Direct determination of the $^{11}\text{C}(\alpha,p)^{14}\text{N}$ reaction rate with CRIB: an alternative synthesis path to the CNO elements

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- **Motivation**
  - $^{11}\text{C}(\alpha,p)^{14}\text{N}$: Breakout path from pp-chain to CNO
  - What to measure

- **Experiment**
  - $^{11}\text{C}$ beam production
  - Experimental setup of the direct measurement
  - Experimental setup of the direct measurement

- **Results**
  - Event ID
  - $^{11}\text{C}(\alpha,p)^{14}\text{N}$ Cross sections
  - Reaction rates

- **Summary**
\(^{11}\text{C}(\alpha,p)^{14}\text{N}: \text{A breakout path from pp-chain}\)

- **Hot hydrogen burning processes:**
  - Breakout from the **hot pp-chain** competing with the \(\beta\)-decay to \(^{11}\text{B}\)
    → simulation of metal-poor stars (Wiescher et al., 1989)
  - Contributes in the \(\nu p\)-process in the neutrino-driven winds in core-collapse supernovae (Wanajo et al., 2010)
    → produce more intermediate-mass, less heavy nuclei around \(A = 100\)

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Wiescher et al. (1989)
\[ {^7}\text{Be}(\alpha,\gamma){^{11}}\text{C}(\alpha,p){^{14}}\text{N}: \text{Contribution in } \nu p\text{-process} \]

- \(^{11}\text{C}(\alpha,p)\) overlaps \(^{7}\text{Be}(\alpha,\gamma)\)
  - \(^{11}\text{C}\) is mostly produced from \(^{7}\text{Be}(\alpha,\gamma)\), and then \((\alpha,p){^{14}}\text{N}\) follows.
  - \(^{11}\text{C}(\alpha,p)\) rate > \(^{7}\text{Be}(\alpha,\gamma)\) rate

- \(^{7}\text{Be}(\alpha,\gamma)\) rate tends to less mass fraction around \(A = 100\).
  - Limited resonance information only for \(T_9 < 2\). (New measurement!! Yamaguchi, NIC_XI_124)

- \(^{11}\text{C}(\alpha,p)\) rate would become more important if \(^{7}\text{Be}(\alpha,\gamma)\) has a higher rate.
  - Time-reversal reaction studies by activation method. \(\Rightarrow\) Gives only \((\alpha,p_0){^{14}}\text{N}\) g.s.
What to measure

- Covered energy ranges of this work by thick-target method with two beams

- Only time-reversal reaction studies by activation method (Ingalls et al., etc.)
  \[ \Rightarrow \text{ give no information for } (\alpha,p_1), (\alpha,p_2), \ldots \text{ cross sections} \]

- Not enough resonance parameters are known.

- First direct measurement
  - Confirm \((\alpha,p_0)\) cross sections
    \[ \Leftrightarrow \text{ data from time-reversal reaction experiments by activation method} \]
  - Determine \((\alpha,p_1), (\alpha,p_2), \ldots \text{ cross sections} \)
\[ ^{11}\text{C Beam Production with CRIB} \]

**CRIB:** Center for Nuclear Study Radioactive Ion Beam separator (U. Tokyo, at RIKEN)

**Production reaction:**

\[ ^{1}\text{H}(^{11}\text{B},^{11}\text{C})n \]

**Primary Beam:**

\[ ^{11}\text{B}^{3+}, 1 \mu\text{A}, 4.6 \text{ MeV/u} \]

**Momentum-dispersive focal plane:**

\[ \Delta p/p < 0.4\% \]

**Wien filter:**

\[ \pm 50 \text{ kV} \]

**Secondary beams:**

- \[ ^{11}\text{C} : 16.9 \text{ MeV}, 1.0 \times 10^5 \text{ pps} \text{ covers } E_{\text{cm}} = 2.3-4.5 \text{ MeV} \]
- \[ ^{11}\text{C} : 10.1 \text{ MeV}, 3.1 \times 10^5 \text{ pps} \text{ covers } E_{\text{cm}} = 0-2.7 \text{ MeV} \]

**Experimental Chamber**
Experimental Setup

- Thick “gas” target method in inverse kinematics

- Measurement: ✔ Beam position ✔ $E_{\text{beam}}$ ✔ Proton position ✔ $E_{\text{proton}}$

- 140-mm-long, 400-Torr gas target

  $\Delta T$ between different transitions; $(\alpha, p_0)^{14}\text{N}_{\text{g.s.}} \leftrightarrow (\alpha, p_1)^{14}\text{N}_{2312} : \sim 5 \text{ ns}$

  ⇒ event ID in TOF vs. $E$ plots

- $\Delta E_{\text{cm}} \sim 50 \text{ keV}, \Delta \Omega/\Omega \sim 10\%$
- Measured TOF looks stretched at lower energies. 
  ⇒ A slew correction is needed.

