Contribution of the $^3He(t,\gamma)^6Li$ reaction to ^6Li production in primordial nucleosynthesis

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(Received 5 July 1990)

The contribution of the $^3He(t,\gamma)^6Li$ reaction to primordial ^6Li production is discussed. We argue that the present knowledge on this reaction is sufficiently restrictive and that this reaction is very unlikely to play an important role in primordial ^6Li production either in the standard or in the inhomogeneous nucleosynthesis scenario.

In a recent publication Madsen[1] argued that the reaction $^3He(t,\gamma)^6Li$, which has been omitted from the nuclear reaction network in the primordial nucleosynthesis calculation,[2,3] might give an important contribution to the ^6Li production in the early Universe, and its abundance might be substantially larger than has been thought. In this Brief Report we point out that the present experimental[4–6] and theoretical knowledge[7] on this reaction is sufficiently restrictive that it almost rules out the above possibility. We have also carried out a nucleosynthesis network calculation with $^3He(t,\gamma)^6Li$ taken into account with the expectation that its inclusion might affect the ^6Li abundance, but we have found this quite unlikely. We also mention that this reaction is unlikely to play any important role also in the inhomogeneous nucleosynthesis scenario.

The reaction $^3He(t,\gamma)^6Li$ proceeds through the $E1$ transition, and its cross section is expected to be much larger than that for $^4He(d,\gamma)^6Li$ which takes place only through the $E2$ and $M1$ transitions. Experiment[4–6] in fact shows that this is true, and the cross section in the energy range responsible for primordial nucleosynthesis is almost as large as that of $^4He(t,\gamma)^7Li$. This large cross section [about 4000 times larger than $^4He(d,\gamma)^6Li$], however, is compensated by relatively small abundances of ^3H and ^3He compared to d and ^4He, respectively, and the net increment of the primordial ^6Li abundance is at most a few percent.

There are three experiments that measured $^3He(t,\gamma)^6Li$ for $E_{c.m.} < 1$ MeV.[4–6] In particular, Blatt *et al.*[6] measured the cross section for the energy range down to $E_{c.m.} = 0.26$ MeV. From their experiment we extract the astrophysical S factor as shown in Fig. 1, which is described well by

$$S(E) = 2.57\times 10^{-5}\ \text{MeV b}(1+12.1E+3.91E^2) \quad (1)$$

for $E \leq 2$ MeV (E in MeV; the suffix c.m. is suppressed), where we added two contributions of the radiative transitions to the $J^P(T)=1^+(0)$ (ground state) and the $0^+(1)$ ($E=2.56$ MeV) final states (14%). The radiative transition to the $3^+(0)$ ($E=2.19$ MeV) state is followed by a fast decay into ^4He+d and does not contribute to ^6Li production. In Fig. 1 we also show for the sake of comparison the S factor for $^4He(t,\gamma)^7$ Li and the Gamow's peak for T_9 (temperature in units of 10^9 K) = 1. It is interesting to note that the S factor for ^3He $(t,\gamma)^6Li$ has a significant energy dependence and it decreases as the energy decreases, in contrast with the case for $^4He(t,\gamma)^7Li$ whose S factor stays almost at a constant value.

Madsen,[1] in contrast with the behavior shown above, assumed that $S(E)$ is energy independent in the low-energy region, and took the value $S(E)\approx S(E=1\ \text{MeV})\approx 5\times 10^{-4}$ MeV b as a lower limit to estimate ^6Li production. This value is already larger than that prescribed by (1), by about a factor of 5 for $T_9=1$. Furthermore, he considered the possibility that the S fac-

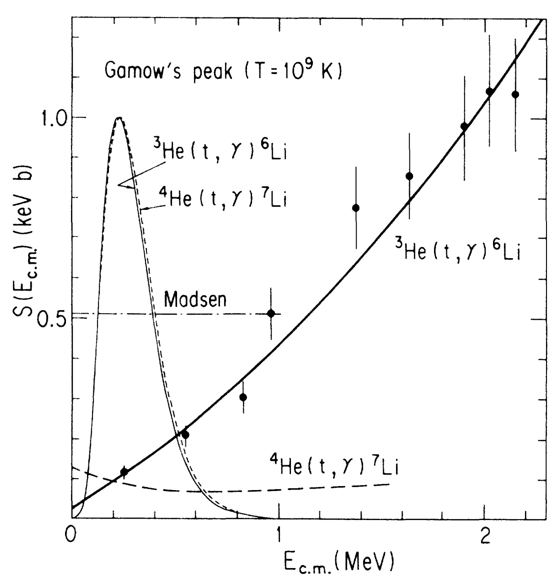

FIG. 1. Astrophysical S factors for $^3He(t,\gamma)^6Li$ extracted from experiment by Blatt *et al.* (Ref. 6) [a thick solid curve represents fit (1)]. The S factor used by Madsen (Ref. 1) is indicated by dot-dashed line. The S factor for $^4He(t,\gamma)^7Li$ as tabulated in Ref. 2 is also shown by a dashed curve. Gamow's peak for $T=10^9$ K is given by two thin curves.

