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 cross sections of the ^{7}Be$(n, \alpha)^4$He reaction for *p*-wave neutrons were experimentally determined at $E_{\text{c.m.}} = 0.20$–0.81 MeV slightly above the big bang nucleosynthesis (BBN) energy window for the first time on the basis of the detailed balance principle by measuring the time-reverse reaction. The obtained cross sections are much larger than the cross sections for *s*-wave neutrons inferred from the recent measurement at the n_TOF facility in CERN, but significantly smaller than the theoretical estimation widely used in the BBN calculations. The present results suggest the ^{7}Be$(n, \alpha)^4$He reaction rate is not large enough to solve the cosmological lithium problem, and this conclusion agrees with the recent result from the direct measurement of the *s*-wave cross sections using a low-energy neutron beam and the evaluated nuclear data library ENDF/B-VII.1.

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 for testing cosmological theories by comparing the predicted values with the observations.

The BBN theory relies on nuclear reactions among primordial light elements and their electroweak decays. This theory has only one free parameter "baryon density," which is related to the baryon-to-photon ratio. A precise value for the baryon density was reported from the anisotropy analysis of the cosmic microwave background by the Planck satellite [1].

The theoretical predictions of the primordial abundances agree reasonably well with the observations for helium and deuterium. However, there remains a serious problem that the ^{7}Li abundance does not agree with any theoretical BBN calculations. The primordial abundance of ^{7}Li inferred from observations of metal-poor stars is ^{7}Li/H $= 1.6 \pm 0.3 \times 10^{-10}$ [2], whereas the calculated values by the BBN theory is as large as ^{7}Li/H $= 4.68 \pm 0.67 \times 10^{-10}$ [3]. This discrepancy is known as the cosmological lithium problem, and has been of great interest in recent years.

Several ideas have been proposed for solving this problem [4]. 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 [5], decay of

supersymmetric particles [6], 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, $\gamma)^7$Be reaction. Direct measurements of the cross section for the ^{3}He$(^4$He, $\gamma)^7$Be reaction were extensively carried out in the past by several groups, 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 [7].

Recently, 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$(n, \alpha)^4$He reaction.

The effective energy windows for the neutron induced reactions are given in Ref. [8] as $E_0 \pm 1/2\Delta E_0$ where $E_0 = 0.086(l + 1/2)T_9$ MeV and $\Delta E_0 = 0.097(l + 1/2)^{1/2}T_9$ MeV. For *s*-wave neutrons at low energies, the cross sections follow the $1/v$ rule; i.e., the cross sections are inversely proportional to the velocity of neutrons [9]. Therefore, the reaction rate has a peak at lower energies, whereas the centrifugal barrier shifts the effective energy to higher energies for higher partial waves. At the BBN temperature around $T_9 \sim 0.7$, the effective energy window is $E = 30 \pm 24$ and 90 ± 42 keV for the *s*- and *p*-wave neutrons, respectively. Unfortunately, few highly uncertain

data on the cross section of the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction at the cosmological energy are available to date.

Since ^7Be is a short-lived nucleus, it is not easy to directly measure the cross section for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction. This reaction cross sections were previously measured at the thermal energy much lower than the BBN energy [10]. Very recently, the cross section for this reaction was measured using a radioactive ^7Be target irradiated by a low-energy neutron beam at 10 meV–10 keV [11]. In this measurement, two α particles emitted from the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction were detected.

Such low-energy reactions proceed via the s wave only. Actually, the energy dependence of the measured cross section in Ref. [11] agrees with the $1/v$ rule, and therefore, no sizable p-wave component was observed at $E_n < 10 \text{ keV}$. This result suggests the p-wave cross section is less than a few hundreds μb at $E_n \sim 10 \text{ keV}$. In the s-wave reaction, negative-parity states at $E_x \sim 19 \text{ MeV}$ near the neutron-decay threshold in ^8Be are formed, at first. Since the direct 2α decay of these negative-parity states is forbidden due to the parity conservation, the two α particles must be emitted after the γ decay populating low-lying positive natural-parity states. The branching ratio of the electromagnetic decay above the particle emission threshold is generally small, and thus, the cross section for the ^7Be destruction by s-wave neutrons is suppressed.

