Measurement of the cross section for the $^4\text{He}(\alpha,n)^7\text{Be}$ reaction as a possible solution to the cosmological lithium problem

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Big Bang Nucleosynthesis (BBN)

Primordial nucleosynthesis is considered to have taken place from 10 sec to 20 min after the Big Bang.

Theoretical estimates of the primordial abundance can be compared with the observation.

Primordial abundance is an important probe for the early universe.

Baryon density is determined to be
\[ \Omega_b h^2 = (2.23 \pm 0.02) \times 10^{-2} \]
by the Planck satellite.

BBN theory gives three times larger than the observation.

\[ \left( \frac{\text{Li}}{\text{H}} \right)_{\text{BBN}} = (5.12^{+0.71}_{-0.62}) \times 10^{-10} \]
Possible Solution to the Li problem

✓ Improvement of the stellar models.
✓ New physics beyond the standard BBN model
  • Cosmological variation of fundamental constants.
  • Decay of supersymmetric particles.
✓ Better understanding of cosmological nuclear reaction rates.
  • Main origin of $^7\text{Li}$ is EC decay of $^7\text{Be}$.
  • Enhancement of the destruction rate of $^7\text{Be}$ might solve the Li problem.
Primordial Li production/Be destruction

Main origin of $^7\text{Li}$: EC decay of $^7\text{Be}$

Most dominant $^7\text{Be}$ destruction channel: $^7\text{Be}(n,p)^7\text{Li}$
→ Extensively studied. No room to modify the known rate.

Next dominant channel: $^7\text{Be}(n,\alpha)^4\text{He}$
→ No experimental data at cosmological energies ($T_9 \sim 0.6–0.8$).
→ Both $^7\text{Be}$ and neutron are unstable.

New measurement is desired.

Previous Experiment


Trick is needed because both $^7$Be and neutron are unstable.

Measure the Inverse Reaction

$^7$Be reaction

$^7$Be$(1/2^-, 0; 0.429$ MeV) + n $^8$Be

$^7$Be$(3/2^-, g. s.) + n $^8$Be

$^7$Be stopper
5.8 cm $^5$He gas target

$^7$Be

$^4$He Beam
39.0–49.5 MeV

1 atm He + 11 µm Kapton

$^7$Be

478-keV $\gamma$-ray was measured off-line.

Inverse reaction

$^4$He $^4$He $^8$Be

$^4$He + $^4$He

$E_{c.m.} = 19.4$ MeV

$E_{c.m.} = 19.0$ MeV

$E = 478$ MeV

$Q_{EC} = 861.815$
Previous Results


\[ E_{\text{cm}} = 0.73 - 4.8 \text{ MeV} \]

Measurements for the \(^4\text{He}(\alpha, n)^7\text{Be}\) reaction must be done at lower energies.

CM Energy in the inverse reaction \(E_{\text{cm}} = 0.73 - 4.8\) MeV

Higher than cosmological energies.

**TABLE II.** \(\alpha + \alpha + n \rightarrow ^7\text{Be}\) Cross Sections.

<table>
<thead>
<tr>
<th>(E_{\alpha}) (MeV) (±100 keV)</th>
<th>(\sigma) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.43</td>
<td>26.3 ± 3.1</td>
</tr>
<tr>
<td>39.96</td>
<td>49.0 ± 4.7</td>
</tr>
<tr>
<td>41.67</td>
<td>40.3 ± 4.8</td>
</tr>
<tr>
<td>42.23</td>
<td>30.3 ± 3.0</td>
</tr>
<tr>
<td>43.00</td>
<td>22.6 ± 3.4</td>
</tr>
<tr>
<td>44.34</td>
<td>68.0 ± 6.2</td>
</tr>
<tr>
<td>44.52</td>
<td>72.9 ± 8.4</td>
</tr>
<tr>
<td>44.69</td>
<td>72.1 ± 6.3</td>
</tr>
<tr>
<td>47.36</td>
<td>35.1 ± 4.6</td>
</tr>
</tbody>
</table>
Liquid Scintillator (NE213)

200 mm

50 mm

Experimental Setup

Experiment has been done at Neutron TOF Facility in RCNP, Osaka.

