_2| \cdot \cos \theta}{4m_\alpha}
\]

\[
\cos \theta = \frac{P_{x_1}^2 \cdot P_{x_2}^2 + P_{y_1}^2 \cdot P_{y_2}^2 + P_{z_1}^2 \cdot P_{z_2}^2}{|P_1| \cdot |P_2|}
\]
Separating events which decay via the $0^+$ state in $^8$Be and the $2^+$ state in $^8$Be
Separate the events which go through the $^8\text{Be}(2^+)$ and $^8\text{Be}(0^+)$ to obtain branching ratios.

$$1^{2}\text{C}^* \longrightarrow \alpha_1 + ^8\text{Be}(2^+) + ^8\text{Be}(0^+)$$

<table>
<thead>
<tr>
<th>$^{12}\text{C}^*$ state (MeV) and $J^\pi$</th>
<th>$^8\text{Be}(0^+)$</th>
<th>$^8\text{Be}(2^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.65,$0^+$</td>
<td>100 %</td>
<td>—</td>
</tr>
<tr>
<td>9.64,$3^-$</td>
<td>96 %</td>
<td>4 %</td>
</tr>
<tr>
<td>10.84,$1^-$</td>
<td>75 %</td>
<td>25 %</td>
</tr>
<tr>
<td>11.83,$2^-$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>12.71,$1^+$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>13.35,(2$^-$)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14.08,$4^+$</td>
<td>33 %</td>
<td>66 %</td>
</tr>
<tr>
<td>16.11,$2^+$</td>
<td>5 %</td>
<td>95 %</td>
</tr>
</tbody>
</table>

- States which decay through the $2^+$ state

- State which decay through the $0^+$ state

Excitation Energy in $^{12}\text{C}$ (MeV)
Determine the decay mechanism:
- Compare the energy distribution of the alphas with simulations based on the R-matrix formalism

Some $^{12}\text{C}$ states of interest:
- $12.71$ MeV
- Sequential with interference
- $13.35$ MeV
- $J^\pi$ (2- or 4-)?
The 12.71(1⁺) MeV state in $^{12}$C

Candidate for direct decay (Korsheninnikov):
- Narrow width ($\Gamma = 18.1$ eV)
- Forbidden $^8$Be (0⁺) decay
  - $Q_\alpha = 2.2$ MeV and $\Gamma = 1.37$ MeV for $^8$Be (2⁺) decay
- Sequential decay with interference effects included (Balamuth):
  - $E_{\alpha_1} = 1.52$ MeV
  - $E_{\alpha_2} = E_{\alpha_3} = 1.58$ MeV

Balamuth PRC10 1974  
Korsheninnikov SJNP52 1990
Comparison of the 12.71 MeV resonance to previous experimental results

green: sequential
red: seq. with interferences
blue: direct
Fynbo et al. PRL 91 2003

black: data (this work)
red: seq. with interf.
What is the $J^\pi$

- Literature as $2^-$
- New models $4^-$

- Data
- simulation with $2^-$
- simulation with $4^-$

13.35 MeV

$E_i(\alpha)$ MeV

Cluster Model

7.275 MeV + $E_R = E_{12C^*}$

Alvarez-Rodriguez in preparation
Conclusions

– We concentrated on the study of the excited states in $^{12}$C$^\ast$.
– We selected events of three alphas to study the decay mechanism through the $^8$Be(gs) and the $^8$Be($2^+$).
– The $J^\pi$ of several states have been confirmed and we tentatively determined the $J^\pi$ of the 13.35 MeV state.
– The study of the 12.7 MeV state in $^{12}$C gives us confidence to further study the decay mechanism of the 16.1 MeV state in $^{12}$C
  – Decay via $^8$Be($4^+$)?
  – Direct/Sequential
– We determined branching ratios of decay through the $^8$Be(gs) and $^8$Be($2^+$).
Outlook

April 2006
- 4 telescopes
- ISOLDE Si-ball
- \(^3\text{He} @ 2.45 \text{ MeV y 4.5 MeV}\)

\(\varepsilon_{1p}=18\%\) \(\sim 30\) hours \(^{10}\text{B}\)
\(\varepsilon_{3p}=0.5\%\) \(\sim 40\) min. \(^7\text{Li}\)

\(\varepsilon_{1p}=14\%\) \(\sim 21\) hours \(^{10}\text{B}\)
\(\varepsilon_{3p}=0.3\%\) \(\sim 1.5\) hours \(^7\text{Li}\)

\(^{10}\text{B}(^{3}\text{He},p\alpha\alpha\alpha)\) \(^7\text{Li}(^{3}\text{He},p)^9\text{Be}\)

\(\sim 4\) hours \(^{10}\text{B} @ 4.9\) MeV
\(\sim 2\) hours \(^7\text{Li} @ 4.9\) MeV
Future Analysis

• Ab Initio calculations from Argonne is ongoing
• Dalitz plots to determine decay mechanism (direct/sequential)
• Astrophysical relevance: search to see if decay of e.g. 9.65 MeV state is through narrow $^8$Be($0^+$) or its tail
• Take a more detailed look at $^9$B* + $\alpha$ channel
• Get definitive results for branching ratios
Collaborators

M. Alcorta¹, H.B. Jeppesen¹,², M.J.G. Borge¹, H.O.U. Fynbo³, G. Garcia⁴, O. Kirsebom³, M. Madurga¹, G. Nyman⁵, D. Obradors¹,⁴, O. Tengblad¹

¹ Inst. Estructura de la Materia, CSIC, Serrano 113bis, E28006 Madrid, Spain.
² CERN, ISOLDE, PH Department, CH1211 Geneve 23, Switzerland.
³ Inst. for fysik og astronomi, Aarhus Universitet, DK8000 Aarhus C, Denmark.
⁴ CMAM, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain.
⁵ Fundamental Fysik, Chalmers Tekniska Högskola, S41296 Göteborg, Sweden.
• Hoyle state a linear chain of alphas?
• Determine mass of $^8$Be from 2 alphas?
• To study states around 17-18 MeV (although only 600 keV, so maybe can try to study anyway regardless of higher $E$ since won't help much)
• Giant resonance?
  Would have to increase energy in order to go higher up in the spectrum