Among various positive natural-parity states in ^8Be populated by the γ decay, the dominant decay channels proceed through the ground (g.s.) and first excited states because the $E1$ decay probability is proportional to the cube of the decay energy. However, these dominant channels were not measured in Ref. [11] due to difficulties in the low-energy α-particle detection, but the minor decay channels emitting the high-energy α particles via the positive natural-parity states at $E_x > 8 \text{ MeV}$ in ^8Be were measured. The branching ratio between the dominant and minor decay channels was inferred by the theoretical calculation assuming the direct radiative capture mechanism [12]. It should be noted that the total $^7\text{Be}(n, \alpha)^4\text{He}$ cross section for the s-wave neutrons was estimated to be as small as a few mb in the BBN energy window, and the s-wave reaction does not contribute to solving the cosmological lithium problem.

Contrary to the s-wave reaction, where the cross section decreases with the increasing neutron energy according to the $1/v$ rule, the p-wave reaction might become dominant in the BBN energy window. The p-wave cross sections can be determined by measuring the time-reverse $^4\text{He}(\alpha, n)^7\text{Be}$ reaction on the basis of the detailed balance principle. Since resonance states in ^8Be formed by the $\alpha + \alpha$ collision must be positive natural-parity states, these states decay to the ground and first excited states in ^7Be by emitting p-wave neutrons.

The cross section for the $^4\text{He}(\alpha, n)^7\text{Be}$ reaction at the lowest energy ever measured was reported in Ref. [13].

Residual ^7Be nuclei were implanted in aluminum foil, and the number of ^7Be in the foil was determined by the off-line measurement. Although the cross sections leading to the ground and first excited states in ^7Be could not be separated, one can estimate the upper limit of the cross section for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction from the previous data. However, the lowest reaction energy of $E_{\text{c.m.}} = 0.7 \text{ MeV}$ is much higher than the BBN energy window, and this result is not directly related to the cosmological lithium problem.

The cross sections for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction at $E_{\text{c.m.}} = 0.0113$–5.754 MeV were calculated from the cross section for the mirror reactions $^7\text{Li}(p, \alpha)^4\text{He}$ and $^4\text{He}(\alpha, p)^7\text{Li}$ by assuming the charge symmetry [14]. However, whether or not the charge symmetry is still a good approximation at low reaction energies near the threshold is not trivial. Therefore, the direct measurement of the $^4\text{He}(\alpha, n)^7\text{Be}$ reaction at the cosmological energies was strongly desired.

In the present Letter, we have measured the cross section for the $^4\text{He}(\alpha, n)^7\text{Be}$ reaction at low reaction energies. The final states in the residual ^7Be nucleus were unambiguously identified by the on-line spectroscopy of the scattered neutrons. On the basis of the detailed balance principle, we have successfully obtained the cross sections for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction at $E_{\text{c.m.}} = 0.20$–0.81 MeV slightly above the BBN energy window for the first time.

The experiment was carried out at the neutron time-of-flight facility in the Research Center for Nuclear Physics (RCNP), Osaka University [15]. An α beam accelerated up to 39.89 or 39.56 MeV was transported to a He gas target in the beam swinger magnet. During the measurement using the α beam at 39.56 MeV, aluminum plates with the thicknesses of 12 and 24 μm were installed in the beam line to degrade the beam energy to 39.15 and 38.76 MeV. Background particles caused by the beam degraders were swept away with the bending magnets and movable collimator system before the target. Taking the energy loss in the target into account, the beam energies at the center of the He gas target were determined to be 39.64, 39.30, 38.90, and 38.50 MeV as the nominal beam energies in the present Letter. These beam energies are close to the threshold energies at $E_\alpha = 37.98$ and 38.84 MeV for the $^4\text{He}(\alpha, n)^7\text{Be}$ reaction leading to the ground state and the first excited state at $E_x = 429 \text{ keV}$ in ^7Be, respectively. The uncertainties of the beam energies were estimated at 40 keV, while the reaction energies fluctuated about $\pm 100 \text{ keV}$ depending on the position where the reaction occurred in the target due to the difference in the energy loss of α particles.

The scattered neutrons at $E_n = 2$–7 MeV were detected by a BC-501A liquid scintillation detector, which was 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. The detection threshold of the light

output from the BC-501A liquid scintillator was set at 0.153 MeVee. A conventional pulse-shape discrimination technique was applied to distinguish neutrons from γ rays. The detection efficiency of neutrons by the BC-501A liquid scintillation detector was estimated by using the computer code SCINFUL-CG [16]. We also measured the neutron detection efficiency at $E_n = 2.5$, 4.9, and 8.1 MeV using the tagged neutrons emitted from the $d + d \rightarrow {}^3\text{He} + n$ reaction. The measured efficiency was 0.323 ± 0.014, 0.302 ± 0.020, and 0.201 ± 0.017 at $E_n = 2.5$, 4.9, and 8.1 MeV, respectively. The calculated efficiency agrees with the measurement within the measurement uncertainties.

