Study of the contribution of the $^7\text{Be}(d, p)$ reaction to the $^7\text{Li}$ problem in the Big-Bang Nucleosynthesis

Azusa Inoue$^1$, Atsushi Tamii$^1$, Phaikying Chan$^1$, Seiya Hayakawa$^2$, Nobuyuki Kobayashi$^1$, Yukie Maeda$^3$, Kotaro Nonaka$^3$, Tatsushi Shima$^1$, Hideki Shimizu$^2$, Dinh Trong Tran$^1$, Xuan Wang$^1$, Hidetoshi Yamaguchi$^{2,4}$, Lei Yang$^2$, and Zaihong Yang$^1$

$^1$Research Center for Nuclear Physics, Osaka university, 10-1 Mihogaoka, Ibaraki, Osaka Japan
$^2$Center for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako, Saitama, Japan
$^3$Faculty of Engineering, University of Miyazaki, 1-1, Gakuenkibanadainishi, Miyazaki-shi, Miyazaki, Japan
$^4$National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, Japan
E-mail: azusa@rcnp.osaka-u.ac.jp

Abstract. Our research goal is to measure the cross section of the $^7\text{Be}(d, p)$ reaction to find a solution for the cosmological the $^7\text{Li}$ problem, which is an overestimation of the primordial $^7\text{Li}$ abundance in the standard Big-Bang nucleosynthesis (BBN) model. We developed a method to produce an unstable $^7\text{Be}$ target to measure the reaction in normal kinematics in a high-resolution measurement. We performed an experiment to produce the $^7\text{Be}$ target and also to measure the cross section of the $^7\text{Be}(d, p)^8\text{Be}$ reaction with the produced $^7\text{Be}$ target at the tandem facility, Kobe University. A 2.36 MeV proton beam irradiated a Li target to transmute $^7\text{Li}$ particles to $^7\text{Be}$ particles via the $^7\text{Li}(p, n)^7\text{Be}$ reaction. We produced $2.6 \times 10^{13}$ $^7\text{Be}$ particles in the target after two days' proton irradiation. After the target production, the beam ion was changed to deuterons with energies of 0.6, 1.0, and 1.6 MeV to measure the $^7\text{Be}(d, p)^8\text{Be}$ reaction. The outgoing protons were measured by two $\Delta E-E$ silicon telescopes placed at 30° and 45°. We report the preliminary results of this experiment, including the $^7\text{Be}(d, p)$ cross section.

1. Introduction
The overestimation of primordial $^7\text{Li}$ abundance in the standard Big-Bang Nucleosynthesis (BBN) model is a major unresolved problem in modern astrophysics. A recent theoretical BBN model predicts a primordial $^7\text{Li}$ abundance that is about 3 times larger than the recent precise observation (see, e.g., [1]). The difference is quite large, considering the fact that the abundance of the other light nuclei are reproduced well. This is one of the biggest problems in the BBN models and it illustrates the incomplete knowledge of the processes of the primordial formation of our universe.

Primordial BBN began when the universe was 3 minutes old and ended less than half an hour later. $^7\text{Be}$ were produced during the BBN, and it took just several hundred to several thousand seconds (Figure 1). $^7\text{Li}$ nuclei were considered to be produced predominantly by the electron capture decay of $^7\text{Be}$ after the termination of nucleosynthesis in the standard BBN model. The electron capture decay half life of $^7\text{Be}$, 53.22 days = 5 million seconds, is much longer than the timescale of the production of light nuclei after the Big Bang. Thus, one possible scenario to
Figure 1. Low mass region of the nuclear chart showing the main nuclei involved in standard BBN calculations. Light nuclei were produced in several hundred seconds following the Big Bang. \(^7\)Li was produced by the \(\beta\) decay of \(^7\)Be. The \(\beta\) decay half life of \(^7\)Be is 5 million seconds, which is much longer than the timescale of the nuclear reactions.

solve the \(^7\)Li problem is that \(^7\)Be was destroyed in the epoch of the nuclear reactions. All of those nuclear reaction cross sections that destroy \(^7\)Be have not been thoroughly constrained by experimental measurements.

