Transfer and breakup reactions involving \(^7\)Be at ISOLDE

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The Cosmological $^7$Li problem

The primordial abundance of $^7$Li inferred from observational data $\sim$ factor 3 below the abundance predicted by BBN theory using baryon-to-photon ratio $\eta$ from measurements of cosmic microwave background.

**BBN theory using $\eta_b^{WMAP}$:** $^7$Li/H = 5.12 $^{+0.71}_{-0.62}$ $\times$ $10^{-10}$

**Observationally extracted:** $^7$Li/H = 1.58 $^{+0.35}_{-0.20}$ $\times$ $10^{-10}$

**Serious discrepancy**

Good agreement of BBN predicted abundances with observations for $^2$H, $^3, ^4$He.

For decades, one of the important unresolved problems
Nuclear physics aspect of the primordial lithium problem

Possible solutions - Nuclear/Astrophysical/Physics beyond standard BBN

Improved understanding of stellar depletion mechanism of $^7$Li? It is very difficult to justify enough destruction of $^7$Li Ryan (1999)

Destruction of mass-7 nuclides through interaction with WIMP particles, unstable particles in the early universe that could have affected BBN. Cyburt (2006), Goudelis (2016) Fields (2011)

In the condition of BBN, $^7$Li is effectively destroyed through $^7$Li(p,α)$^4$He, to a level that the majority of the surviving $^7$Li is produced indirectly through the decay of $^7$Be ($T_{1/2} = 53.12$ d) after the cessation of nucleosynthesis.

Nuclear aspect of the $^7$Li problem are therefore the reaction rates of $^7$Be production, mainly $^4$He($^3$He,γ)$^7$Be and its destruction through $^7$Be(n,p)$^7$Li, $^7$Be(n,α)$^4$He and $^7$Be(d,p)2α.
Incomplete nuclear physics input for BBN calculations: Can resonant enhancement alleviate this discrepancy?

R. W. Kavanagh
Nuclear Physics 18 (1960) 492

\[ E_{\text{cm}} = 0.6 - 1.3 \text{ MeV}, \text{ reaction rate} \]

relied on an extrapolation to lower energies. Differential cross section multiplied by \(4\pi\) (assuming isotropic angular distribution) and \emph{arbitrarily} by \(3\) (to estimate contribution of higher energy \(^8\text{Be}\) states) \textit{Parker} (1972)

\[ ^7\text{Be}(d,p)^8\text{Be}^* \rightarrow 2\alpha \ (Q = 16.490 \text{ MeV}) \]

upto \(E_x = 11 \text{ MeV}\)
An experiment performed at lower energy found a significantly reduced cross-section in the BBN Gamow window compared to Parker’s estimate.

\[ ^7\text{Be(d,p)}^8\text{Be}^* \rightarrow 2\alpha \ (Q = 16.490 \text{ MeV}) \]

\((E_{7\text{Be}} = 5.55, 1.71 \text{ MeV}) \text{ upto } E_x = 13.8 \text{ MeV} \)

- Kavanagh (1960)
- Angulo (2005), \(^8\text{Be}^* \text{(g.s + 1}\text{st ex.s)}\)

Cross section overestimated previously

Small angular range covered (~ 7-17 deg) and full isotropy for proton angular distribution assumed in calculating average cross section.
Other works suggested resonant enhancement through a 16.7 MeV (5/2+) resonance state in $^9$B Cyburt (2005), Chakravorty (2011)

$^2$H($^7$Be,d)$^7$Be ($E_{^7\text{Be}} = 10$ MeV)

No evidence for a resonance observed

High resolution study of $^9$Be($^3$He,t)$^9$B, $E = 140$ MeV/A, the state is strongly excited.


Without experimental knowledge on its decay properties, conclusion about resonant enhancement to the d + $^7$Be reaction remain uncertain.
Proposed $^7\text{Be}$ destruction mechanism, $d + ^7\text{Be} \rightarrow ^9\text{B}^* \rightarrow p + ^8\text{Be}^*$

The 16.8 MeV state in $^9\text{B}$ formed by fusion of $^7\text{Be} + d$ and decays by proton emission to a highly excited state in $^8\text{Be}$, 16.626 MeV above the ground state, which subsequently breaks up into two $\alpha$ particles.

However, recent work (2019) shows, $d + ^7\text{Be} \rightarrow 2\alpha + p$ may proceed through intermediate state in $^8\text{Be}$ by $^7\text{Be}(d,p)^8\text{Be}(\alpha)^4\text{He}$ or $^5\text{Li}$ by $^7\text{Be}(d, \alpha)^5\text{Li}(p)^4\text{He}$ sequence, or in a “democratic” three-particle decay of the $^9\text{B}$ compound system.