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, which are made of 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 minimized to sustain the gas pressure 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 across 6.3 cm in the He gas was about 0.2 MeV. During the measurement, the temperature and pressure of the He gas were monitored using the Pt resistor and diaphragm gauge.

The measurements were carried out at five scattering angles between 0° and 20° in the laboratory frame. A typical neutron-energy spectrum in the ${}^4\text{He}(\alpha, n){}^7\text{Be}$ reaction measured at $E_\alpha = 39.30$ MeV and $\theta_{\text{lab}} = 0°$ 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 neutron-energy resolution was 250–570 keV at the full width at half maximum. The energy spread of the neutrons was mainly due to the fluctuation of the reaction energy and kinematical effects.

The angular distributions of the differential cross sections are shown in Fig. 2. The solid circles and squares show the differential cross sections for the ground and first excited states in ${}^7\text{Be}$, respectively. The vertical bars present the measurement uncertainties including both the statistical and systematic uncertainties. The cross sections for the first excited state were not measured at $E_\alpha = 38.90$ and 38.50 MeV since these beam energies are below or very close to the threshold energy for the first excited state at $E_\alpha = 38.84$ MeV. Unfortunately, the ${}^4\text{He}(\alpha, n){}^7\text{Be}$ events could not be reliably separated from the background events at $E_\alpha = 38.50$ MeV and $\theta_{\text{c.m.}} = 77.3°$ because the energy resolution was poor due to the kinematical effects.
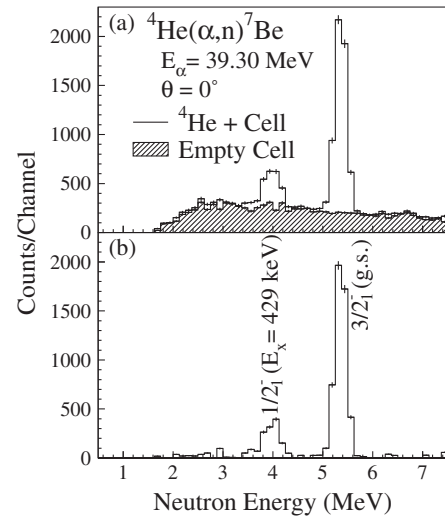

FIG. 1. Neutron energy spectra in the ${}^4\text{He}(\alpha, n){}^7\text{Be}$ reaction measured at $E_\alpha = 39.30$ MeV and $\theta_{\text{lab}} = 0°$. (a) Open and hatched spectra were taken using the He gas-filled and empty cells, respectively. (b) Background-free spectrum obtained by subtracting the background spectrum taken from the empty-cell measurement.

Therefore, the upper limit for the differential cross section was given at the 95% confidence level.

Since the angular distribution of the cross section for the two-body scattering of the identical particles must be symmetric with respect to $\theta_{\text{c.m.}} = 90°$, the measured cross
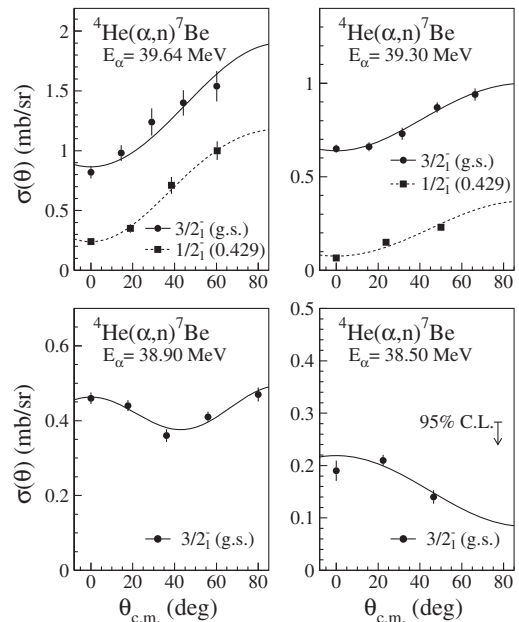