- The lines of each transition have similar derivations 
  ⇒ If \((\alpha, p_0)\) is linearized, other transitions are also linearized.
- Linearized the ‘raw’ TOF data
- The energy ranges for each transition are consistent with the calculations
\(^{11}\text{C} (\alpha, p)^{14}\text{N} \text{ cross sections}\)

- ‘From \((p, \alpha)\)’: Statistical fit to the several time-reversal reaction studies (Takacs et al.)
- ‘This work’: Cross sections for \((\alpha, p_0)\), \((\alpha, p_1)\) and \((\alpha, p_{12})\) integrated assuming isotropy (→ indicated only the statistical errors).
- \((\alpha, p_0)\) mostly determines the reaction rate at stellar temperatures \((T_9 = 1.5-3)\).
The new reaction rate including $(\alpha,p_0)$, $(\alpha,p_1)$ and $(\alpha,p_2)$ is enhanced by 40% at most, and still less than Hauser-Feshback reaction rate.
The first direct measurement of the $^{11}\text{C}(\alpha,p)^{14}\text{N}$ reaction was successfully performed with CRIB by the thick-gas-target inverse-kinematics method at stellar energies. Each transition is separable.

$(\alpha,p_0)$ cross section; mostly consistent with the one from the time-reverse reaction studies. The resonances around 1 MeV may enhance the reaction rate.

$(\alpha,p_{1,2,...})$ contributes about 10% at most for the stellar temperatures ($T_9 < 3$).
Collaborators

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Event identification

Low energy run

High energy run

Proton energy (MeV)

Corrected time (ns)

-60 -50 -40 -30 -20 -10 0 10 20

Proton energy (MeV)

Corrected time (ns)

-60 -50 -40 -30 -20 -10 0 10 20

(\alpha,p_0)

(\alpha,p_1)

(\alpha,p_2)

(\alpha,p_3,4)

+ background
$^{7}\text{Be}(\alpha,\gamma)^{11}\text{C} \& \quad ^{11}\text{C}(\alpha,p)^{14}\text{N}$ (current database)

- $^{11}\text{C}(\alpha,p)^{14}\text{N}$: time-reversal reaction studies by activation method
  - Provides only $(\alpha,p_0)$ rate.

- $^{7}\text{Be}(\alpha,\gamma)^{11}\text{C}$: limited resonance information for only $T_9 < 2$ (Hardie et al. 1984)
  - $^{11}\text{C}(\alpha,p)^{14}\text{N}$ could limit the rate of $^{7}\text{Be}^{11}\text{C}^{14}\text{N}$ sequence if $^{7}\text{Be}(\alpha,\gamma)^{11}\text{C}$ and $^{11}\text{C}(\alpha,p)^{14}\text{N}$
  - New measurement of the $^{7}\text{Be} + \alpha$ resonant scattering at CRIB
    ⇒ Yamaguchi, poster session, NIC_XI_124
Summary of Beams

- Three kinds of beams
  ⇒ High E $^{11}$C, Low E $^{11}$C, $^{11}$B

  - To cover the wide excited energy range
    (High E and Low E $^{11}$C)
  - To confirm the validity of this method over the target
    (⇔ known $^{11}$B($\alpha$, $p$) c.s.)

- Production and background runs ($^4$He, Ar)

<table>
<thead>
<tr>
<th>E_{Beam} [MeV]</th>
<th>$\Delta E_{Beam}$ (FWHM) [MeV]</th>
<th>E_{CM} range [MeV]</th>
<th>Purity [%]</th>
<th>Av. beam rate on target [pps]</th>
<th>$^4$He run time [hrs]</th>
<th>Ar run time [hrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High E $^{11}$C</td>
<td>16.86</td>
<td>0.71 – 0.96</td>
<td>4.5 – 2.3</td>
<td>~100</td>
<td>1.0 x 10^5</td>
<td>28</td>
</tr>
<tr>
<td>Low E $^{11}$C</td>
<td>10.12</td>
<td>0.92 – 1.00</td>
<td>2.7 – 0.0</td>
<td>~100</td>
<td>3.1 x 10^5</td>
<td>78</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>16.87</td>
<td>0.54</td>
<td>4.5 – 2.9</td>
<td>~100</td>
<td>2.6 x 10^5</td>
<td>11</td>
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