PHYSICAL REVIEW C **95**, 055805 (2017)

New measurement of the ^{8}Li(α,n)^{11}B reaction in a lower-energy region below the Coulomb barrier

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(Received 27 August 2016; revised manuscript received 22 March 2017; published 15 May 2017)

The ^{8}Li(α,n)^{11}B reaction is regarded as the key reaction in the inhomogeneous big bang and in type-II supernova nucleosynthesis. Recently, the importance of this reaction to solving the ^{7}Li problem, i.e., the inconsistency between the predicted and the observed primordial ^{7}Li abundances, has also been noted. The most recent cross-section data published by our collaboration group in 2006 [H. Ishiyama *et al.*, Phys. Lett. B **640**, 82 (2006)] cover the 0.7- to 2.6-MeV energy region in the center-of-mass system. Here, we present additional data spanning the 0.45- to 1.8-MeV energy region. Thus, the predominant energy region for the big bang nucleosynthesis, corresponding to $T_9 = 1$ (where T_9 is a temperature unit equivalent to 10^9 K), is almost completely spanned by the previous [H. Ishiyama *et al.*, Phys. Lett. B **640**, 82 (2006)] and present results together.

DOI: 10.1103/PhysRevC.95.055805

I. INTRODUCTION

The ^{8}Li(α,n)^{11}B reaction is considered to be a critical pass-point reaction for the synthesis of CNO elements in the idiosyncratic environments ascribed to the inhomogeneous big bang models [1–3] and type-II supernovae [4,5]. The predominant temperatures are $T_9 = 1$ and $T_9 = 2-3$ for the big bang and supernova nucleosynthesis, respectively, where T_9 is a unit defined as 10^9 K. In particular, this reaction occurs near the Coulomb barrier (the $T_9 = 1$ region) in the case of the inhomogeneous big bang nucleosynthesis and has been intensively studied over the past 3 decades via both theory [6,7] and experiment [8–15].

Because few cosmological observations that support large-scale primordial inhomogeneity exist, the inhomogeneous big bang scenarios may not be considered influential models at present. However, distinctive observations have been made that provide evidence of inhomogeneity in the early universe. For example, the metallicity of the most distant quasars [16] suggests that abundant heavy elements above C may have been produced via primordial nucleosynthesis. Although such high metallicity is not predicted by the standard big bang models, Nakamura *et al.* [17] have shown that this high metallicity can be explained by assuming a small-scale inhomogeneity, which is permitted within the observation limit.

The standard big bang models are strongly supported by the fact that the observed primordial abundances of H, D, ^{3}He, and ^{4}He accord with the predicted values. On the contrary, the calculated ^{7}Li abundances are approximately three or four times larger than the observed values. This inconsistency is known as the ^{7}Li problem. Bertulani and Kajino [18] and Kubono *et al.* [19] have suggested that the framework of the inhomogeneous big bang could provide clues to solve this problem. Even within the framework of the standard big bang, recent studies have been reported in which an extended reaction network incorporating the ^{8}Li(α,n)^{11}B reaction is employed to treat the ^{7}Li problem [20].

Considering these recent discussions, we believe that the ^{8}Li(α,n)^{11}B reaction remains important for understanding nucleosynthesis in the early universe. In this paper, we present additional data on this reaction.

II. EXPERIMENT

In a previous work [8], we presented data for the ^{8}Li(α,n)^{11}B reaction in the center-of-mass energy region between 0.7 and 2.6 MeV. These data cover most of the Gamow-window energies, viz., 0.65–1.95 MeV for $T_9 = 3$, 0.52–1.47 MeV for $T_9 = 2$, and 0.35–0.85 MeV for $T_9 = 1$. Although the previous work was aimed at obtaining cross sections for all energy regions of $T_9 = 1-3$, i.e., 0.35–1.95 MeV, we could not reach the energy region below 0.70 MeV, owing to the high energy of the injected ^{8}Li beams. In the present work, we tried to reach the lower limit of the

