One fewer solution to the cosmological lithium problem

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Data from a recent \textsuperscript{9}Be(\textsuperscript{3}He,t)\textsuperscript{9}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 \textsuperscript{7}Li inferred from observational data is roughly a factor of three below the abundance predicted by the standard theory of big bang nucleosynthesis (BBN)\textsuperscript{[1]} using the baryon-to-photon ratio $\eta = 6.19(15) \times 10^{-10}$\textsuperscript{[2]} determined mainly from measurements of the cosmic microwave background radiation. In contrast, there is good agreement for measurements of the cosmic microwave background radiation in the observationally inferred primordial lithium abundance beyond the Standard Model of particle physics\textsuperscript{[4]}, errors possibilities, the discrepancy could be due to new physics. The present paper addresses the last possibility.

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

A recent theoretical paper\textsuperscript{[7]} explores the possibility of enhancing \textsuperscript{7}Be destruction through resonant reactions with $p$, $d$, $t$, \textsuperscript{3}He, \alpha, leading to compound states in \textsuperscript{8}B, \textsuperscript{9}B, \textsuperscript{10}B, \textsuperscript{10}C, \textsuperscript{11}C, respectively. The paper concludes that, of the known excited states in these isotopes\textsuperscript{[4,5]}, only the 16.8 MeV state in \textsuperscript{9}B has the potential to significantly influence \textsuperscript{7}Be destruction\textsuperscript{[2]}. (Note that in Ref.\textsuperscript{[8]} this state is referred to as the 16.7 MeV state.) The proposed destruction mechanism is shown schematically in Fig.\textsuperscript{1}.

The 16.8 MeV state in \textsuperscript{9}B is formed by the fusion of \textsuperscript{9}Be with a deuteron and decays by proton emission to a highly excited state in \textsuperscript{8}Be, 16.626 MeV above the ground state, which subsequently breaks up into two \alpha 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 \textsuperscript{8}Be and not e.g. the ground state will be explained below.

The reaction rate depends critically on the resonance energy, $E_r$, i.e. the energy of the 16.8 MeV state relative to the $d + \textsuperscript{7}Be$ threshold at $S_d = 16.4901(10)$ MeV\textsuperscript{[9]}: 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, $\Gamma_d$, for being formed in the $d + \textsuperscript{7}Be$ channel, but also an appreciable width, $\Gamma - \Gamma_d$, for not decaying back to $d + \textsuperscript{7}Be$. The energetically allowed decay modes competing with deuteron emission are: $\gamma$, $p$, $\alpha$, and \textsuperscript{3}He. However, $\gamma$ and \textsuperscript{3}He can safely be neglected. A deuteron width, $\Gamma_d$, 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.\textsuperscript{[2]} shows that the cosmological lithium problem can be resolved provided $E_r \simeq 170 - 220$ keV, $\Gamma_d \simeq 10 - 40$ keV, and $\Gamma - \Gamma_d \simeq 0$. At the time Ref.\textsuperscript{[2]} 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\textsuperscript{[11,12]}, its energy had been determined to be 16.7 MeV with an un-
certainty of 100 keV, and only an upper limit of 100 keV existed on its total width. Its spin and parity had not been determined, though a tentative 5/2+ assignment had been made based on comparison to the mirror nucleus, 9Be. No information existed on its decay properties.

As noted in Ref. [2], the simultaneous requirement of $E_r \approx 170 - 220$ keV and $\Gamma_d \approx 10 - 40$ keV is physically possible, but 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 $\alpha$ 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 8Be. The two are nearly maximally mixed in isospin (I) 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 7Li 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 7Be core in its ground state. The analysis in Ref. [13] suggests that the structure of the 16.8 MeV state in 9Be is primarily that of a $2s_{1/2}$ proton orbiting the I = 1 component of the 2+ doublet. As noted in Ref. [3], this provided reason to think that the overlap between the 16.6 MeV state in 9Be and $p + {}^8$Be might indeed be considerably larger for the 16.626 MeV state than for any of the lower-lying states in 8Be.

The nuclear physics input for BBN calculations has recently been reexamined in Ref. [17], which includes new reactions, studies the potential effects of reactions for which data do not exist, studies the effects of non-thermal 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 7Li and 7Be. Ref. [17] concludes that there is little chance of solving the cosmological lithium problem with conventional nuclear physics, but retains the destruction mechanism proposed by Ref. [2] as an “alluring” possibility.

A very recent paper reports a new 9Be(9He,t)9B 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 $\gamma$ 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 7Be(d,p) reaction rate by adding the extra term 21:

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

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 $d + 7\text{Be} \rightarrow 9\text{Be}^* \rightarrow p + {}^8\text{Be}^*$, given by the single-channel, single-level approximation of the $R$-matrix theory 22:

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

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

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

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 7Be. Furthermore, $\Gamma = \Gamma_\gamma + \Gamma_p + \Gamma_d + \Gamma_{3\text{He}} + \Gamma_\alpha$ is the total width. We assume $\Gamma_\gamma$, $\Gamma_{3\text{He}}$, and $\Gamma_\alpha$ to be negligible and $\Gamma_p$ to be dominated by the decay to the 16.626 MeV state in 8Be. As 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:

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

where $P_\ell$ is the penetrability, $\ell$ is the orbital angular momentum, $\gamma_d$ ($\gamma_p$) 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 $S_p = -0.1851(10) \text{ MeV}$ 3. We note that Eq. 4 is only approximately valid, as it assumes that the width of the 16.626 MeV state in 8Be can be neglected, whereas the state actually has a considerable width of 108.1(5) keV 9 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

$$\Delta = -(S_{\ell=1}(E) - B) \gamma_d^2 - (S_{\ell=0}(E') - B') \gamma_p^2,$$
We find that a permissible choice of $\gamma_a$ does not have complete liberty in our choice of $\gamma_0$. The superscript 0 refers to the value at resonance energy and $\Gamma_0$ in the narrow resonance approximation is also shown.

Relying on the data from the new $^9$Be($^3$He,$t$)$^7$B measurement \cite{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, i.e. at $E = E_r$. To maximize the reaction rate, we chose $\gamma_d$ and $\gamma_p$ such that $\Gamma_0^d = \Gamma_0^p = 0.5 \Gamma_0^0$. We do not have complete liberty in our choice of $\gamma_d$ and $\gamma_p$ as they should not exceed the corresponding Wigner limits, $\gamma_{W,d} = 3\hbar^2/(2\mu_2 a_2^2)$ and $\gamma_{W,p} = 3\hbar^2/(2\mu_3 a_1^3)$. We find that a permissible choice of $\gamma_d$ only exists for $a_2 > 6.5$ fm, whereas a permissible choice of $\gamma_p$ exists for essentially any value of $a_1$. For the present calculation, we chose $a_2 = 7$ fm and $a_1 = 5$ 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. \cite{7}, $a_2 = 7$ 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 $^7$Li abundance caused by the inclusion of the resonant contribution of the 16.8 MeV state in $^9$B to the $^7$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 in 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 $^8$Be or $\alpha$ emission to $^5$Li, a similar reduction in $^7$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. \cite{14}.

In summary, we have shown that the 16.8 MeV state in $^9$B is unable to enhance the $^7$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 \cite{18}, the reduction in $^7$Li abundance owing to the inclusion of the resonant contribution of the 16.8 MeV state to the $^7$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. \cite{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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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Maximal resonant contribution of the 16.8 MeV state in $^7$Be to the $^7$Be($d$, $p$) reaction rate calculated from Eq. (1) versus temperature. For comparison, the rate calculated using the narrow resonance approximation is also shown.}
\end{figure}

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