$^7\text{Be} + d$ measured at $E_{\text{cm}} \approx 0.2 - 1.5$ MeV, measured cross sections dominated by the $(d,\alpha)$ channel towards which prior experiments mostly insensitive.
A new resonance at 0.36(5) MeV observed which reduces the predicted abundance of primordial $^7$Li but not sufficiently to solve it. Additional experiments with improved statistics needed to reduce the uncertainty in the resonance energy. R-matrix analysis: 16.849 (5) MeV, $5/2^+$ state in $^9$B?

BBN $d + ^7$Be rate (CF88) and Rijal (FSU19) rates are hardly different

Speculation: Is it the same as the $^9$B state at $E_{cm} = 0.31(1)$ MeV by Scholl (2011)?
Experiment IS 554 @

5 MeV/u $^7$Be on CH$_2$ (15 µm), CD$_2$ (15 µm) and $^{208}$Pb (1 mg/cm$^2$) targets, beam intensity $I \sim 5 \times 10^5$ pps

Charge particle detector setup
1 x S3 annular DSSD (24 x 32 strips, 1000 µm) covering front angles 8° – 25°
5 x W1 DSSD (16 x 16 strips, 60 µm) in pentagon geometry covering angles 40° – 80°
2 x BB7 DSSD (32 x 32 strips, 60 µm and 140 µm) at backward angles 110° – 140°
The W1 and BB7 DSSDs are backed by 1500 µm thick unsegmented pads
$^7\text{Be}$ on CD$_2$  

$\Delta E$ vs $E_{\text{tot}}$ curve from $^7\text{Be}$ on CD$_2$ target in DSSD1. Angular correction applied on $\Delta E$. Gates for energy matching applied.

$^7\text{Be} + \text{d}$ elastic scattering
\textbf{Preliminary}

\textbf{\( ^7 \text{Be} + d \) elastic scattering}

\textbf{\( ^7 \text{Be} + ^{12} \text{C} \) elastic scattering}

Data only from S3 detector

Data only from the pentagon detectors

\textbf{IS 554}
$^7\text{Be}(d, p)^8\text{Be}^*$

CD$_2$ target proton impurity ($\sim 2\%$). Elastic protons from the proton impurity overlaps with transfer protons.

Elastic protons subtracted using $^7\text{Be}$ runs on CH$_2$ target

Excitation energy spectrum of $^8\text{Be}^*$ from CD$_2$ runs with proton impurity

Excitation from CD$_2$

Excitation energy spectrum of $^8\text{Be}^*$ from CD$_2$ runs (in blue, after removing elastic protons) and CH$_2$ runs (in red)

Preliminary
Excitation energy of $^8$Be* (after removing elastic protons)

Preliminary
Energy vs theta of the protons of $^7$Be(d,p)$^8$Be*

Excitation energy of $^8$Be*

Simulations

Analysis of back angle data going on
Detection of 16.84 MeV $(5/2^+)$ resonance state from $^7\text{Be} + d \rightarrow ^9\text{B}$ using supersymmetric quantum mechanics

Unstable or unbound systems, with very shallow potentials, pose serious numerical challenges in detecting resonance states. We could successfully circumvent this problem by using supersymmetric quantum mechanics.

This transforms the shallow well to a deep well-barrier isospectral potential, generating resonance state wavefunction. The resonance state energies obtained were found to be in excellent agreement with the experimental values.


Energy and angular correlations of coincident alphas detected by the pentagon DSSDs. Simulations show the energy correlation of the alphas emitted from the 16.63 MeV state of $^8$Be.
Outlook

Primordial $^7$Li abundance essentially determined by the $^7$Be production and destruction channel

The production channel $^3$He($\alpha$,γ)$^7$Be leads to an overall uncertainty $\sim$ 7%. Broggini (2012)

The destruction channel $^7$Be($d,p$)$^2\alpha$ via the 16.8 MeV state in $^9$B is unable to enhance the reaction rate by the amount needed to resolve the cosmological lithium problem. Speculation on the new resonance at 0.36 MeV corresponding to the 16.8 MeV state of $^9$B. The decay properties of the state remains to be known.

$^7$Be destruction involving neutrons $^7$Be(n,p)$^7$Li, $^7$Be(n, $\alpha$)$^4$He does not solve the anomaly. Damone (2018), Barbagallo (2016)

It is not yet time for a firm conclusion about the anomaly from our data. However, the indications are that it may not be possible to find a solution from nuclear physics alone.

It would be interesting in future to see if the lithium problem truly points to new fundamental physics.
IS 554 collaboration

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