Measurement of the cross section of the ^{8}Li$(d,\alpha)^6$He reaction of possible relevance to big bang nucleosynthesis

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We report measurements of the cross section of the ^{8}Li$(d,\alpha)^6$He reaction in the energy range $E_{c.m.} = 2.3$–3.5 MeV using a ^{8}Li-radioactive beam on a CD_2 foil. The astrophysical S factor and reaction rate were calculated from the measured cross section. The ^{6}He nuclei produced in the reaction were detected in solid-state detector telescopes. This reaction might have affected the primordial abundance of ^{6}Li in big bang nucleosynthesis, since ^{6}He beta decays to ^{6}Li. However, several big bang nucleosynthesis network calculations were found to be insensitive to this reaction, suggesting that the ^{8}Li$(d,\alpha)^6$He reaction does not affect ^{6}Li primordial production.

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The baryon density of the universe may be constrained by comparing the light-element nucleosynthesis yields with observationally determined primordial abundances. Historically, two nucleosynthesis models, inhomogeneous and standard, have been used to predict the abundances of D, ^{3}He, ^{4}He, and ^{7}Li [1–4]. Constraints on the baryon density are imposed by comparing the observed and predicted abundances of these nuclei. The observation of ^{6}Li in old stars is difficult because the absorption line is weak and difficult to separate from the ^{7}Li line. However, recent observations have produced an estimate of the abundance of ^{6}Li in a few very old stars in the galactic halo [5,6]. Therefore, the abundance of ^{6}Li can provide an additional constraint on the baryon density. The predicted abundance of ^{6}Li results entirely from the ^{2}H$(\alpha,\gamma)^6$Li and ^{6}Li$(p,\alpha)^3$He reactions in the standard big-bang nucleosynthesis (SBBN) model [1]. On the other hand, the inhomogeneous big-bang nucleosynthesis (IBBN) model might also synthesize primordial ^{6}Li via other reactions.

Thus, we consider the possibility that in the IBBN ^{6}Li has been synthesized by ^{8}Li$(d,\alpha)^6$He$(\overline{\nu_e}e^-)^6$Li. In order to understand more quantitatively the significance of the ^{8}Li$(d,\alpha)^6$He reaction to the synthesis of ^{6}Li in the IBBN model, we have measured its cross section at relevant low energies. We have also performed several IBBN model calculations.

In this paper, we present the measured total cross sections for the reaction ^{8}Li$(d,\alpha)^6$He at three different laboratory energies ranging from 11.44 MeV to 17.43 MeV, from which we deduce the relevant laboratory reaction rate. We then include our current reaction rate for the ^{8}Li$(d,\alpha)^6$He reaction in calculations of the primordial abundance of ^{6}Li in IBBN models; these results are also presented.

In this experiment, we used the Notre Dame–Michigan radioactive beam facility, which operates in the following way. A stable ^{7}Li ion beam was produced using a SNICS II Sputter Ion Source and accelerated to the required energies, which varied between 18 and 21 MeV, by the FN Tandem Van de Graaff accelerator. This beam was then focused onto a 12.7-μm beryllium foil target in the production chamber located just upstream of the first superconducting solenoid magnet [7].

Secondary ^{8}Li beams of energies 11.44, 14.51, and 17.43 MeV over the angular range from 3° to 6° were produced via the ^{9}Be$(^7$Li$,^8$Li$)^8$Be reaction at incident ^{7}Li energies of 18.5 ± 0.02 and 21 ± 0.02 MeV. In order to achieve the 11.44 MeV energy, a 4-μm nickel foil was placed into the middle chamber to eliminate the necessity of further changing the energy of the incident ^{7}Li beam.

We have estimated an uncertainty in the laboratory energy at which the ^{8}Li beam is incident onto the secondary CD_2

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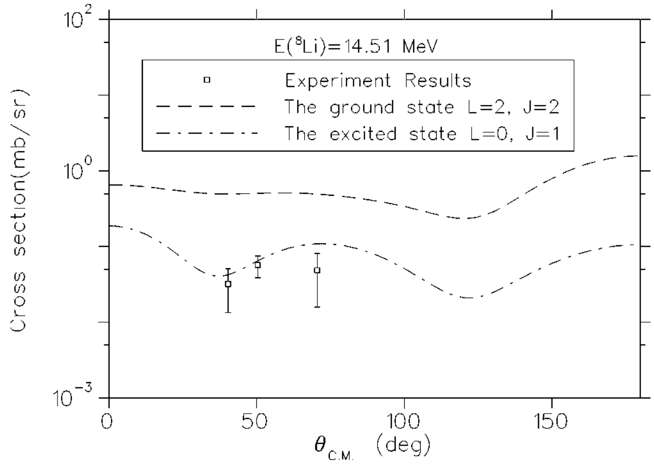

