Measurement of the $^7\text{Be}(n, p)\ ^7\text{Li}$ cross section in EAR2@n_TOF for the Cosmological Lithium Problem

Nuclei in the Cosmos June 24-29, 2018 Laboratori Nazionali del Gran Sasso, Assergi, Italy

The Cosmological Lithium Problem

Results for the $^7$Be$(n, \alpha)$ cross-section

Experimental Set-up for the $^7$Be$(n, p)$ cross-section

Results for the $^7$Be$(n, p)$ measurement

Conclusions
The Cosmological Lithium Problem

Observations

Theoretical predictions

\[ \eta \equiv \frac{N_b}{N_\gamma} = 2.74 \times 10^{-8} \Omega_b h^2 \]

\[ \left( \frac{\text{Li}}{H} \right)_{BBN} \approx (5.14^{+0.71}_{-0.62}) \times 10^{-10} \]

\[ \left( \frac{\text{Li}}{H} \right)_{\text{obs}} \approx (1.58^{+0.06}_{-0.44}) \times 10^{-10} \]

Discrepancy of a factor 3 between observations and BBN modeling!
Nuclear solutions

95% of the primordial $^7\text{Li}$ comes from electron capture decay of the $^7\text{Be}$. Therefore the production and destruction of $^7\text{Be}$ is the key to understand the $^7\text{Li}$ abundance resulting from the Big Bang Nucleosynthesis.

Possible $^7\text{Be}$ destruction channels

- $^7\text{Be} (n, p) ^7\text{Li}$
  - 97% of the total destruction rate of $^7\text{Be}$

- $^7\text{Be} (n, \alpha) ^4\text{He}$
  - 2.5% of the total destruction rate of $^7\text{Be}$

Lack of experimental data due to the intrinsic difficulty of the measurement:

- Short half life of $^7\text{Be}$ (53 days) with a specific activity of 13 GBq/µg
  - High flux neutron beam is required
The high flux and the wide energy range (2 meV < $E_n < 100$ MeV) in EAR2 allows to:

- measure samples of very small mass ($<<1$ mg)
- measure short-lived radioisotopes (down to a few weeks)
- collect data on a much shorter time
- measure (n,charged particle) reactions with thin samples
Available data for $^7\text{Be}(n, \alpha)\alpha$

$^7\text{Be}(n,\alpha)$ only one measurements:

- Bassi at al., 1963, Thermal neutron energy

reaction rate by Wagoner (1969):

s-wave component:
1/ν normalized at thermal

p-wave component:
$\sim E^{1/2}$
Set-up for $^7\text{Be}(n, \alpha)\alpha$

- $Q = 19$ MeV
- $2\alpha$ coincidence

Silicon Sandwich: high sensitivity

Chemical purification is sufficient

Low cross section

High efficiency needed

Large mass (µg)

Silicon Sandwich in beam

No isotopic separation

Electrodeposition on a 5-µm-thick Al foil

droplet deposition on a 0.6-µm-thick polyethylene foil
$^7$Be(n, $\alpha$)$\alpha$ results and publication

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Available data for $^7$Be(n,p)

$^7$Be(n,p) three measurements:

- Koehler at al., 1988, 0.025 eV- 13.5 keV
- Gledenov et al., 1987, 0.025 eV- ~500 eV
- Andrzejewsk et al., 1991, ~25 keV
\[ \text{Reference reaction: } ^6\text{Li}(n, t) \quad ^4\text{He} \]
$^7\text{Be}(n, p)\ ^7\text{Li}$: Sample preparation @PSI/ISOLDE

- 200 GBq of $^7\text{Be}$ extracted from the cooling water of the SINQ spallation source at PSI
- Transported to ISOLDE at CERN and installed in the ion source to produce 30 keV ion beam.
- $^7\text{Be}$ beam separated by means of a magnetic dipole, and implanted on a 20 m thick aluminum backing.
- Sample of 1 GBq $^7\text{Be}$ (~80 ng) transported to EAR2@n_TOF and placed in the neutron beam.

