

One fewer solution to the cosmological lithium problem

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Data from a recent ${}^9\text{Be}({}^3\text{He},t){}^9\text{B}$ 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 ${}^7\text{Li}$ inferred from observational data is roughly a factor of 3 below the abundance predicted by the standard theory of big bang nucleosynthesis (BBN) [1] using the baryon-to-photon ratio $\eta = 6.19(15) \times 10^{-10}$ [2] determined mainly from measurements of the cosmic microwave background radiation. In contrast, there is good agreement for ${}^2\text{H}$ and ${}^4\text{He}$. Taking into account the estimated uncertainties on the observationally inferred and the theoretically deduced ${}^7\text{Li}$ abundances, the significance of the discrepancy is $(4.2\text{--}5.3)\sigma$ [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,¹ or incomplete nuclear physics input for the BBN calculations. This Brief Report addresses the last possibility.

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

A recent theoretical paper [7] explores the possibility of enhancing ${}^7\text{Be}$ destruction through resonant reactions with p , d , t , ${}^3\text{He}$, and α , leading to compound states in ${}^8\text{B}$, ${}^9\text{B}$, ${}^{10}\text{B}$, ${}^{10}\text{C}$, and ${}^{11}\text{C}$, respectively. The paper concludes that, of the known excited states in these isotopes [8,9], only the 16.8-MeV state in ${}^9\text{B}$ has the potential to significantly influence ${}^7\text{Be}$ 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 ${}^9\text{B}$ is formed by the fusion of ${}^7\text{Be}$ with a deuteron 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 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 ${}^8\text{Be}$ 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 $d + {}^7\text{Be}$ threshold at $S_d = 16.4901(10)$ 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 $d + {}^7\text{Be}$ channel, but also an appreciable width, $\Gamma - \Gamma_d$, for not decaying back to $d + {}^7\text{Be}$. The energetically allowed decay modes competing with deuteron emission are γ , p , α , and ${}^3\text{He}$. However, γ and ${}^3\text{He}$ 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 $E_r \simeq 170\text{--}220$ keV, $\Gamma_d \simeq 10\text{--}40$ keV, and $\Gamma - \Gamma_d \simeq \Gamma_d$. At the time Ref. [7] was written, the known properties of the 16.8-MeV state did not contradict these requirements: The 16.8-MeV state had been observed in two experiments [11,12]. Its energy was determined to be 16.7 MeV with an uncertainty of 100 keV, and only an upper limit of 100 keV existed on its total width. Its spin and parity were not determined, though a tentative $5/2^+$ assignment was made [13] based on comparison to the mirror nucleus, ${}^9\text{Be}$. No information existed on its decay properties.

As noted in Ref. [7], the simultaneous requirement of $E_r \simeq 170\text{--}220$ keV and $\Gamma_d \simeq 10\text{--}40$ 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 ${}^8\text{Be}$, because decays to the lower-lying states in ${}^8\text{Be}$ would have produced protons of sufficient energy to be detected by the experimental setup of Ref. [14].

*Corresponding author: oliverk@triumf.ca¹Lithium may be destroyed in metal-poor stars through diffusion and turbulent mixing [5].²Reference [10] offers a more optimistic view, but only by adopting a somewhat flexible approach to basic principles of nuclear physics.

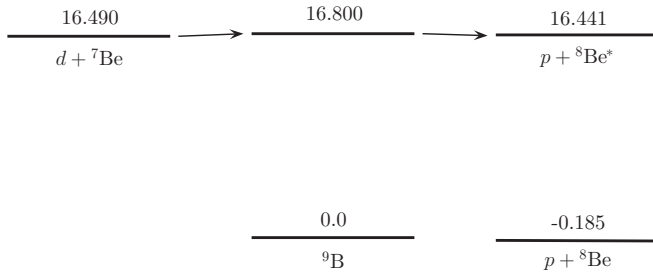


FIG. 1. Schematic illustration of the proposed ${}^7\text{Be}$ destruction mechanism, $d + {}^7\text{Be} \rightarrow {}^9\text{B}^* \rightarrow p + {}^8\text{Be}^*$. The energies are in MeV relative to the ground state of ${}^9\text{B}$. Subsequently, ${}^8\text{Be}^*$ breaks up into two α particles.

Slightly above the 16.626-MeV state, at 16.922 MeV, lies another 2^+ state in ${}^8\text{Be}$. 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 ${}^7\text{Li}$ 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 ${}^7\text{Be}$ core in its ground state [16]. The analysis in Ref. [13] suggests that the structure of the 16.8-MeV state in ${}^9\text{B}$ 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 ${}^9\text{B}$ and $p + {}^8\text{Be}^*$ might indeed be considerably larger for the 16.626-MeV state than for any of the lower-lying states in ${}^8\text{Be}$.

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 than charged particles, and includes thermal excitation of the first excited states in ${}^7\text{Li}$ and ${}^7\text{Be}$. Reference [17] concludes that there is little chance of solving the cosmological lithium problem with conventional nuclear physics, but it retains the destruction mechanism proposed by Ref. [7] as an “alluring” possibility.

A very recent paper [18] reports on a new ${}^9\text{Be}({}^3\text{He}, t){}^9\text{B}$ measurement performed with the purpose of studying Gamow-Teller transition strengths in the $A = 9$ system. The beam energy was 140 MeV/nucleon, and tritons were detected in a high-resolution spectrometer at scattering angles around 0° . The excitation energy resolution achieved was 30 keV. The 16.8-MeV state is strongly excited, and its energy and width are determined to be 16.800(10) MeV and 81(5) keV, respectively, in good agreement with the two previous experiments. The nearby $J^\pi = 1/2^-, I = 3/2$ state at 17.076(4) MeV is also strongly excited and its energy is well known from its γ decay to the ground state. This gives strong confidence in the new energy determination. It is also worth noting that the observed angular distribution of the 16.8-MeV state is consistent with the proposed $5/2^+$ assignment.

