Time-reversal measurement of the p-wave cross sections of the ^{7}Be$(n,\alpha)^4$He reaction for the cosmological Li problem

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The primordial abundances of the light elements produced in the Big Bang nucleosynthesis (BBN) provide important insights into the early universe. Accurate estimation of the primordial abundances is crucial to test the cosmological theories by comparing the predicted values with the observations.

A comparison between the theoretical predictions and the observations is in good agreement with those for the helium and deuterium. However, there remains a serious problem: The ^{7}Li abundance does not agree with any theoretical BBN calculations. This discrepancy is known as the cosmological lithium problem, and has been of great interest in recent years [1]. Several ideas have been proposed to solve this problem. One idea is to improve the current understanding of the stellar processes that exhaust lithium in metal-poor stars. Other ideas are to find new physics beyond the standard BBN model, *e.g.*, cosmological variation of fundamental constants [2], decay of supersymmetric particles [3], and so on. However, there is no experimental evidence to confirm these models.

From a view of nuclear physics, nuclear-reaction rates involved in the BBN theory should be examined. The main process of the ^{7}Li production in the BBN is the electron-capture decay of ^{7}Be, which is synthesized in the ^{3}He(^{4}He,γ)^{7}Be reaction. Direct measurements of the cross section for the ^{3}He(^{4}He,γ)^{7}Be reaction were extensively carried out in the past, and uncertainties in this thermonuclear reaction rate are now very small. There is no room to modify the ^{7}Be production rate to solve the lithium problem [4].

It was pointed out that the ^{7}Li abundance will be greatly reduced in the BBN calculation if the destruction rate of ^{7}Be is enhanced. One of the candidate channels to destruct ^{7}Be is the ^{7}Be(n,α)^{4}He reaction. Unfortunately, the ^{7}Be(n,α)^{4}He reaction at the cosmological energy has been scarcely examined. In the present work, we have measured the cross section for the ^{4}He(α,n)^{7}Be reaction, which is the time reverse reaction of the ^{7}Be$(n,\alpha)^4$He reaction. On the basis of the detailed balance principle, we obtained the cross sections for the ^{7}Be(n,α)^{4}He reaction at low energies of $E_{c.m.}$ = 0.20–0.81 MeV close to the BBN energy window for the first time.

The experiment was carried out at the N0 course in Research Center for Nuclear Physics (RCNP), Osaka University [5]. An α beam accelerated by the AVF cyclotron was transported to the He gas target in the beam swinger magnet. The scattered neutrons were detected by a BC-501A liquid scintillation detector located at 13-m away from the target. The sensitive volume of the scintillation detector was a cylindrical shape with the diameter of 200 mm and the depth of 50 mm along the neutron trajectory. A conventional pulse-shape discrimination technique was used to distinguish neutrons from γ rays. The detection efficiency of neutrons by the BC-501 liquid scintillation detector was estimated by using the computer code SCINFUL-CG [6]. We also measured the neutron detection efficiency using the tagged neutrons emitted from the $d + d \to {}^3$He $+ n$ reaction. The calculated efficiency agrees with the measurement within the measurement uncertainties.

A He gas target was used in the present work. The He gas was filled at 1 atm in the target cell with the effective length of 6.3 cm. The target cell has the entrance and exit windows with the diameter of 12 mm, and those windows are sealed with the 6-μm aramid films. The window material was carefully chosen from three candidates (tantalum, Havar alloy, and aramid) through the background measurements and its thickness was optimized by the mechanical consideration of the breaking strength. The mass thicknesses of the He gas and aramid films were 1.0 and 1.7 mg/cm^2, respectively, and the energy loss of the α beam in the He gas target was about 0.5 MeV. The temperature and pressure of the He gas were monitored during the measurement.

A typical neutron-energy spectrum in the ^{4}He(α,n)^{7}Be reaction measured at $E_\alpha = 39.30$ MeV and $\theta_{lab} = 0°$ is shown in Fig. 1. The two prominent peaks due to the ground $(3/2_1^-)$ and first excited $(1/2_1^-)$ states are clearly observed on the continuous background due to the window films in Fig. 1(a). The background-free spectra were successfully obtained by subtracting background spectra taken from the empty-cell measurement as seen in Fig. 1(b).