First time a neutron measurement performed with a sample produced at a Radioactive Beam Facility (ISOLDE)
Reference reaction: $^6\text{Li}(n, t) \ ^4\text{He}$
$^7$Be coincidences

$^7$Be

protons

$n + ^7$Be $\rightarrow p + ^7$Li

$Q = 1.644$ MeV
Background check

Counts

Counts $^7$Be
Counts Backing

Upper Limit

Energy (eV)

Counts
The $^7$Be(n, p) $^7$Li reduced cross section measured at n TOF compared with the results of previous measurements and with the ENDF/B-VII.1 library.

Results and implications

Resonance fit

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Comparison of the reaction rates for the $^7\text{Be}(n, p)\ ^7\text{Li}$ reaction

The cross section of the $^7$Li(p, n) $^7$Be obtained by time-reversing the n TOF data of the $^7$Be(n, p) $^7$Li reaction.

Results and implications
The $^{7}\text{Be}(n,p)^{7}\text{Li}$ cross-section measurement has been performed at n_TOF-EAR2, using a 1.1 GBq and 20MBq pure samples implanted at GLM beam line of ISOLDE, starting from a 200 GBq $^{7}\text{Be}$ solution collected at PSI.

At n_TOF the $^{7}\text{Be}(n,p)^{7}\text{Li}$ cross-section has been measured for the first time in the energetic range of interest for the problem.

The reaction rate of the $^{7}\text{Be}(n,p)^{7}\text{Li}$ performed @n_TOF cause a decrease of 10% of the abundance predicted for the primordial $^{7}\text{Li}$.

Our results exclude the channels $(n,a)$ and $(n,p)$ as a solution for the problem that could be reduced in the hypothesis in which mixing mechanisms such as gravitational settling or atomic diffusion are able to lower the superficial abundance of lithium in the stars of low metallicity.
The bare truth is beyond this wall... we just need to find the proper tool to climb it over!
Backup slides
\[
\sigma_{Be} = \frac{C_{Be}(E_n)}{C_{Li}(E_n)} \cdot \frac{\varepsilon_{Li}}{\varepsilon_{Be}} \cdot \frac{f_{cLi}}{f_{cBe}} \cdot \sigma_{Li}(E_n) \cdot \frac{1}{N_S}
\]

\(f_c\) : Convolution of the normalized neutron beam spatial profile and target nuclei distribution (\(b^{-1}\)).
Sources of background

**Background**

- Pile up of γ rays from the $^7Be$ decay
- Pile up of protons from the competing $^7Be(n, p)\ 7Li$ reaction
- Production of $^8Li$ via neutron capture on $^7Li$, which undergoes β decay into $^8Be$
- $^9Be(n, 2n),\ 7Li(p, \gamma),\ 7Be(p, \gamma)$

**Solutions**

- 2 MeV threshold on the signal amplitude
- Coincident signals of uncorrelated Si detectors
- only the 3.03 MeV state of $^8Be$ populated by $^8Li$ decay, α emitted with an energy of 1.5 MeV
- corresponding signals at a much shorter neutron time of flight
Samples

<table>
<thead>
<tr>
<th>Vaporization</th>
<th>Molecular Plating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backing</td>
<td>Stretched PE (0.6 µm)</td>
</tr>
<tr>
<td>Activity</td>
<td>20 GBq</td>
</tr>
<tr>
<td>Diameter</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

2 different samples: Molecular plating (3.5 µg total mass) Vaporization of droplets

Prepared in hot-cell at PSI
First signal

Alpha coincidence
$^7\text{Be}(\text{n, }\alpha)^4\text{He reaction}$
$^7$Be(n, α) $^4$He reaction
The first exited state in $^7\text{Li}$ at 478 keV has a spin and parity $J^\pi = 1/2^-$. Therefore, if a $J^\pi = 2^-$ is formed by s-wave neutron on $^7\text{Be}$, the state cannot decay into $^7\text{Li}(1\text{st})$ by emitting $l=0$ (no sufficient angular momentum), nor $l=1$ (no parity conservation) protons. Because the $2^-$ state just above threshold in $^8\text{Be}$ dominates the reaction mechanisms in a wide energy range, it is possible to estimate the $(n,p_1)$ contribution to the $^7\text{Be}(n,p)^7\text{Li}$ cross section by calculating the ration of penetrabilities of $l=2$ to $l=0$ protons in the $p + ^7\text{Li}(1s)$ exit channel. The result of this estimate is shown in the figure below.
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## 7Be(n, p) 7Li reaction

