One fewer solution to the cosmological lithium problem

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Data from a recent 9Be(3He,α)7B measurement are used to rule out a possible solution to the cosmological lithium problem based on conventional nuclear physics.

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The primordial abundance of 7Li inferred from observational data is roughly a factor of 3 below the abundance predicted by the standard model of big bang nucleosynthesis (BBN) [1] using the baryon-to-photon ratio η = 6.19(15) × 10^{-10} [2] determined mainly from measurements of the cosmic microwave background radiation. In contrast, there is good agreement for 2H and 4He. Taking into account the estimated uncertainties on the observationally inferred and the theoretically deduced 7Li abundances, the significance of the discrepancy is (4.2–5.3)σ [3]. This constitutes one of the important unresolved problems of present-day astrophysics and is termed the cosmological lithium problem. Among other possibilities, the discrepancy could be due to new physics beyond the standard model of particle physics [4], errors in the observationally inferred primordial lithium abundance, or incomplete nuclear physics input for the BBN calculations. This Brief Report addresses the last possibility.

In standard BBN theory, assuming η = 6.19(15) × 10^{-10}, most 7Li is produced in the form of 7Be. Only much later, when the universe has cooled sufficiently for nuclei and electrons to combine into atoms, does 7Be decay to 7Li through electron capture. The temperature range of 7Be production is T ≥ 0.3–0.6 GK, where the main mechanism for 7Be production is 3He(α,γ)7Be while the main mechanism for 7Be destruction is 7Be(n,p)6Li followed by 7Li(p,α)4He. The rates of these reactions as well as those that control the supply of neutrons, protons, 3He, and α particles are known with better than 10% precision at BBN temperatures [6], resulting in an uncertainty of only 13% on the calculated 7Li abundance [3].

A recent theoretical paper [7] explores the possibility of enhancing 7Be destruction through resonant reactions with p, d, t, 3He, and α, leading to compound states in 8B, 9B, 10B, 11C, and 12C, respectively. The paper concludes that, of the known excited states in these isotopes [8,9], only the 16.8-MeV state in 9B has the potential to significantly influence 7Be destruction.2 (Note that in Ref. [7] this state is referred to as the 16.7 MeV state.) The proposed destruction mechanism is shown schematically in Fig. 1. The 16.8-MeV state in 9B is formed by the fusion of 7Be with a deuteron and decays by proton emission to a highly excited state in 8Be, 16.626 MeV above the ground state, which subsequently breaks up into two α particles. (The last step is not shown in the figure.) The reason why the decay must proceed by proton emission to the 16.626-MeV state in 8Be and not, for example, the ground state is explained later.

The reaction rate depends critically on the resonance energy, E_r (i.e., the energy of the 16.8-MeV state relative to the d + 7Be threshold at E_d = 16.4901(10) MeV [8]): if too far above the threshold, the tunneling process will be too slow at BBN temperatures. Furthermore, for the proposed destruction mechanism to be efficient, the 16.8-MeV state must have an appreciable width, Γ_d, for being formed in the d + 7Be channel, but also an appreciable width, Γ_d, for not decaying back to d + 7Be. The energetically allowed decay modes competing with deuteron emission are γ, p, α, and 3He. However, γ and 3He can safely be neglected. A deuteron width, Γ_d, of the required magnitude can only be realized if the 16.8-MeV state is not too close to the threshold. The analysis of Ref. [7] shows that the cosmological lithium problem can be resolved provided E_r ≃ 170–220 keV, Γ_d ≃ 10–40 keV, and Γ_d ≃ 10–40 keV, resulting in an uncertainty of only 13% on the calculated 7Li abundance [3].

