

# Measurement of the cross section for the ${}^4\text{He}(\alpha, n){}^7\text{Be}$ reaction as a possible solution to the cosmological lithium problem

T Kawabata<sup>1</sup>, T Furuno<sup>1</sup>, M Ichikawa<sup>1</sup>, N Iwasa<sup>2</sup>, Y Kanada-En'yo<sup>1</sup>, A Koshikawa<sup>1</sup>, S Kubono<sup>3</sup>, E Miyawaki<sup>1</sup>, T Morimoto<sup>1</sup>, M Murata<sup>1</sup>, T Nanamura<sup>1</sup>, S Nishimura<sup>3</sup>, Y Shikata<sup>1</sup>, Y Takahashi<sup>1</sup>, T Takeda<sup>1</sup>, M Tsumura<sup>1</sup>, K Watanabe<sup>1</sup>

<sup>1</sup> Department of Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan

<sup>2</sup> Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

<sup>3</sup> RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

E-mail: kawabata@scphys.kyoto-u.ac.jp

**Abstract.** The cross section for the  ${}^4\text{He}(\alpha, n){}^7\text{Be}$  reaction was measured at low energies between  $E_\alpha = 38.50$  and  $39.64$  MeV motivated by the cosmological lithium problem. On the basis of the detailed balance principle, the cross section for the  ${}^7\text{Be}(n, \alpha){}^4\text{He}$  reaction was obtained at  $E_{c.m.} = 0.20$ – $0.81$  MeV close to the Big Bang nucleosynthesis (BBN) energy window for the first time. 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.

## 1. Introduction

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. The theoretical predictions of the primordial abundances reasonably well agree with the observations for the helium and deuterium. However, there remains a serious problem that the  ${}^7\text{Li}$  abundance does not agree with any theoretical BBN calculations. The primordial abundance of  ${}^7\text{Li}$  inferred from observations of metal-poor stars is three times smaller than the calculated values by the BBN theory. This discrepancy is known as the cosmological lithium problem [1], and has been of great interest in recent years.

From a view of nuclear physics, nuclear-reaction rates involved in the BBN theory should be examined. The main process of the  ${}^7\text{Li}$  production in the BBN is the electron-capture decay of  ${}^7\text{Be}$ , which is synthesized in the  ${}^3\text{He}({}^4\text{He}, \gamma){}^7\text{Be}$  reaction. Direct measurements of the cross section for the  ${}^3\text{He}({}^4\text{He}, \gamma){}^7\text{Be}$  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  ${}^7\text{Be}$  production rate to solve the lithium problem [2].

Recently, it was pointed out that the  ${}^7\text{Li}$  abundance will be greatly reduced in the BBN calculation if the destruction rate of  ${}^7\text{Be}$  is enhanced. One of the candidate channels to destruct



${}^7\text{Be}$  is the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction. However, the cross section for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction at the cosmological energy has been scarcely measured. Since both  ${}^7\text{Be}$  and neutron are short-lived nuclei, it is difficult to directly measure the cross section for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction. Thus, the cross section for the time reverse reaction should be measured. In the present work, we have measured the cross section for the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction at low reaction energies. On the basis of the detailed balance principle, we obtained the cross sections for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction at  $E_{c.m.} = 0.20\text{--}0.81$  MeV close to the BBN energy window for the first time.

## 2. Experiment and Results

The experiment was carried out at the N0 course in Research Center for Nuclear Physics (RCNP), Osaka University [3]. An  $\alpha$  beam accelerated by the AVF cyclotron was transported to the He gas target in the beam swinger magnet. 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 work. The uncertainties of the beam energies were estimated at 40 keV.

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  $\gamma$  rays. The detection efficiency of neutrons by the BC-501 liquid scintillation detector was estimated by using the computer code SCINFUL-CG [4]. We also measured the neutron detection efficiency using the tagged neutrons emitted from the  $d + d \rightarrow {}^3\text{He} + n$  reaction. The calculated efficiency agrees with the measurement within the measurement uncertainties.

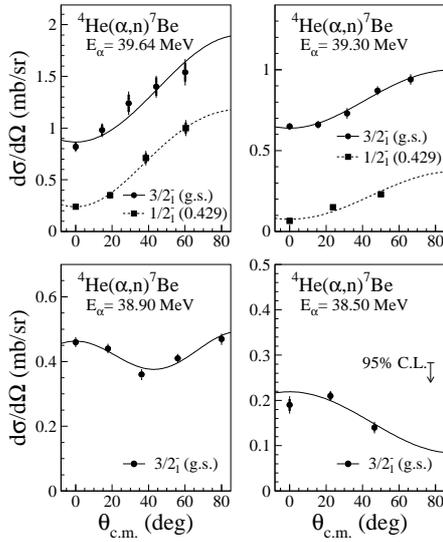
A He gas target was used in the present work. The He gas was filled at 1 atm in the target cell with the effective length of 6.3 cm. The target cell has the entrance and exit windows with the diameter of 12 mm, and those windows are sealed with the 6- $\mu\text{m}$  aramid films. The mass thicknesses of the He gas and aramid films were 1.0 and 1.7 mg/cm<sup>2</sup>, respectively, and the energy loss of the  $\alpha$  beam in the He gas target was about 0.5 MeV. The temperature and pressure of the He gas were monitored during the measurement.

The angular distributions of the differential cross sections for the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction are shown in Fig. 1. The solid circles and squares show the differential cross sections for the ground and first excited states in  ${}^7\text{Be}$ , respectively. The thick vertical bars present the statistical uncertainties, while the thin vertical bars present the total uncertainties including both the statistical and systematic uncertainties. 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  $\theta_{c.m.} = 77.3^\circ$ , because the kinematical energy spread of the scattered neutrons is large. Therefore, the upper limit for the differential cross section was given at the 95% confidence level.