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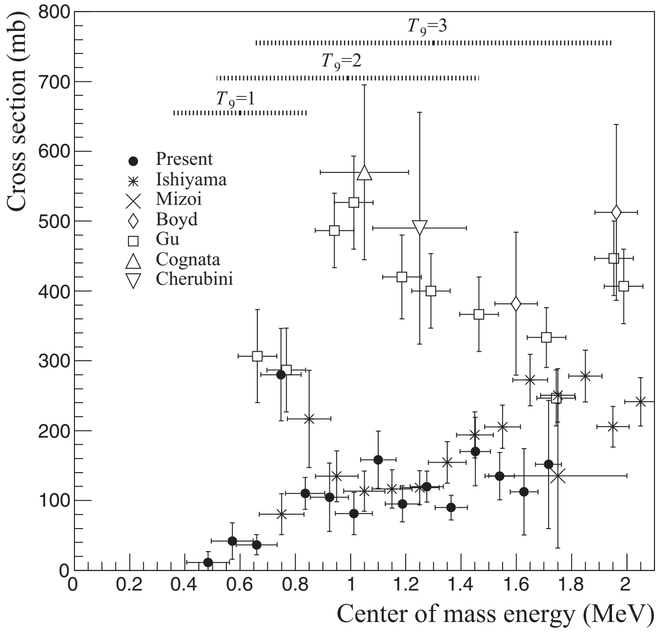

FIG. 1. Cross sections of the ^{8}Li(α,n)^{11}B reaction. The present and previous experimental results are plotted using the indicated markers. Gamow energies corresponding to $T_9 = 1$, 2, and 3 are drawn for reference.

$T_9 = 1$ energy region by decreasing the ^{8}Li-beam injection energy. Previously, we produced ^{8}Li beams with a mean energy of 15.1 MeV by irradiating 24.0-MeV ^{7}Li beams on a 42-μm-thick ^{9}Be target with a tilt angle of 130° with respect to the primary beam axis. Presently, we produce ^{8}Li beams of a mean energy of 12.5 MeV by irradiating 23.0-MeV ^{7}Li beams on a ^{9}Be target of the same thickness as that used previously, with a tilt angle of 140°. The in-flight selection of ^{8}Li ions was performed in the same way as in the previous experiment, where we used the recoil-mass separator at the JAERI tandem accelerator to select ^{8}Li ions [21]. The ^{8}Li-ion energies were measured particle-by-particle using the time-of-flight method. Our detector system [22] consists of an active-target-type gas counter, the MSTPC [23], and segmented plastic-scintillator neutron counters. The energy and momentum of ^{11}B were derived from the MSTPC, and those of the neutrons were determined by the plastic scintillators; therefore, we could exclusively analyze the reaction. The MSTPC was filled with a gas mixture of 90% ^{4}He and 10% CO$_2$, and its pressure was adjusted to be 18.7 and 29.3 kPa in the present and previous experiments, respectively. Through these changes to the experimental conditions, we expected that we could observe the reactions down to 0.35 MeV. The experimental procedure and the analysis method were similar to those used previously [8].

III. RESULTS

Figure 1 shows the present result of the excitation function of the ^{8}Li(α,n)^{11}B reaction. For comparison, other results[8,11–15] are also plotted. Boyd *et al.* [11] and Gu *et al.* [12] measured ^{11}B production, and Cherubini *et al.* [14] and La Cognata *et al.* [15] measured neutron production. Their experimental methods are so-called inclusive measurements; on the other hand, ours [8,13] is an exclusive measurement. The reason for the differences in the cross sections between the former and the latter methods remains unclear. Although we cannot present the reason for the differences based on the present results, the present data show good agreement with the previous exclusive measurements within the error bars in the overlapping energy region.

With the present work, we successfully show additional cross-section data below 0.70 MeV. It should be noted that a resonancelike structure appears around 0.75 MeV, while it appeared around 0.85 MeV in the previous experiment [8]. Their peak energies and heights are consistent within the error bars. The lowest-energy data point is located at 0.48 MeV and 11 mb, where we obtained three events. Here is the statistical limit of the present experiment. Paradellis *et al.* [9] performed the inverse-reaction experiment, $^{11}\text{B} + n \rightarrow \alpha + {}^8\text{Li}$, and presented the cross sections of $^8\text{Li} + \alpha \rightarrow n + {}^{11}\text{B}$ (ground state). Their results, for example, are 7.3 mb for 0.48 MeV, 3.2 mb for 0.44 MeV, and 1.5 mb for 0.38 MeV; therefore, we expected that the cross sections of $^8\text{Li} + \alpha \rightarrow n + {}^{11}\text{B}$ (for all possible states) would be at most on the order of 10 mb, which is consistent with the experimental result.

