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Experimental study on the ^{7}Be(n, p)^{7}Li and the ^{7}Be(n, α)^{4}He reactions for cosmological lithium problem

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We have measured two important neutron-induced reactions ^{7}Be(n, p)^{7}Li and ^{7}Be(n, α)^{4}He which are supposed to reduce the primordial abundance of ^{7}Li in the Big-Bang nucleosynthesis. We applied the Trojan Horse method by using a ^{7}Be radioactive isotope beam with the Center-for-Nuclear-Study Radioactive Isotope Beam separator in inverse kinematics. The preliminary excitation functions suggest that the (n, p_0) and the (n, α) channels are basically consistent with the recent experimental studies, and the first-ever data of the (n, p_1) channel may provide a significant extra contribution. We also performed a multi-channel R-matrix analysis to these three channels, confirming the present and the previous data from the point of view of the resonance structure. The result over the thermal neutron energy to the order of mega electron volt enables us to discuss the possible revision of the reaction rate and its impact on the cosmological lithium problem.

KEYWORDS: Trojan Horse method, Radioactive isotope beam, Cosmological Li problem, Big Bang Nucleosynthesis

1. Introduction

It has been known for decades that the prediction of the primordial ^{7}Li abundance by the standard Big-Bang Nucleosynthesis (BBN) model [1] is about 3 times larger than the observation [2], which is the so-called cosmological ^{7}Li problem. Although a number of ideas have been proposed to solve it [3], no consensual solution has been determined yet. As the basis for any BBN models, nuclear reaction rates involved in the BBN should be accurately evaluated, as there are still lack or incompleteness of data near the BBN energies. The radiogenic ^{7}Li abundance by the BBN strongly depends on the ^{7}Be production and destruction rates rather than those of ^{7}Li itself. This is because the survived ^{7}Be will eventually decay into ^{7}Li via the electron capture after the BBN ends, while ^{7}Li may immediately be destroyed through the ^{7}Li$(p,\alpha)^{4}$He reaction during the BBN. The neutron-induced reactions on ^{7}Be are expected to have the larger contribution than other possible charged-particle-induced reactions due to the abundance of neutron in the BBN era and its lacking of Coulomb barrier. However, such experimental data still lack information in the BBN energy range arising from the experimental difficulties that both nuclides n and ^{7}Be are radioactive.

The ^{7}Be$(n,p)^{7}$Li reaction is considered as the main process to destroy ^{7}Be. Recently, a direct measurement has been performed at the n_TOF facility [4], revising the cross sections upward from the previous direct data [5]. However, this experiment with a neutron beam suffered from the ^{14}N(n,p) background as the neutron beam energy increases, and the data in the BBN energy region still have large uncertainties. The derived reaction rate in the BBN temperature region thus has a limited enhancement from the widely-adopted reaction rate [6]. In spite of the update on the ^{7}Be$(n,p_0)^{7}$Li reaction, the contribution of the transition to the first excited state of ^{7}Li, ^{7}Be$(n,p_1)^{7}$Li*, at the BBN energies has never been discussed sufficiently, which motivated us to perform a further experiment. Another important neutron-induced reaction channel ^{7}Be$(n,\alpha)^{4}$He has not been investigated either until recently [7–11], still lacking in direct data with reasonable uncertainties at the BBN energies. Thus studies of the both reactions are still needed to determine the total ^{7}Be+n cross section contributing in the BBN energy region.

2. Experimental Method

To avoid experimental difficulties in direct measurement arising from use of the ^{7}Be target and the neutron beam, we performed an indirect measurement by applying the Trojan Horse method (THM) [12–14]. For our case, the THM allows measurement of the cross section of a two-body reaction ^{7}Be$(n,p)^{7}$Li (or ^{7}Be$(n,\alpha)^{4}$He) by properly selecting the quasi-free (QF) component of a suitable two-to-three-body reaction ^{2}H(^{7}Be,^{7}Lip)^{1}H (or ^{2}H(^{7}Be,$\alpha\alpha$)^{1}H). Deuteron is known as a successful "Trojan horse" (TH) nucleus to perform QF reactions thanks to its configuration $d = n \oplus p$ with a relatively low n–p binding energy. We selected the proper kinematics so that the neutron inside the TH deuteron took part in the binary process with ^{7}Be as the "participant", while the proton acted as the "spectator" which maintained the same momentum distribution as inside the deuteron before and after the breakup. One of the advantages of the THM is that the sub-process ^{7}Be–n can approach astrophysically-relevant low energies by releasing the n–p binding energy although the induced energies can be selected well above the Coulomb barrier of the ^{7}Be+d interacting channel. In the most simple theoretical description of THM by means of the plane wave impulse approximation, the cross section of the QF reaction ^{2}H(^{7}Be,^{7}Lip)^{1}H (or ^{2}H(^{7}Be,$\alpha\alpha$)^{1}H) can be proportional to the one of the binary processes ^{7}Be$(n,p)^{7}$Li (or ^{7}Be$(n,\alpha)^{4}$He) via the formula [13, 14]

$$\frac{d^3\sigma}{dE\,d\Omega_p\,d\Omega_{^7\mathrm{Be}}} \propto \mathrm{KF}\cdot|\Phi(p_{np})|^2\cdot\frac{d\sigma}{d\Omega_{\mathrm{c.m.}}}^{\mathrm{HOES}}, \quad (1)$$