- Experiment has been done at Neutron TOF Facility in RCNP, Osaka.
- 4He beam
  - 38.0—39.4 MeV
- TOF path 13 m
- Target
- Collimator
- Measured angles 0—20°
- Neutron Counter (Liq. Sci.)
- 1 atm He gas
- 12 µm Alamid 6 µm
- Beam
- Viewers natC Ta
- Alamid 6 µm
- 43 mm
- 34 mm
- 12 mm
- 60 mm
- Liquid Scintillator (NE213)
- 200 mm
- 50 mm
Experimental Results

Measured cross sections were fit to obtain the total cross section.

Cross sections at lower energies were successfully determined.
Comparison with compilations

Measured cross sections were converted to those for the inverse reaction.

Cross sections at lower energies:
- Systematically smaller than the estimation by Wagoner widely used in the BBN calculation, but close to ENDF/B-VII.1

\[ \sigma(\alpha,n) \rightarrow \sigma(n,\alpha) \]

\[ \hat{S}_A = 2S_A + 1 \]

Detailed balance

\[ \frac{4\text{He}(\alpha,n)\text{Be}}{7\text{Be}(n,\alpha)4\text{He}} \]

\[ \frac{\sigma(A + B \rightarrow C + D)}{\sigma(C + D \rightarrow A + B)} = \frac{(1 + \delta_{AB})\hat{S}_C\hat{S}_Dk_{CD}^2}{(1 + \delta_{CD})\hat{S}_A\hat{S}_Bk_{AB}^2} \]

\[ \text{Estimation from } 7\text{Li}(p,\alpha)4\text{He} \]

\[ \sigma_{(n,\alpha)} = \frac{P_l^n}{P_l^p} \sigma_{(p,\alpha)}, P_l = \frac{kR}{F_l^2(E,R) + G_l^2(E,R)} \]

Cross sections at lower energies:
- Systematically smaller than the estimation by Wagoner widely used in the BBN calculation, but close to ENDF/B-VII.1

\[ 7\text{Be}(n,\alpha)4\text{He} \] does not contribute to destruct \[ 7\text{Be}. \]
Summary

- Measurement of the $^7\text{Be}(n,\alpha)^4\text{He}$ reaction as a possible solution for the cosmological $^7\text{Li}$ problem.
  - First measurement at the cosmological energy.
  - Successfully measured down to $E_{cm} = 0.26$ MeV.
  - Cross sections are much smaller than the previous estimation widely used in the BBN calculation.
  - No enhancement in the $^7\text{Be}$ destruction mode.
Collaboration

A bachelor thesis work
by undergraduate students in Kyoto


Department of Physics, Kyoto University

S. Kubono, S. Nishimura

RIKEN

N. Iwasa

Department of Physics, Tohoku University
Observation of Primordial Li abundance

Primordial Li abundance can be determined from the observation of metal-poor stars.

\[
\frac{(\text{Li}/\text{H})_{\text{obs}}}{10^{-10}} = (1.23^{+0.34}_{-0.16}) \times 10^{-10}
\]

The observation shows a plateau in lithium versus metallicity.
Neutron Detection

Pulse shape discrimination was done to identify neutron events.

Detection Efficiency

Neutron events were successfully selected.

Neutron spectrum

γ flash

y flash
Comparison with compilations

Measured cross sections were converted to those for the inverse reaction.

Cross sections at lower energies:
✓ Systematically smaller than the estimation by Wagoner widely used in the BBN calculation, but close to ENDF/B-VII.1

$^7\text{Be}(n,\alpha)^4\text{He}$ does not contribute to destruct $^7\text{Be}$. 

Detailed balance

$$ 
{^4\text{He}(a,n)^7\text{Be}} \rightarrow {^7\text{Be}(n,\alpha)^4\text{He}} 
$$

$$
\frac{\sigma(A + B \rightarrow C + D)}{\sigma(C + D \rightarrow A + B)} = \frac{(1 + \delta_{AB}) \hat{S}_C \hat{S}_D k_{CD}^2}{(1 + \delta_{CD}) \hat{S}_A \hat{S}_B k_{AB}^2}
$$

$\hat{S}_A = 2S_A + 1$

Estimation from $^7\text{Li}(p,\alpha)^4\text{He}$

$$
\sigma_{(n,\alpha)} = \frac{P_n}{P_p} \sigma_{(p,\alpha)}
$$

$$
P_l = \frac{kR}{F_l^2(E,R) + G_l^2(E,R)}
$$