IV. DISCUSSION

La Cognata *et al.* [24] proposed an idea to solve the discrepancy between the exclusive and inclusive results. They claimed that the discrepancy could be ascribed to the threshold of the neutron detectors. The experiments of Boyd *et al.* [11] and Gu *et al.* [12] only detected ^{11}B and were not ultimately affected by the neutron detection efficiency. Cherubini *et al.* [14] and La Cognata *et al.* [24] only counted the number of neutrons using the ^{3}He gas detector, which could detect thermal neutrons, leading them to conclude that the neutron detection efficiency never affects them. In contrast, we employed a plastic scintillator, whose energy threshold for neutron detection is generally a few hundred keV, for neutron detection. Figure 2 shows the level schemes of the ^{8}Li(α,n)^{11}B reaction system. Intermediate states of compound ^{12}B* are not drawn, because they are out of the scope of the present discussion. A neutron is emitted with a lower kinetic energy if ^{11}B is produced in a higher excited state. The excited states of ^{11}B are well established. Thus, we can do a kinematics calculation to derive neutron energies by assuming a reaction energy. The neutron energies as a function of the laboratory angle are plotted in Fig. 3, assuming that a reaction occurs at a center-of-mass energy of 1.05 MeV, where the cross-section difference is the largest. The energy distributions of neutrons for each state of ^{11}B are drawn. La Cognata *et al.* [24] performed GEANT simulations and concluded that our plastic scintillators had an energy threshold of 500 keV. Their simulation results insist that most parts of the neutrons emitted from the highly excited ^{11}B could not be detected by our detectors. Therefore, the undetectable neutrons diminish our cross sections.

We investigate their claim herein. As described in Ref. [22], we measured the detection efficiency of the neutron counters

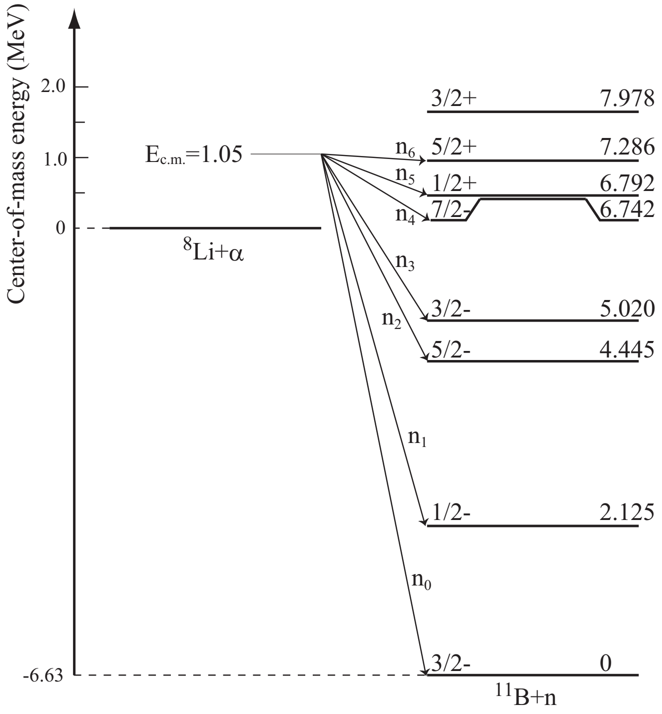

FIG. 2. Level scheme of the $^{8}\mathrm{Li} + \alpha \rightarrow {}^{11}\mathrm{B} + n$ reaction. n_i indicates a neutron going to each state of ^{11}B, assuming that a reaction occurs at the center-of-mass energy, $E_{\mathrm{c.m.}} = 1.05$ MeV.

by using a ^{252}Cf fission source and a derived valid value of the detection efficiencies down to 200 keV. For additional information, we introduced the other experiments performed by Miyatake *et al.* [25], who are among the coauthors of this paper. They measured 380-keV neutrons from a β-delayed decay of ^{17}N using a plastic scintillator, called the BICRON BC408, which was the same as the model we used in the exclusive experiments. The plastic scintillators provided an effectual performance of detecting a few-hundred-keV neutron. These facts implied that a 500-keV threshold was irrational in discussing the discrepancy. For further investigation, we explained the reason why we did not consider the neutron-energy threshold affecting the exclusive results. Figure 4 shows the solid-angle ratios of the center-of-mass system with respect to the laboratory system as a function of the laboratory angle. These curves presented forward peaks caused by the effect of kinematic focus. The neutrons emitted from a higher excited state of ^{11}B presented a stronger forward distribution. As shown in Fig. 3, all the forward neutrons had a sufficiently high energy to be detected by the plastic scintillators.