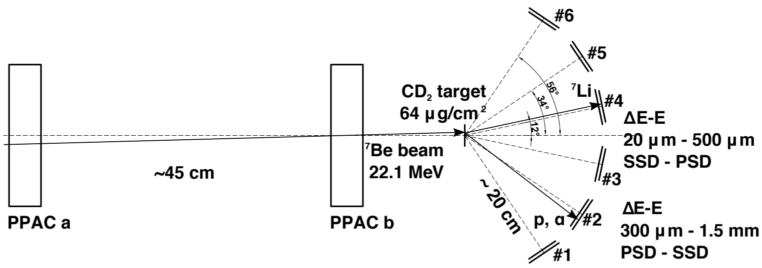

Fig. 1. Schematic view of the experimental setup.

where KF represents the kinematic factor, $|\Phi(p_{np})|^2$ is the square of the Fourier transform of the radial wave function describing the n–p intercluster motion, and $\frac{d\sigma}{d\Omega}^{\rm HOES}_{\rm c.m.}$ is the half-off-energy-shell (HOES) differential cross section for the two-body reaction of interest. Historically TH deuteron has been used for many proton-induced reaction measurements, and recently usability for neutron-induced reaction measurmenets has also been proved [15, 16]. A former study of the ^{7}Be$(n, \alpha)^4$He reaction via the ^{2}H(^{7}Be$, \alpha\alpha)^1$H reaction is already performed [11] in collaboration with the present work. In that experiment, we observed α–α coincidence only, aiming at deducing the ^{7}Be$(n, \alpha)^4$He reaction cross section at the BBN energies.

We performed the THM experiment with a ^{7}Be beam at the CRIB (Center-for-Nuclear-Study Radioactive Isotope beam separator [21]) facility. We aimed at measuring not only the ^{7}Be$(n, \alpha)^4$He reaction but also the ^{7}Be$(n, p)^7$Li reaction by expanding the idea of the former collaborating experiment [11]. We installed six ΔE–E telescopes as shown in Fig. 1. The larger-angle telescopes #1, #2, #5 and #6 were responsible for light-particle detection such as protons and α particles, while the forward-angle telescopes #3 and #4 aimed at the heavy ion ^{7}Li appearing in the exit channel of the ^{2}H(^{7}Be,^{7}Li$p)^1$H reaction which were not used in [11] experiment. With this telescope configuration, the ^{2}H(^{7}Be,^{7}Li$p)^1$H reaction was observed by detecting ^{7}Li–p coincidence in telescope pairs of #3–#5, #3–#6, #4–#2 or #4–#1 covering the QF kinematics. The α–α coincidence measurement were simultaneously available as well in telescope pairs of #1–#5 or #2–#6 with the same setup. The present setup allows better angular and energy resolutions than those of the former work [11] by installing Parallel Plate Avalanche Counters (PPACs [22]) for event-by-event beam tracking, a thinner CD_2 target of 64 μg/cm^2, silicon detectors with a better position resolution, and with a higher incident beam energy with smaller energy spread of 22.1±0.1 MeV. The ΔE–E particle identification was successful to select the particles of interest such as ^{7}Li, α and protons.

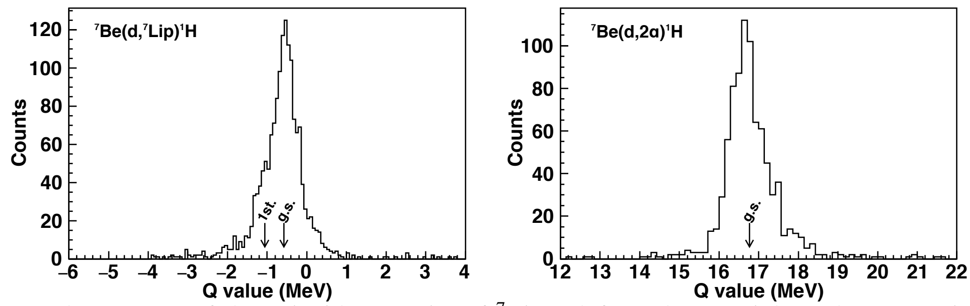

Fig. 2. Q-value spectra of the coincidence pairs of ^{7}Li–p (left) and α–α (right). The arrows indicate the known Q values of the ^{7}Be(d,^{7}Li$p)^1$H reaction for the ground state and the first excited state of ^{7}Li, and the ^{7}Be$(d, \alpha\alpha)^1$H reaction, respectively.