### List of the 12th most important reactions in the BBN network

<table>
<thead>
<tr>
<th>code index</th>
<th>reaction</th>
<th>adopted</th>
<th>options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^3H(u, \gamma)D$</td>
<td>ando</td>
<td>ando skm</td>
</tr>
<tr>
<td>2</td>
<td>$^3He(n,p)T$</td>
<td>stlb</td>
<td>stlb de04 skm</td>
</tr>
<tr>
<td>3</td>
<td>$^7Be(n,p)^7Li$</td>
<td>ntof</td>
<td>ntof cy04 skm</td>
</tr>
<tr>
<td>4</td>
<td>$^7Be(n,\alpha)^4He$</td>
<td>ntof</td>
<td>wag ntof</td>
</tr>
<tr>
<td>5</td>
<td>$D(p,\gamma)^3He$</td>
<td>ill6</td>
<td>ill6 skm</td>
</tr>
<tr>
<td>6</td>
<td>$^7Li(p,\alpha)^4He$</td>
<td>stlb</td>
<td>stlb cf88 de04 skm</td>
</tr>
<tr>
<td>7</td>
<td>$T(\alpha,\gamma)^7Li$</td>
<td>stlb</td>
<td>stlb skm</td>
</tr>
<tr>
<td>8</td>
<td>$^3He(\alpha,\gamma)^7Be$</td>
<td>ill6</td>
<td>ill6 ncr2 skm cd08</td>
</tr>
<tr>
<td>9</td>
<td>$D(d,n)^3He$</td>
<td>stlb</td>
<td>stlb skm</td>
</tr>
<tr>
<td>10</td>
<td>$D(d,p)T$</td>
<td>stlb</td>
<td>stlb skm</td>
</tr>
<tr>
<td>11</td>
<td>$T(d,n)^4He$</td>
<td>stlb</td>
<td>stlb de04 cf88 skm</td>
</tr>
<tr>
<td>12</td>
<td>$^3He(d,p)^4He$</td>
<td>stlb</td>
<td>stlb de04 skm</td>
</tr>
</tbody>
</table>

# references:
- Caughlan and Fowler, APNMT 40, 293 (1988)
- Descouvemont et al., APNMT 88, 203 (2004)
- Cyburt, PRD 70, 023505 (2004)
- ncr2: fit to mcare2 library
- stlb: fit to starlib table
- ntof: rate from n_TOF experiments
### $^7\text{Be}(n, p)\, ^7\text{Li}$ reaction

<table>
<thead>
<tr>
<th>Case</th>
<th>$Y_p$</th>
<th>D/H [$10^{-5}$]</th>
<th>$^3\text{He}/\text{H}$ [$10^{-5}$]</th>
<th>$^7\text{Li}/\text{H}$ [$10^{-10}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>present with standard rates</td>
<td>0.246</td>
<td>2.43</td>
<td>1.08</td>
<td>5.46</td>
</tr>
<tr>
<td>present with new rate ($\eta_{10} = 6.09$)</td>
<td>0.248</td>
<td>2.43</td>
<td>1.08</td>
<td>$5.26 \pm 0.40$</td>
</tr>
<tr>
<td>present with new rate ($5.8 \leq \eta_{10} \leq 6.6$)</td>
<td>0.246</td>
<td>2.43</td>
<td>1.08</td>
<td>$4.73 - 6.23$</td>
</tr>
<tr>
<td>observations</td>
<td>0.245 ± 0.003</td>
<td>2.569 ± 0.027</td>
<td>-</td>
<td>$1.6 \pm 0.3$</td>
</tr>
</tbody>
</table>

### Graph

- **Li7**
- **Be7**
- **Li7 total**
- **Li7 total (new rates)**

**X-axis:** $\eta$

**Y-axis:** abundance

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Experimental set-up

\( \text{Activity} \quad 1.1 \text{ GBq} \)

\( \text{Radius} \quad 2.5 \text{ mm} \)

\( \text{LiF Sample} \)

\( xy \quad 5 \times 5 \text{ cm}^2 \)

\( z \quad 1.66 \mu\text{m} \)