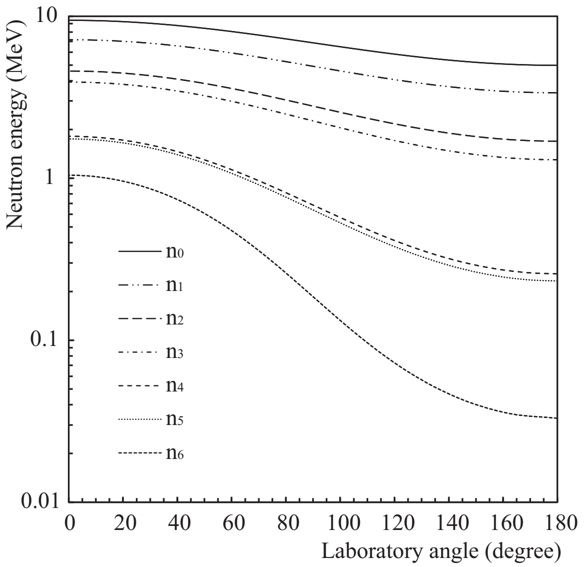

FIG. 3. Neutron energy as a function of laboratory angle. Assuming that reaction occurs at $E_{\mathrm{c.m.}} = 1.05$ MeV and that ^{11}B is excited in each state.

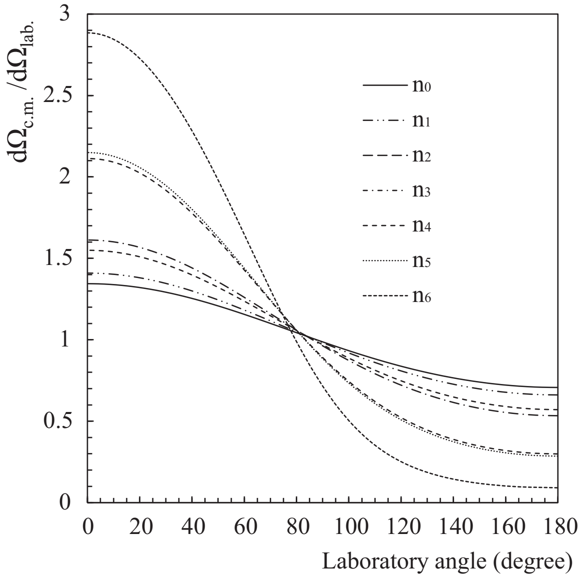

FIG. 4. Solid-angle ratio of the center-of-mass system ($\Omega_{\mathrm{c.m.}}$) with respect to the laboratory system ($\Omega_{\mathrm{lab.}}$) as a function of laboratory angle. Assuming that the reaction occurs at $E_{\mathrm{c.m.}} = 1.05$ MeV and that ^{11}B is excited in each state.

As regards the lower-energy region, the cross sections around 0.8 MeV, where the resonancelike structure appeared, concurred with those obtained by Gu *et al.* [12]. This consistency was paradoxical. Therefore, we considered that the threshold of the neutron counters should not be the key to solving the discrepancy.

V. SUMMARY AND OUTLOOK

We now summarize the present work. We present new data regarding the ^{8}Li(α,n)^{11}B reaction for the energy region between 0.45 and 1.80 MeV. This work added new points in the excitation function in the lower-energy region of $T_9 = 1$. By considering the previous and present results, the peak energy of the resonancelike structure would be located between 0.75 and 0.85 MeV. To determine the peak energy more precisely, we should perform an experiment with an improved energy resolution of the ^{8}Li beams. In addition, we could explore the lower-energy few-millibarn region by improving the beam intensity. An experiment with an isotope-separation-online-type accelerator is a candidate for our next project.

We hope that the preset result will provide further understanding of the ^{7}Li problem together with other network reactions. On the other hand, the source of the discrepancy between the exclusive and inclusive results remains unclear. As Kubono *et al.* [19] have noted, experiments using other methods should be designed to solve this problem.

ACKNOWLEDGMENTS

This work was supported by MEXT (Japan) KAKENHI, Grant No. JP15340085 and JSPS (Japan) KAKENHI, Grant No. JP05F05308.

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