FIG. 1. Angular distribution for ^{6}He particles, compared with DWBA estimates at $E_{c.m.} = 2.9 \pm 0.3$ MeV

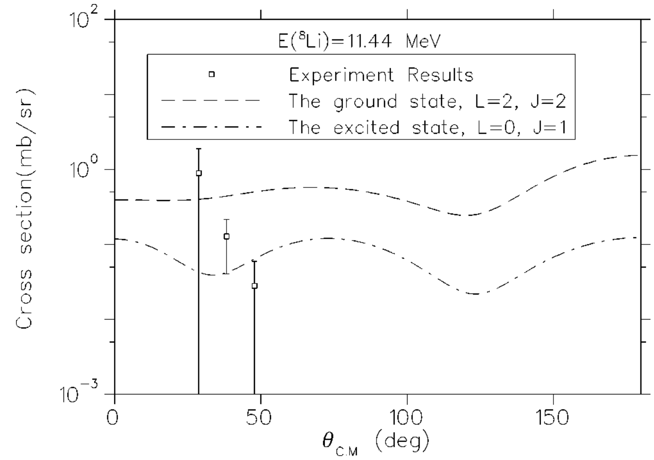

FIG. 2. Angular distribution for ^{6}He particles, compared with DWBA estimates at $E_{c.m.} = 2.3 \pm 0.3$ MeV.

target of around ± 0.3 MeV. This is due to the range of angular acceptance and straggling in the primary target and the degrader when present. The ^{8}Li ions were separated from other reaction products by means of a superconducting solenoid and three collimators. After the separation, the secondary ^{8}Li beam had an intensity of $\sim 10^5$ particles per second. These ions were sent onto the secondary CD_2 target which had a thickness of 1.94 mg/cm^2. The consequent energy width of the target was 4.4 MeV for the lowest incident energy to 2.9 MeV for the highest. Convolving this uncertainty together with that associated with the energy of the incident ions, the angular acceptance of the detector, and resulting possible different path lengths for ions through the target results in approximately ± 0.4 to ± 0.3 MeV, respectively, to the total center of mass energy uncertainty.

The events from the ^{8}Li$(d,\alpha)^6$He reaction were recorded in two ΔE-E telescopes, each consisting of one 50-μm-thick silicon surface-barrier transmission detector and a 414-μm-thick silicon surface barrier stopping detector. These two detector telescopes (ΔE-E) were mounted on a single rotatable support such that they were always 45° apart and on opposite sides of the beam. The distance between detectors and the target was made as small as possible allowing each to cover a solid angle of 0.13 sr.

ΔE-E particle identification spectra for all energy and angle combinations were obtained. In these spectra, protons, deuterons, tritons, and alpha particles appear clearly, while very few ^{6}He ions were apparent. We determined the particle identification gate for the ^{6}He particles using two different methods, which were found to produce consistent results. The first was to locate the ^{6}He event box via a linear equation between ΔE and MZ^2/E knowing the energy calibration in ΔE and E. The second was to estimate empirically the locations in ΔE-E space where the ^{6}He nuclei should appear by scaling to the observed locus of ^{4}He nuclei. The width and energy limits of the ^{6}He gate were deduced from kinematics and by including the measured energy resolution.

A natural carbon target was also used for the purpose of background subtraction since some alpha particles came from the reactions with carbon in the CD_2 target. An empty target run was performed to check for contamination that came directly from the beam.

Figures 1 and 2 show the differential cross section at the two energies indicated. The data came from the ΔE-E detector telescopes for three different angles at the energies 14.51 MeV and 11.44 MeV of ^{8}Li in the laboratory frame. Also shown in the figures are results of zero-range distorted-wave Born approximation (DWBA) calculations, calculated with the code DWUCK4 [8]. The optical potentials used to describe the elastic scattering for ^{4}He + ^{6}He and ^{2}H+^{8}Li channels were for ^{4}He+^{6}Li and a generalized potential for ^{2}H+^{8}Li, respectively [9]. Because the ground state of ^{8}Li has $J^\pi = 2^+$, the reaction to the ground state of ^{6}He must proceed by an $L=2$ transfer. However, the reaction to the ^{6}He(2^+) first excited state could involve an $L=0$ transfer; this would be expected to dominate in the low-energy environments of BBN.