To assess the consequence of the new experimental data for the proposed destruction mechanism, we employ the standard Kawano-Wagoner BBN code [19,20]. We modify the ${}^7\text{Be}(d, p)$

reaction rate by adding the extra term [21]

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

where N_A is Avogadro’s constant, μ_{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 $d + {}^7\text{Be} \rightarrow {}^9\text{B}^* \rightarrow p + {}^8\text{Be}^*$, given by the single-channel, single-level approximation of the R -matrix theory [22]:

$$\sigma(E) = \pi \hat{\lambda}^2 \omega \frac{\Gamma_d (\Gamma - \Gamma_d)}{(E - E_r - \Delta)^2 + (\Gamma/2)^2},$$

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

$$\omega = \frac{2J + 1}{(2j_1 + 1)(2j_2 + 1)} = \frac{2 \times \frac{5}{2} + 1}{(2 \times 1 + 1)(2 \times \frac{3}{2} + 1)} = 0.5,$$

where $J = 5/2$ 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 ${}^7\text{Be}$. Furthermore, $\Gamma = \Gamma_\gamma + \Gamma_p + \Gamma_d + \Gamma_{{}^3\text{He}} + \Gamma_\alpha$ is the total width. We assume Γ_γ , $\Gamma_{{}^3\text{He}}$, and Γ_α to be negligible and Γ_p to be dominated by the decay to the 16.626-MeV state in ${}^8\text{Be}$. Because the 16.8-MeV state is located close to threshold, the energy dependence of the deuteron width must be taken into account [23]:

$$\Gamma_d = 2P_{\ell=1}(E)\gamma_d^2.$$

Similarly, for the proton width,

$$\Gamma_p = 2P_{\ell=0}(E')\gamma_p^2, \quad (2)$$

where P_ℓ is the penetrability, ℓ is the orbital angular momentum, γ_d (γ_p) is the deuteron (proton) reduced width, and E' is the $p + {}^8\text{Be}^*$ relative kinetic energy,

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

with $S_p = -0.1851(10)$ MeV [8]. We note that Eq. (2) is only approximately valid, because it assumes that the width of the 16.626-MeV state in ${}^8\text{Be}$ 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, Δ , is calculated as

$$\Delta = -[S_{\ell=1}(E) - B]\gamma_d^2 - [S_{\ell=0}(E') - B']\gamma_p^2,$$

where S_ℓ is the shift function, and the boundary conditions are $B = S_{\ell=1}(E_r)$ and $B' = S_{\ell=0}(E'_r)$. The definitions of P_ℓ and S_ℓ are given in Ref. [22]. To evaluate P_ℓ and S_ℓ , suitable channel radii, a_{27} and a_{18} , must be chosen for the formation and destruction channel.

Relying on the data from the new ${}^9\text{Be}({}^3\text{He}, t){}^9\text{B}$ measurement [18], we use $E_r = 310(10)$ keV for the resonance energy and $\Gamma^0 = 81(5)$ 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 γ_d and γ_p such that $\Gamma_d^0 = \Gamma_p^0 = 0.5\Gamma^0$. We do not have complete liberty in our choice of γ_d and γ_p because they should not exceed the corresponding Wigner limits, $\gamma_{W,d}^2 = 3\hbar^2/(2\mu_{27}a_{27}^2)$ and

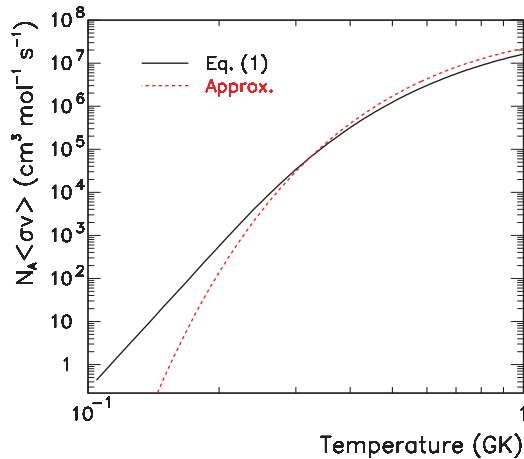


FIG. 2. (Color online) Maximal resonant contribution of the 16.8-MeV state in ${}^9\text{B}$ to the ${}^7\text{Be}(d, p)$ reaction rate calculated from Eq. (1) vs temperature. For comparison, the rate calculated using the narrow resonance approximation is also shown.

$\gamma_{W,p}^2 = 3\hbar^2/(2\mu_{18}a_{18}^2)$. We find that a permissible choice of γ_d only exists for $a_{27} > 6.5$ fm, whereas a permissible choice of γ_p exists for essentially any value of a_{18} . For the present calculation, we chose $a_{27} = 7$ fm and $a_{18} = 5$ fm, yielding $\gamma_d^2/\gamma_{W,d}^2 = 0.93$ and $\gamma_p^2/\gamma_{W,p}^2 = 0.09$. As argued in Ref. [7], $a_{27} = 7$ fm represents a physically plausible choice of channel radius. The temperature dependence of the reaction rate 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 ${}^9\text{B}$ to

the ${}^7\text{Be}(d, p)$ 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 α 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 ${}^9\text{B}$ is unable to enhance the ${}^7\text{Be}(d, p)$ 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 ${}^7\text{Be}(d, p)$ 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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