tor increases by a factor of $10-10^4$ toward the low-energy region relevant to primordial nucleosynthesis. He also calculated ^{6}Li production for such hypothetical cases and emphasized the importance of measuring the ^{3}He$(t,\gamma)^6$Li cross section in the low-energy region.

Here we argue that such a possibility of a drastically enhanced S factor is already ruled out from the present knowledge. We first point out that the energy dependence of this reaction is well understood in terms of the direct capture model, which predicts correctly the energy dependence of this reaction from $E_{\mathrm{c.m.}}=0.25$ to 10 MeV.[7] While the direct capture model does not predict the normalization, the possibility that the measured cross section is seriously in error in its normalization is excluded from the $E1$ sum rule.[8] The sum rule predicts that $\int\sigma(E_\gamma)dE_\gamma\approx 90$ MeV mb with σ the total $E1$ photodisintegration cross section. The data by Blatt *et al.*[6] contribute by $\frac{1}{9}$ to this sum rule, and 75% of the total amount is already saturated by reactions including (γ,t), (γ,p) and (γ,n).[9] Hence the normalization of the measurement of Blatt *et al.* cannot be in error by more than a factor of 3. We also note that the measurement by Kohler and Austin[4] at $E_{\mathrm{c.m.}}=0.55$ MeV agrees with the data by Blatt *et al.* to an accuracy of 10%.

It is quite unlikely to expect a resonance that increases much the S factor at the energy relevant to nucleosynthesis. Since the threshold of ^{3}H$+^3$He relative to the ^{6}Li ground state is quite high (15.8 MeV), many channels including the three-body channel ^{4}He$+n+p$ ($E_{\mathrm{th}}=3.7$ MeV) are already open, which makes the total width of the resonance well over 1 MeV. This means that a sharp resonance is impossible, and such a resonance that contributes largely to nucleosynthesis, if it exists, should affect the data which are measured approximately with a 0.25-MeV step. From the presently available data, we can conclude that such a resonance contribution to the S factor, if any, is small.

Corresponding to (1), the thermally averaged cross section of ^{3}He$(t,\gamma)^6$Li is written to be

$$N_A\langle\sigma v\rangle=2.21\times10^5T_9^{-2/3}\exp(-7.720/T_9^{1/3})\times(1+2.68T_9^{2/3}+0.868T_9+0.192T_9^{4/3}+0.174T_9^{5/3}+0.044T_9^2)\,, \qquad (2)$$

with N_A the Avogadro number and v the thermal velocity. We then carry out a standard nucleosynthesis calculation using the reaction network given by Caughlan and Fowler.[2] Figure 2 shows the primordial ^{6}Li and ^{7}Li abundance as a function of the baryon to photon ratio $\eta=n_B/n_\gamma$. Two curves for ^{6}Li show its abundance with and without ^{3}He$(t,\gamma)^6$Li where we used the ^{3}He$(t,\gamma)^6$Li reaction cross section 3 times that of (1) and (2) to draw a conservative upper limit. [If the value of (2) is used, the difference between the two curves is one third of that displayed.] The ^{7}Li abundance is in good agreement with that in Ref. 3. We see that ^{3}He$(t,\gamma)^6$Li is more important for the small baryon density,[1] but it does not increase the ^{6}Li abundance more than by 4% for $\eta=n_B/n_\gamma\gtrsim10^{-10}$ (Ref. 3) (with a factor of 3 for the reaction cross section). The increment is by 25% at $\eta=10^{-11}$. The primordial ^{6}Li abundance remains to be smaller than 10^{-3} times that of ^{7}Li, and it is too small to be measured spectroscopically in Population II stars with the present technique. (The present limit is ^{6}Li/^{7}Li<0.1 derived from a hot metal-poor halo subdwarf HD84937.[10])