The complexities of deuteron potential transfer reactions have been studied for many years. Of particular importance is the need for well matching; i.e., the potential well sizes of the entrance and exit channel optical potentials and of the bound state should be very similar [10]. However, the optical parameter sets that were available to describe the entrance and exit channels did not satisfy this condition very well. Thus we varied the parameters to determine the sensitivity of our results to the assumed parameter sets. We found that variations of $\pm 5\%$ in the real central potential well depth produced not more that a 5% change in the integrated cross section, which is the quantity of interest here. Varying the bound-state radius from 1.15 to 1.25 fm (roughly the mean value between the radii of the real central potentials of the entrance and exit channels) was found to affect the integrated cross section by less than 5%. We also studied the energy dependence of the DWBA cross sections to see if energy averaging might be important to our results. Although differences in the cross sections did approach a factor of 2 at 0°, they were less than 30% over the angular range of our data and less than 10% over the energy spread of each data point. The absolute normalization of the DWBA results is somewhat uncertain, especially for deuteron transfer reactions,

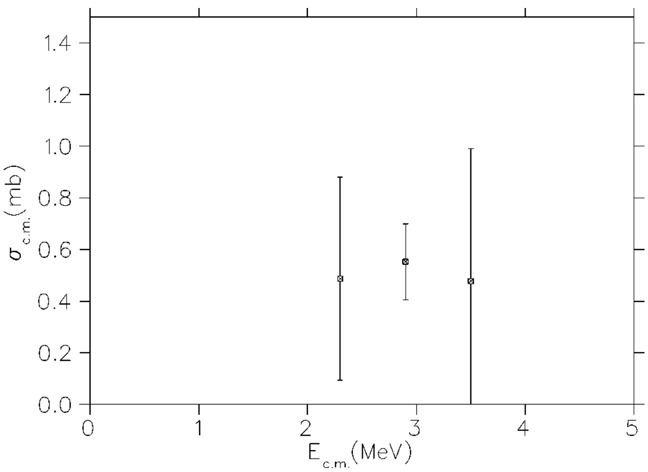

FIG. 3. Energy dependence of the measured ^{6}Li$(d,\alpha)^{6}$He particles cross section.

due to the zero-range scaling factor. The factor used in the present analysis is 20×10^{4} MeV^2 fm^2 [11].

We conclude that the results of this study have very little dependence on the details of the DWBA calculations. This is apparently related to the low energies at which this study was conducted. The dominance of the Coulomb barrier which, together with large Q value, would tend to make this reaction very surface peaked, means that the reaction depends almost entirely on the tail of the bound-state wave function. Increasing the radius of that well results (when the code searches to produce the correct binding energy) in a compensatory reduction in the depth of the potential well, which tends to give a similar distribution tail. Of course, the transferred deuterons also are fairly tightly bound; were they loosely bound, the result might have been quite different.

The total measured cross section for each energy was calculated by integrating the scaled experimental differential cross sections over 4π solid angle. Figure 3 shows the resulting measured total cross sections.

To calculate the thermonuclear nonresonant reaction rate for the charged-particle nuclear reactions, the energy-dependent cross section was converted to the astrophysical S factor [12]. A weighted average for the values of $S(E)$ then yields

$$S(E_0)=14.2(\mathrm{keV\,b}) \tag{1}$$

for the ^{8}Li$(d,\alpha)^{6}$He reaction.

If we assume a constant astrophysical S factor (the poor statistics would not permit any other assumption), the reaction rate obtained is [12]

$$N_A\langle\sigma v\rangle=\frac{1.37\times10^{8}}{T_9{}^{2/3}}e^{-10.348/T_9^{1/3}}\ \mathrm{cm^3\,s^{-1}\,mol^{-1}}, \tag{2}$$

where T_9 is the temperature in 10^9 K. We considered the possibility that resonances might affect this reaction. However, there are no known states above 24 MeV in ^{10}Be that might affect the ^{8}Li$+d$ reaction, and we have therefore discounted possible resonance contribution leaving only the nonresonant reaction rate as discussed above.