As noted in Ref. [7], the simultaneous requirement of E_r ≃ 170–220 keV and Γ_d ≃ 10–40 keV is physically possible, but it implies some rather special properties for the 16.8-MeV state: a reduced deuteron width comparable to the Wigner limit and a very large channel radius of at least 9 fm. In addition, the proposed destruction mechanism could only be reconciled with the direct measurement of Ref. [14] with considerable difficulty: the proton and α decay of the 16.8-MeV state had to be dominated by a single proton-decay branch to the 16.626-MeV, 2+ state in 8Be, because decays to the lower-lying states in 8Be would have produced protons of sufficient energy to be detected by the experimental setup of Ref. [14].
Slightly above the 16.626-MeV state, at 16.922 MeV, lies another $2^+$ state in $^8$Be. The two are nearly maximally mixed in isospin ($I$) [15] and are often referred to as the $2^+$ doublet. The structure of the 16.626-MeV state is primarily that of a $1p_{1/2}$ proton orbiting a $^7$Li core in its ground state, and the structure of the 16.922-MeV state is primarily that of a $1p_{1/2}$ neutron orbiting a $^7$Be core in its ground state [16]. The analysis in Ref. [13] suggests that the structure of the 16.8-MeV state in $^9$B is primarily that of a $2s_{1/2}$ proton orbiting the $I = 1$ component of the $2^+$ doublet. As noted in Ref. [7], this provided reason to think that the overlap between the 16.8-MeV state in $^9$B and $p + ^8$Be* might indeed be considerably larger for the 16.626-MeV state than for any of the lower-lying states in $^8$Be.

The nuclear physics input for BBN calculations was recently reexamined in Ref. [17], which includes new reactions, studies the potential effects of reactions for which data do not exist, studies the effects of nonthermal particles (highly energetic particles produced in exothermic reactions), in particular neutrons which take much longer to thermalize relative to the ground state of $^7$B. Subsequently, $^7$Be breaks up into two $\alpha$ particles.

![Schematic illustration of the proposed $^7$Be destruction mechanism](image)

FIG. 1. Schematic illustration of the proposed $^7$Be destruction mechanism, $d + ^7$Be $\rightarrow ^9$Be$^*$ $\rightarrow p + ^8$Be*. The energies are in MeV relative to the ground state of $^9$B. Subsequently, $^9$B breaks up into two $\alpha$ particles.

reaction rate by adding the extra term [21]

$$N_A\langle \sigma v \rangle = N_A\left(8/\pi \mu_{27}\right)^{1/2}(kT)^{-3/2} \times \int_0^\infty E\sigma(E)\exp(-E/kT)dE,$$  

(1)

where $N_A$ is Avogadro’s constant, $\mu_{27}$ is the reduced mass, $k$ is Boltzmann’s constant, $T$ is the temperature, $E$ is the relative kinetic energy, and $\sigma(E)$ is the cross section for $d + ^7$Be $\rightarrow ^9$Be$^*$ $\rightarrow p + ^8$Be*, given by the single-channel, single-level approximation of the $R$-matrix theory [22]:

$$\sigma(E) = \frac{\pi \hbar^2 \omega}{(E - E_r - \Delta \ell^2 + \Delta /2)^2},$$

where $\hat{\lambda} = \hbar/p = \hbar/(2\mu_{27}E)^{1/2}$, and $\omega$ is a statistical weight factor that depends on the spins involved,

$$\omega = \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} = \frac{2 \times \frac{5}{2} + 1}{(2 \times 1 + 1)(2 \times \frac{3}{2} + 1)} = 0.5,$$

with $J = 5/2$ is the (assumed) spin of the 16.8-MeV state, $J_1 = 1$ is the spin of the deuteron, and $J_2 = 3/2$ is the spin of $^7$Be. Furthermore, $\Gamma = \Gamma_y + \Gamma_p + \Gamma_\ell + \Gamma_{pHe} + \Gamma_\alpha$ is the total width. We assume $\Gamma_y$, $\Gamma_{pHe}$, and $\Gamma_\alpha$ to be negligible and $\Gamma_p$ to be dominated by the decay to the 16.626-MeV state in $^8$Be. Because the 16.8-MeV state is located close to threshold, the energy dependence of the deuteron width must be taken into account [23]:

$$\Gamma_d = 2P_{t=1}(E)y_d^2.$$  

Similarly, for the proton width,

$$\Gamma_p = 2P_{t=0}(E')y_p^2,$$  

(2)

where $P_t$ is the penetrability, $\ell$ is the orbital angular momentum, $y_d$ ($y_p$) is the deuteron (proton) reduced width, and $E'$ is the $p + ^8$Be* relative kinetic energy.