FIG. 2. Angular distribution of the differential cross sections for the ${}^4\text{He}(\alpha, n){}^7\text{Be}$ reaction. The solid circles and squares show differential cross sections for the ground and first excited states in ${}^7\text{Be}$, respectively. The solid and dashed lines are series of the even-order Legendre polynomials to fit the experimental data.
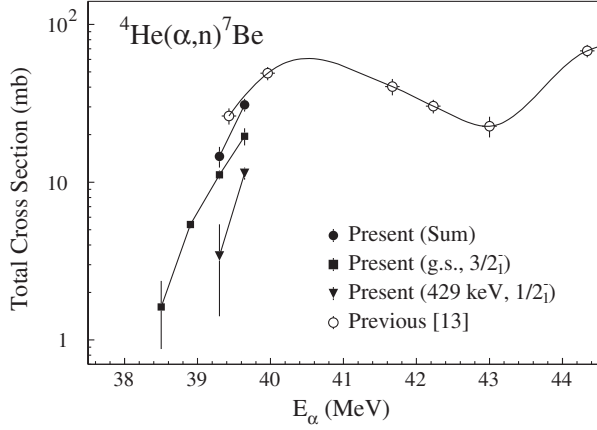
FIG. 3. Measured total cross sections of the ^{4}He$(\alpha, n)^7$Be reaction for the ground (solid squares) and first excited (solid triangles) states. The sum of the two states is shown by solid circles. Previous results from Ref. [13] are shown by the open circles. The solid lines interpolating the data points are drawn for a guide to the eye.

section can be fitted by a series of even-order Legendre polynomials

$$\sigma(\theta) = \frac{\sigma}{4\pi}\left(1 + \sum_{\substack{l=2 \\ l:\,\text{even}}}^{l_{\max}} \alpha_l P_l(\cos\theta)\right),$$

and the total cross section σ was obtained. Because the present measurement was carried out at beam energies close to the $n + {}^7$Be threshold energy, the Legendre polynomial expansion should involve a few low-order terms only. We decided $l_{\max} = 4$ for the ground state at $E_\alpha \geq 38.90$ MeV and 2 for the other states. The fit functions are shown by the solid and dashed lines in Fig. 2.

The total cross sections were evaluated by using the different $l_{\max}$ values in order to estimate the uncertainties stemming from the assumption about the $l_{\max}$ values, and the variation of the total cross sections was found to be less than 10% in most cases except the low energy cases where the number of the measured angles is 3.

The obtained total cross sections are shown in Fig. 3. The solid squares and triangles are the present results for the ground and first excited states. The sum of the two states are shown by the solid circles to directly compare the present results with the previous results [13] presented by the open circles. The solid lines interpolating the data points are drawn for a guide to the eye. The present and previous results agree within the measurement uncertainties around $E_\alpha = 39.4$ MeV. It should be noted that the present measurement extends the experimental data toward lower energies down to $E_\alpha = 38.50$ MeV for the first time.

The cross section for the first excited state decreases with the beam energy more rapidly than that for the ground state. This fact is naturally understood from the threshold effect; i.e., the neutron penetrability for the p-wave centrifugal barrier and the phase space volume for the first excited state

are strongly suppressed as the reaction energies approach the threshold energy at $E_\alpha = 38.84$ MeV.

From a view of the cosmological lithium problem, the total cross section for the ^{7}Be$(n, \alpha)^4$He reaction is important. The cross section for the reaction $A + B \to C + D$ is related to that for the time-reverse reaction $C + D \to A + B$ by the detailed balance principle

$$\frac{\sigma(A + B \to C + D)}{\sigma(C + D \to A + B)} = \frac{(1 + \delta_{AB})\hat{S}_C\,\hat{S}_D\,k^2_{CD}}{(1 + \delta_{CD})\hat{S}_A\,\hat{S}_B\,k^2_{AB}}, \quad (1)$$

where $\hat{S}_A = 2S_A + 1$. S_A is the spin of A, and $\hbar k_{AB}$ is the relative momentum in the $A + B$ channel. δ_{AB} equals 1 if A and B are identical, or 0 if not. The measured ^{4}He$(\alpha, n)^7$Be cross sections for the ground and first excited states in ^{7}Be are separately converted to the cross section of the time-reverse reactions for p-wave neutrons. The solid circles and squares in Fig. 4 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, and the peak of the thermal-energy distribution at $T_9 = 0.7$ given by the Maxwell-Boltzmann distribution is located in the effective-energy window as shown in the top panel of Fig. 4.