We also considered the role of ^{3}He$(t,\gamma)^6$Li in the inho-

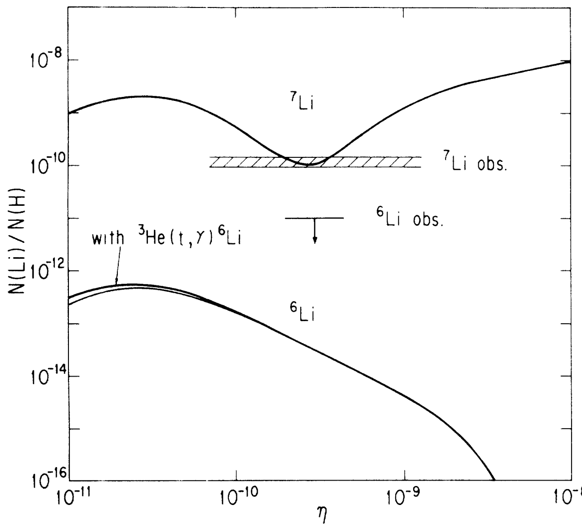

FIG. 2. Primordial production of ^{6}Li and ^{7}Li in standard big-bang nucleosynthesis (in the number ratio relative to the hydrogen abundance). The upper curve for ^{6}Li represents the abundance with the reaction ^{3}He$(t,\gamma)^6$Li included using its cross section 3 times that of (2), and the lower curve shows the abundance without this reaction. The range allowed by the observations (Refs. 10 and 11) is also indicated.

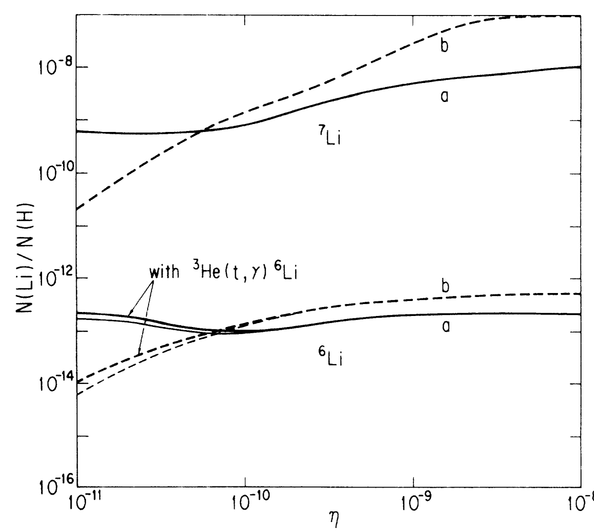

FIG. 3. Primordial production of ^{6}Li and ^{7}Li in the inhomogeneous nucleosynthesis scenario for parameters (a) $f_v=0.5$, $R=10^3$ (solid curves) and (b) $f_v=5\times10^{-3}$, $R=10^5$ (dashed curves). The meaning of the curves for ^{6}Li is the same as in Fig. 2.

mogeneous nucleosynthesis scenario recently discussed.[12–15] We took the calculational scheme by Alcock, Fuller, and Mathews.[13] We made calculations for a few choices of parameters satisfying $Rf_v \gtrsim 10\Omega_B$,[15] where R is the ratio of baryon-number density in high-density zones to that in low-density zones, f_v is the volume fraction of high-density zones at the end of the QCD phase transition and Ω_B is the baryon density parameter in units of the critical density. (If this condition is not satisfied, the effect of inhomogeneity is not important.[15]) We found again $N(^6\text{Li})/N(^7\text{Li})$ is smaller than 10^{-3} and the contribution of $^3\text{He}(t,\gamma)^6\text{Li}$ is not important for all parameters we tried. Figure 3 shows two typical cases: (i) $R=10^3$, $f_v=0.5$, and (ii) $R=10^5$, $f_v=5\times10^{-3}$, to exemplify the situation.

From the argument given in this Brief Report, we should conclude that inclusion of the $^3\text{He}(t,\gamma)^6\text{Li}$ reaction does not modify our understanding of primordial ^{6}Li production. The cross section of this reaction is already well constrained, and a new measurement of this reaction to be made in the low-energy regime, even if it would revise the value of the previously measured cross section by an order of magnitude, would bring practically nothing of significance to the art of primordial nucleosynthesis.

One of us (M. F.) would like to thank Haruhiko Morinaga and David Schramm for useful discussions. The work was supported in part by JSPS-NSF Cooperative Research Grants (Nos. MPCR-185 and EPAR-071) and by Grants-in-Aid (Nos. 01540253 and 02211207) of the Ministry of Education.

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