3. Result and discussion

By selecting coincidence pairs of ^{7}Li–p or α–α, we confirmed that the reconstructed Q-value spectra were consistent with the known Q values of ^{7}Be(d,^{7}Lip)^{1}H (−0.580 MeV), ^{7}Be(d,^{7}Li$^*p_1$)^{1}H (−1.058 MeV) and ^{7}Be($d, \alpha\alpha$)^{1}H (16.766 MeV), respectively. Figure. 2 shows the Q-value spectra observed in the coincidence pairs of ^{7}Li–p (left) and α–α (right) with the corresponding Q values indicated by arrows. We also confirmed that the momentum distributions of the spectator proton in the exit three-body channels are consistent with that of the well-known p–n intercluster motion inside the deuteron nucleus expressed by the Hulthén function in momentum space, both for the ^{7}Be(d,^{7}Lip)^{1}H and the ^{7}Be($d, \alpha\alpha$)^{1}H data. Figure 3 describes that the QF mechanism well appears at least in the lower momentum regions. We decided to adopt the data cut by $|p_s| < 60$ MeV/c for the further analysis.

As for the penetrability correction and normalization of the HOES cross section, the ^{7}Be(n, α)^{4}He excitation function near the neutron threshold is expected to be characterized mostly by the p-wave resonant states due to the parity conservation. The present p-wave-corrected excitation function appears consistent with the previous data [7,9] in a wide energy range up to 2 MeV. For the ^{7}Be(n, p_0)^{7}Li reaction, the s-wave penetrability (thus no centrifugal barrier) seems consistent with the data deduced from the time-reversal reactions [23, 26], and also with the existence of the s-wave 2^- state near the neutron threshold as mentioned later. We obtained the p_0/p_1 ratio of the HOES cross sections as a function of the excitation energy by the Gaussian fitting to the Q-value spectra. The ^{7}Be(n, p_1)^{7}Li* channel is observed for the first time around the BBN energies, and assumed to be corrected and normalized in the same manner as the (n, p_0) channel. The normalized ^{7}Be(n, p_1)^{7}Li* cross section may smoothly connect from mega electron volts to the thermal neutron data from Ref. [4, 5] by the $1/v$ law.

A multi-channel R-matrix analysis was desired to confirm the penetrability correction and the normalization of the present THM data more strictly from the point of view of the resonance structure in the compound nucleus ^{8}B. It may also help with interpolation and extrapolation of the data for the reaction rate calculation. We expect that a comprehensive explanation of these three channels may confirm the reliability of both the present and the previous data. In the previous R-matrix analysis work [27], four dominant partial waves were selected, which characterize the basic resonant features of the ^{7}Be(n, p)^{7}Li reaction; 1) the 2^- resonance at E_x = 18.91 MeV ($E_{\mathrm{c.m.}}$ = 2.7 keV) dominantly enhances the cross section in a wide energy range from the neutron threshold up to mega electron volts, 2) the resonance at $E_{\mathrm{c.m.}} \sim 330$ keV corresponds to the doublet 3^+ states at 19.07 and 19.24 MeV which are supposed to have different isospin structures: the former essentially decays through

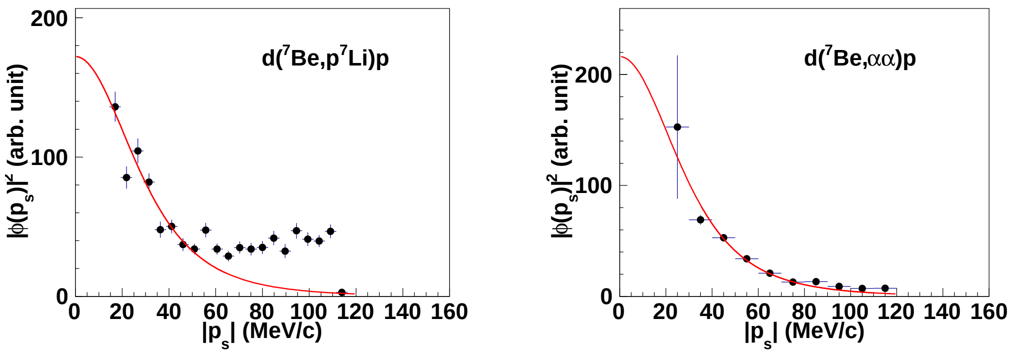

Fig. 3. Momentum distributions of the spectator proton in the ^{2}H(^{7}Be,^{7}Lip)^{1}H channel (left) and the ^{2}H(^{7}Be, $\alpha\alpha$)^{1}H channel (right). The red solid lines indicates those of p–n intercluster motion inside deuteron nucleus described by the well-known Hulthén function in momentum space.