The cross sections evaluated by the indirect methods are compared with the present results in Fig. 4. The estimation from $p + {}^7$Li scattering [14] is plotted by the open triangles, whereas the cross section from the evaluated
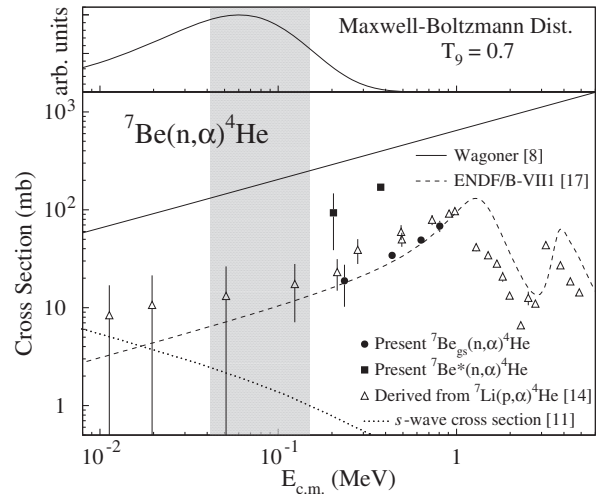

FIG. 4. Measured total cross sections for the ^{7}Be$(n, \alpha)^4$He reaction on the ground (solid circles) and first excited (solid squares) states. The cross sections for the first excited state are larger than those for the ground state, but those for the first excited state make no sizable contribution to the destruction rate of ^{7}Be at the BBN temperature. The solid line, dotted line, open triangles, and dashed line in the bottom panel are the previous evaluations from Refs. [8,11,14], and [17], respectively. The solid line in the top panel shows the Maxwell-Boltzmann distribution at $T_9 = 0.7$. The shaded area presents the effective-energy window for the p-wave reaction at $T_9 = 0.6$–0.8.

nuclear data library ENDF/B-VII.1 [17] 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 $^7\text{Be}_{\text{g.s.}}(n, \alpha)^4\text{He}$ reaction but inconsistent with the measurement in Ref. [11] around $E_n \sim 10$ keV. ENDF/B-VII.1 suggests the p-wave cross section is about 3 mb, whereas no sizable p-wave component was observed in Ref. [11].

The cross section for s-wave neutrons inferred in Ref. [11] is shown by the dotted line. It is smaller than the cross section for p-wave neutrons around the thermal energy at $T_9 \sim 0.7$, and thus, the p-wave reaction is dominant compared to the s-wave reaction in the BBN energy window.

The cross section for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction was first estimated by Wagoner [8] as shown by the solid line in the bottom panel of Fig. 4. Currently, this evaluation is widely used in the BBN calculations. The present values of the $^7\text{Be}(n, \alpha)^4\text{He}$ cross sections are much smaller than the calculation by Wagoner. The cross sections of the first excited state at $E_x = 429$ keV in ^7Be are larger than those of the ground state owing to the kinematical factors in Eq. (1). Although low-lying excited states can be thermally populated in the high-temperature environment, the excitation energy of the first excited state is too high to make a sizable contribution to the destruction rate of ^7Be at the BBN temperature. Moreover, the cross sections for the $^7\text{Be}^*(n, \alpha)^4\text{He}$ reaction are still smaller than the estimation by Wagoner. As a conclusion, the present results suggest that the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction does not solve the cosmological lithium problem.

In summary, the cross sections for the $^4\text{He}(\alpha, n)^7\text{Be}$ reaction were measured at low energies between $E_\alpha = 38.50$ and 39.64 MeV. The final states in the residual ^7Be nucleus were unambiguously identified by the on-line spectroscopy of the scattered neutrons. On the basis of the detailed balance principle, the cross sections for the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction were obtained at $E_{\text{c.m.}} = 0.20$–0.81 MeV, slightly above the BBN energy window for the first time. It was found that the p-wave reaction is dominant compared to the s-wave reaction in the BBN energy window; however, the obtained cross sections are significantly smaller than the theoretical estimation widely used in the BBN calculations. The present results suggest the $^7\text{Be}(n, \alpha)^4\text{He}$ reaction rate is not large enough to solve the cosmological lithium problem. This conclusion agrees with the recent result from the direct measurement of the s-wave cross sections using a low-energy neutron beam [11] and the evaluated nuclear data library ENDF/B-VII.1 [17].

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