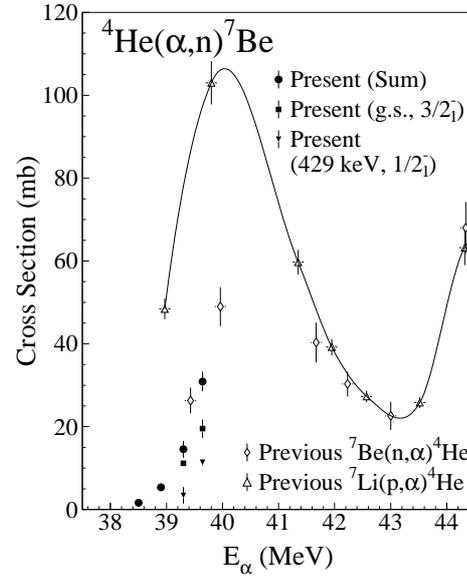
Since the angular distribution of the cross section for the two-body scattering of the identical particles must be symmetric with respect to  $\theta_{c.m.} = 90^\circ$  in the center of mass frame, the measured cross section can be fitted by a series of the even-odd Legendre polynomials:

$$\sigma(\theta) = \frac{\sigma}{4\pi} \sum_{l=0}^{l_{max}} \alpha_l P_l(\cos \theta).$$

Because the present measurement was carried out at beam energies close to the  $n + {}^7\text{Be}$  threshold energy, the Legendre polynomial expansion should involve a few of 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. 1. The total cross sections were obtained by integrating the fit functions over the whole solid angle. We also evaluated the total cross sections by using the different  $l_{max}$  values in order to estimate the uncertainties stem from the assumption about the  $l_{max}$  values.



**Figure 1.** Angular distribution of the differential cross sections for the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction. The solid circles and squares show the 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.



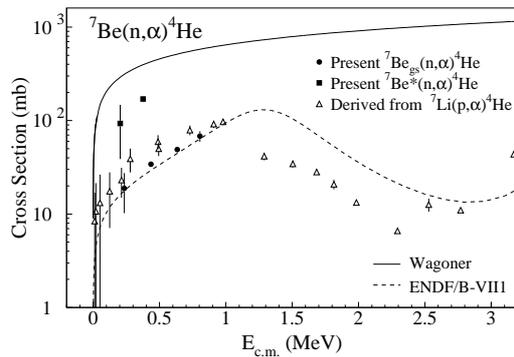
**Figure 2.** Measured total cross sections of the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction for the ground (solid squares) and first excited (solid triangles) states. The sum of the two states is shown by solid circles. Previous results of the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  and  ${}^4\text{He}(\alpha,p){}^7\text{Li}$  reactions [5] are shown by the open diamonds and triangles, respectively. The solid line interpolating the open triangles is drawn for eye-guide.

### 3. Discussion

The present results are compared with the previous results taken from Ref. [5] in Fig. 2. 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 from Ref. [5]. The previous results of the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  and  ${}^4\text{He}(\alpha,p){}^7\text{Li}$  reactions are shown by the open diamonds and triangles, and the solid line interpolating the open triangles is drawn for eye-guide. The both measurements of the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction overlap around  $E_\alpha = 39.4$  MeV, and they agree within the measurement uncertainties. 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 total cross sections for the  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  reaction are similar to those for the mirror  ${}^4\text{He}(\alpha,p){}^7\text{Li}$  reaction at higher beam energies, but the two reactions split at lower energies due to the threshold effect because the  $n + {}^7\text{Be}$  threshold at  $E_x = 18.9$  MeV in  ${}^8\text{Be}$  is higher than the  $p + {}^7\text{Li}$  threshold by 1.6 MeV.

From a view of the cosmological lithium problem, the total cross section for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction is important. The measured  ${}^4\text{He}(\alpha,n){}^7\text{Be}$  cross sections for the ground and first excited states in  ${}^7\text{Be}$  are separately converted to the cross section for the time reverse reactions on the basis of the detailed balance principle. The solid circles and squares in Fig. 3 show the total cross sections of the  $(n,\alpha)$  reaction on the ground and first excited states in  ${}^7\text{Be}$ . The cross sections evaluated in Ref. [6] are also plotted by the open triangles together with the cross section from the evaluated nuclear data library ENDF/B-VII.1 [7] shown by the dashed line. The evaluated cross sections are very close to the present data for the  ${}^7\text{Be}_{g.s.}(n,\alpha){}^4\text{He}$  reaction.



**Figure 3.** Measured total cross sections for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction on the ground (solid circles) and first excited (solid squares) states. The open triangles, solid line, and dashed line are the previous evaluations taken from Refs. [6], [8], and [7], respectively.

The cross section for the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction was first estimated by Wagoner in Ref. [8] as shown by the solid line in Fig. 3, which was 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 Wagoner's calculation. The cross sections on the first excited state in  ${}^7\text{Be}$  are larger than those on the ground state. Since the low-lying excited states can be thermally populated in the high-temperature environment, the first excited state at  $E_x = 429$  keV in  ${}^7\text{Be}$  could contribute to the  ${}^7\text{Be}$  destruction in principle. However, its excitation energy is too high to make a sizable contribution to the destruction rate at the BBN temperature. Moreover, the cross sections for the  ${}^7\text{Be}^*(n,\alpha){}^4\text{He}$  reaction are still smaller than the Wagoner's calculation. As a conclusion, the present results suggest the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  reaction does not solve the cosmological lithium problem.

#### 4. 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. 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  $E_{c.m.} = 0.20$ – $0.81$  MeV close to the BBN energy window for the first time. 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.

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