The measured ^{4}He(α,n)^{7}Be cross sections for the ground and first excited states in ^{7}Be were separately converted to the cross section for the time reverse reactions on the basis of the detailed balance principle.

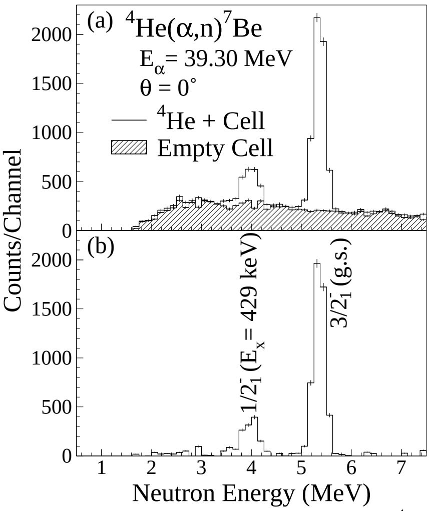

Figure 1: Neutron energy spectra in the ^{4}He(α,n)^{7}Be reaction measured at $E_\alpha = 39.30$ MeV and $\theta_{lab} = 0°$.

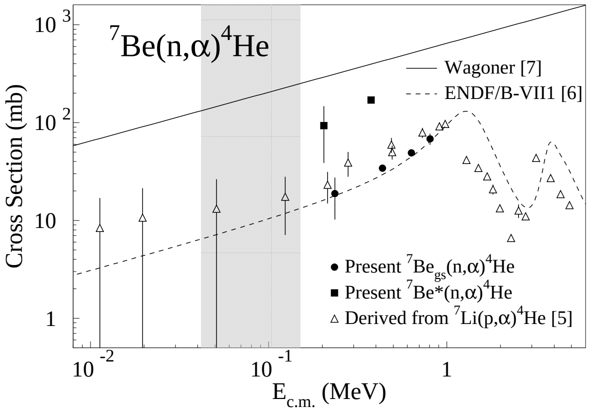

Figure 2: Measured total cross sections for the ^{7}Be(n,α)^{4}He reaction compared with the previous evaluations.

The solid circles and squares in Fig. 2 show the total cross sections of the (n, α) reaction on the ground and first excited states in ^{7}Be. The shaded area presents the effective-energy window for the p-wave reaction at $T_9 = 0.6$–0.8.

The cross sections evaluated by the indirect methods are compared with the present results. The estimation from $p + {}^7$Li scattering [7] is plotted by the open triangles in Fig. 2, whereas the cross section from the evaluated nuclear data library ENDF/B-VII.1 [8] based on the R-matrix analysis of several indirect reactions is shown by the dashed line. It was found that these evaluated cross sections are very close to the present data for the ^{7}Be$_{g.s.}$(n,α)^{4}He reaction.

The cross section for the ^{7}Be(n,α)^{4}He reaction was first estimated by Wagoner [9] as shown by the solid line in Fig. 2. Currently, this evaluation is widely used in the BBN calculations. The present values of the ^{7}Be(n,α)^{4}He cross sections are much smaller than the Wagoner's calculation. Thus, we concluded that the present results suggest that the ^{7}Be(n,α)^{4}He reaction does not solve the cosmological lithium problem.

The present work was performed primarily as a graduation research by the undergraduate senior students at Kyoto University (KADAIKENKYU P4) over the three school years. All the processes of the research project, *i.e.*, planning, development, measurement, and analysis were done by the undergraduate students under the supervision of the faculties. The authors are grateful to RCNP for the deep understanding about the importance of the undergraduate education through the hands-on training at the large accelerator facility. The authors also thank the cyclotron crews at RCNP for their efforts to provide a clean and stable beam, and Prof. T. Wakasa from Kyushu University for his kind support to carry out the present measurement at the neutron time-of-flight facility. This work was supported by JSPS KAKENHI Grant Numbers JP26287058 and JP15H02091.

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