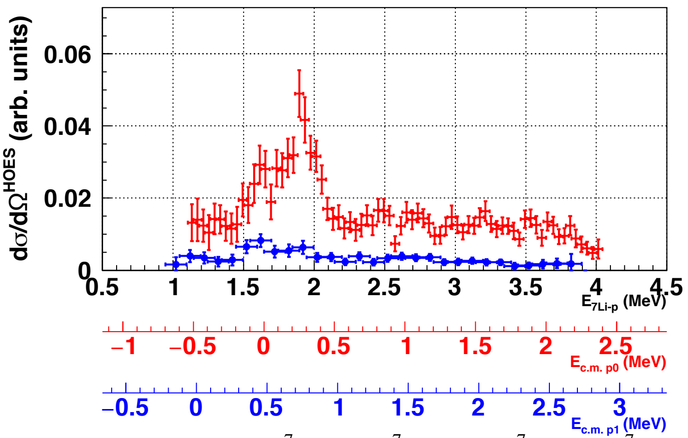

Fig. 4. HOES differential cross sections of the ^{7}Be$(n, p_0)^7$Li and the ^{7}Be$(n, p_1)^7$Li* channels as functions of the ^{8}Be excitation energy. Axes of the center-of-mass energy for the (n, p_0) and the (n, p_1) channels are also displayed together.

proton emission whereas the latter presents a substantial ratio in the neutron channel, thus only the latter was adopted, 3) the 3^+ state at 21.5 MeV well reproduces the resonance at $E_{\text{c.m.}} \sim 2.66$ MeV, 4) A 2^+ non-resonant state was needed to express the high-energy enhancement of the cross section as the "background contribution". Based on the above study, we expanded the *R*-matrix analysis to the p_1 and α channels as well on simple conditions as follows; 1) fixing the known J^π and the resonance energies, 2) adopting partial waves with only $l \leq 3$ angular momenta, 3) excluding the excited states with no neutron emission reported, 4) fitting only at $E_{\text{c.m.}} < 1.2$ MeV. The *R*-matrix fitting was performed using AZURE2 code [28]. The procedure of fitting is then; 1) starting from the n and p_0 channels with parameters taken from Ref. [27], 2) fixing the p_0 parameters, and fitting only the n, p_1 and the α channels, 3) fixing the p_1 and α channels, and fitting the n and p channels again, 4) fixing converged parameters and iterating the above. Then the χ^2 apparently converged close to unity. We successfully reproduced the basic features of these excitation functions [4, 5, 7–10, 23, 26] simultaneously with most partial widths not to violate the known total widths nor the Wigner limits. The peak in the (n, p_1) channel around $E_{\text{c.m.}} \sim 0.5$ MeV is very likely to arise from 1^- resonant state at $E_x = 19.5$ MeV, which may characterize the cross section around the BBN energy region. The fact that this *s*-wave resonance is dominant supports the validity of the penetrability correction described above. A possible variation in the (n, p_1) cross section was also estimated by varying the p_1 partial width and the resonance energy of the 1^- state from the best-fit values to reproduce the 1σ deviation of the experimental data. Accordingly, the (n, p_1) reaction cross section would amount up to about 10% of that of (n, p_0) at the relevant energies below 100 keV. By combining the above result and the latest (n, p_0) reaction cross section [4], the total ^{7}Be$(n, p)^7$Li reaction rate may be about 15% higher than that of Ref. [2] in the BBN temperature range, which may result in about a 10% reduction of the primordial ^{7}Li abundance according to the sensitivity to this reaction [2]. Definitive numbers of the resonance parameters will come out with further data analysis and confirmation.

4. Summary

We performed the THM measurements of the BBN reactions ^{7}Be$(n, p)^7$Li and ^{7}Be$(n, \alpha)^4$He simultaneously via the ^{7}Be$(d,^7$Li$p)^1$H and the ^{7}Be$(d, \alpha\alpha)^1$H reactions, respectively, at CRIB. The preliminary excitation functions for the (n, p_0) and the (n, α) channels are roughly consistent with the previous studies. In addition, we showed that the BBN energy region is accessible with our measurement and there is possible significant contribution of ^{7}Be$(n, p_1)^7$Li*. We are currently aiming to confirm the normalization and penetrability correction of the present THM data by performing a multi-channel *R*-matrix analysis. We successfully fitted the excitation functions with reasonable parameter sets from the point of view of the resonance structure. The ^{7}Be(n, p_1)^{7}Li* contribution to the reaction rate may account for about 1/10 of that of (n, p_0) channel thanks to the possible enhancement of the cross section by the 1^- state at E_x = 19.5 MeV.

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