$$E' = E + S_d - S_p - 16.626 \text{ MeV},$$

with $S_p = -0.185(10) \text{ MeV}$ [8]. We note that Eq. (2) is only approximately valid, because it assumes that the width of the 16.626-MeV state in $^9$Be can be neglected, whereas the state actually has a considerable width of 108.1(5) keV [8] with an asymmetric line shape owing to interference with the 16.922-MeV state. Still, the approximation is adequate for the present analysis. Finally, the shift, $\Delta$, is calculated as

$$\Delta = -[S_{t=1}(E) - B'_1]y_d^2 - [S_{t=0}(E') - B'_1]y_p^2,$$

where $S_t$ is the shift function, and the boundary conditions are $B = S_{t=1}(E_r)$ and $B' = S_{t=0}(E_r)$. The definitions of $P_t$ and $S_t$ are given in Ref. [22]. To evaluate $P_t$ and $S_t$, suitable channel radii, $a_{27}$ and $a_9$, must be chosen for the formation and destruction channel.

Relying on the data from the new $^9$Be($^3$He,$t$)$^9$B measurement [18], we use $E_r = 310(10) \text{ keV}$ for the resonance energy and $\Gamma_0 = 81(5) \text{ keV}$ for the total width. The superscript 0 refers to the value at resonance energy, that is, at $E = E_r$. To maximize the reaction rate, we chose $\gamma_d$ and $\gamma_p$ such that $\Gamma_{d0} = \Gamma_{p0} = 0.5 \Gamma_0$. We do not have complete liberty in our choice of $\gamma_d$ and $\gamma_p$ because they should not exceed the corresponding Wigner limits, $\gamma_{d,a}^2 = 3\hbar^2/(2\mu_{27}a_{27}^2)$ and
The narrow resonance approximation is also shown. Eq. (1) vs temperature. For comparison, the rate calculated using the 16.8-MeV state in $^9\text{Be}$ of $\gamma$-$p$ reaction rate calculated from Eq. (1) is shown in Fig. 2. For comparison, we also show the rate obtained in the narrow resonance approximation. We find that the reduction in $^7\text{Li}$ abundance caused by the inclusion of the resonant contribution of the 16.8-MeV state in $^9\text{Be}$ to the $^7\text{Be}(d, \gamma)$ reaction rate is at most 3.5(8)%. This result is essentially independent of the choice of channel radii. The quoted uncertainty mainly reflects the 10-keV uncertainty on the energy determination of the 16.8-MeV state with a small contribution (0.2%) from the 5-keV uncertainty on the width determination.

We stress that the assumption of a dominant proton-decay branch to the 16.626-MeV state is by no means important to the conclusion of the present analysis. If the decay is assumed to proceed by proton emission to lower-lying states in $^8\text{Be}$ or $\alpha$ emission to $^5\text{Li}$, a similar reduction in $^7\text{Li}$ abundance is obtained. The assumption of a dominant proton-decay branch to the 16.626-MeV state was made mainly to avoid conflict with the direct measurement of Ref. [14].

In summary, we have shown that the 16.8-MeV state in $^9\text{Be}$ is unable to enhance the $^7\text{Be}(d, \gamma)$ reaction rate by the amount needed to resolve the cosmological lithium problem. With the new precise determination of the energy of the 16.8-MeV state [18], the reduction in $^7\text{Li}$ abundance owing to the inclusion of the resonant contribution of the 16.8-MeV state to the $^7\text{Be}(d, \gamma)$ reaction rate is at most 3.5(8)% and probably much lower depending on the decay properties of the 16.8-MeV state, which remain unknown. In line with Ref. [17], we conclude that all possibilities for solving the cosmological lithium problem by conventional nuclear physics means now seem to have been exhausted.

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