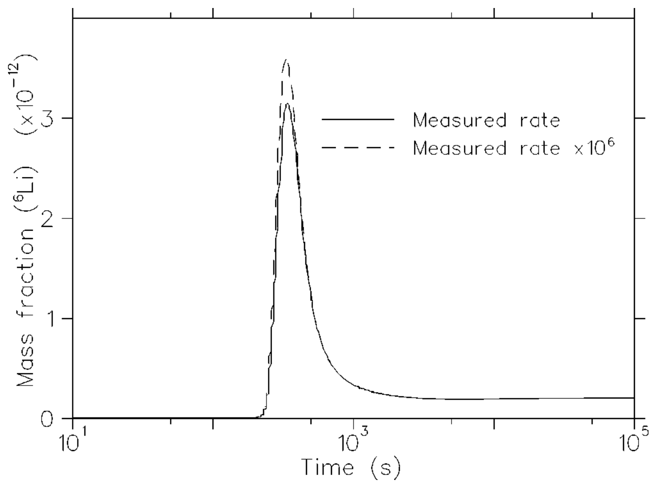

FIG. 4. The ^{6}Li abundence results of IBBN model calculations with the experimentally determined new reaction rate (solid line) and an assumed rate which is larger than the measured rate by a factor of 10^6 (dashed line).

The motivation for this study was the possibility that the ^{8}Li$(d,\alpha)^{6}$He reaction might contribute to the abundance of ^{6}Li in IBBN models. This element has been observed in metal poor stars and may reflect the primordial abundance of ^{6}Li. Thus, its abundance can provide another test of BBN models by providing an additional constraint on the baryon density (η).

The predicted ^{6}Li abundance in the SBBN model is particularly small because of the extremely small reaction cross section of the only reaction by which it is made: ^{2}H$(\alpha,\gamma)^{6}$Li. However, in the IBBN model, ^{6}Li can be synthesized in other ways. In the IBBN formalism two extra processes are included which create the ^{6}Li abundance: ^{8}Li$(d,\alpha)^{6}$He$(\overline{\nu_e}e^-)^{6}$Li and ^{9}Be$(p,\alpha)^{6}$Li. We have performed several IBBN calculations in the parameter space of $\eta=2\times10^{-10}$; $r=50$, 100, 200, and 10^3 cm; $R=10^3$, 10^4; and $f_v{}^{1/3}=0.5$, 0.25, where η is the baryon-to-photon ratio, f_v is the volume fraction of the high-density region, r is the mean separation between fluctuation sites at the time of the QCD phase transition, and R is the ratio of densities of proton-rich to neutron-rich regions.

Our new rate for the $d+{}^{8}$Li reaction has no effect on the production of ^{6}Li or on enhancing the abundances of heavier elements. Thus, our result suggests that this reaction is not important for IBBN model calculations. We also studied what reaction enhancement was required to change the results of the IBBN calculations. By inserting the measured reaction rate for ^{8}Li$(d,\alpha)^{6}$He, multiplied by a factor of 10^6, the maximum mass fraction of ^{6}Li, occurring at a time of about 340 s, increased (Fig. 4) by about 15%, but by the end of BBN returned to the same value of 2.58×10^{-13}. The corresponding maximum in the ^{8}Li abundance was reduced by a factor of about 2. We also determined decreases in CNO abundances of about 15% because of the reduced ^{8}Li abundance. These decreases persisted through the BBN epoch.

We have experimentally determined the total cross section for the reaction ^{8}Li$(d,\alpha)^{6}$He at energies close to those characteristic of big-bang nucleosynthesis and from this deduced the relevant reaction rate. The yield that we have measured could be a sum of $L=0$ and $L=2$ yields, corresponding, respectively, to the yields to the ^{6}He first excited state and the ^{6}He ground state. The measured angular distributions do not select one or the other, but the DWBA results suggest that, if both occur, the $L=2$ cross section will tend to dominate. However, this result pertains to the energies at which we measured the cross sections; at the somewhat lower energies of BBN, the $L=0$ would be expected to dominate. We can, by assuming that all the observed yield is from $L=0$, infer an upper limit on the $L=0$ cross section and, hence, on the astrophysical S factor that should be applied at the lower energies of BBN for this reaction. Since the newly added reaction rate produced no observable effect within the IBBN parameter space we studied, even when enhanced by a huge factor, the results of the inhomogeneous model calculations suggest that our new reaction rate has little influence on the production of ^{6}Li and heavier nuclei: C, N, and O. A possible caveat might arise from uncertainties in the DWBA analysis. The uncertainties associated with the DWBA appear to be far smaller than the enhancements needed for this reaction to have an effect, so would not be expected to influence the conclusions. Thus, barring an extremely strong resonance, in light of the calculations presented here it is unlikely any experimental result could significantly affect the predicted abundances produced in the big bang.

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