There are several routes to destroy \(^7\)Be, for example the \(^7\)Be(\(d, p\))\(^8\)Be, the \(^7\)Be(\(n, \alpha\)) or \(^7\)Be(\(n, p\)) reactions are considered [2]. We focus on the \(^7\)Be(\(d, p\))\(^8\)Be reaction since the contribution from \(^7\)Be(\(d, p\))\(^8\)Be is suggested to be larger than \(^7\)Be(\(n, \alpha\))\(^4\)He [3, 4]. We measured the \(^7\)Be(\(d, p\))\(^8\)Be reaction with a \(^7\)Be target since the available data are insufficient in accuracy and in the relevant energy range [5, 6, 7]. An advantage to measure the reaction in direct kinematics is that we can reconstruct the reaction from the measurement of the outgoing proton alone without measuring the two alpha particles, while maintaining a sufficient energy resolution. The technical development of the unstable \(^7\)Be target production is quite challenging, but it interesting and also important for the future of the research for unstable nuclei.

2. Experiment
The experiment was performed at the tandem facility in Kobe University. We performed several runs, completed in January 2019. The experiment is separated into two steps: \(^7\)Be target production followed by the \(^7\)Be(\(d, p\)) reaction measurement.

2.1. Target production
The first step was production of a \(^7\)Be target. A schematic picture of the setup for the target production is shown in Figure 2.

A self-supporting, natural Li target (\(\(^7\)Li abundance = 92.5\%\)) was placed as a host at the target position (the optical center of the beam axis) to produce the \(^7\)Be via the \(^7\)Li(\(p, n\))\(^7\)Be reaction. The proton beam was accelerated to 2.36 MeV, and the average intensity was 400 nA. The beam intensity was maintained for bombardment over 2 days to produce each target. The thickness of the Li target was 30 \(\mu\)m. Figure 3 shows the cross section of the \(^7\)Li(\(p, n\))\(^7\)Be reaction. The shaded region corresponds to the laboratory energy of the proton beam in the \(^7\)Li target for production of \(^7\)Be, following the energy loss calculation of the proton beam in the 30 \(\mu\)m Li target.

The proton beam irradiated the target for two days. We evaluated the amount of activated \(^7\)Be by detecting 477-keV \(\gamma\)-rays with a LaBr\(_3\) detector after the proton irradiation. The \(\gamma\) ray is emitted in the electron capture process of \(^7\)Be with a branching ratio of 10.5\%. We produced \(2.6\times10^{13}\) \(^7\)Be particles in the target after two days’ proton irradiation.
Figure 2. Schematic diagram of the process for producing the $^7$Be target. A collimator with 2-mm diameter is placed in front of the Li target to define the position of the $^7$Be target production. Above the target is a cartoon of the Li target during the proton irradiation. $^7$Li particles are transmuted to $^7$Be during proton irradiation.

Figure 3. Cross-section data of the $^7$Li($p$, n)$^7$Be reaction [8]. The shaded region shows the incident proton energy covered in the present work.

2.2. Cross section measurement

The beam species was switched to $^2$H immediately after the proton irradiation and the target activation measurement. The incident deuteron beam energies were accelerated to 0.6, 1.0, and 1.6 MeV. The outgoing proton were measured by two $\Delta$E-E Si telescopes each consisting of 4 layers, placed at 30° and 45°. A schematic picture of the detector setup is shown in Figure 4.

The angular coverage of the detectors was 24°–36° and 39°–51°, respectively. The first layer of each Si telescope is 300 $\mu$m and the remaining three layers are each 500 $\mu$m, at each angle. A 30 $\mu$m Cu plate was placed in front of each Si telescope, to avoid background induced by low-energy charged-particles (e.g., protons from $^6$Li($d$, p), $^{16}$O($d$, p) etc.) which can damage the detectors; the reaction Q-values for $^7$Be($d$, p), $^7$Li($d$, p), and $^{16}$O($d$, p) reactions are 16.7, 5.03, and 1.92 MeV, respectively [9]. This is actually an advantage of this measurement that Q-values for $^7$Be($d$, p) is relatively higher than the other reactions. The deuteron beam current was measured by a current integrator to determine the number of incident beam particles.
Figure 4. Two $\Delta E\text{-}E$ Si telescopes, each comprised of four layers, were placed at $30^\circ$ and $45^\circ$ at a distance of 54 mm from the center of the target. A collimator with 3-mm diameter is placed in front of the Li ($^7\text{Be}$) target.

3. Analysis

Figure 5 shows typical $\Delta E\text{-}E$ two dimensional histograms, after the background was subtracted. The proton loci are evident. The number of events were determined by applying a software gate to the measured energies, as shown in Figure 6.

Figure 5. Selected background-subtracted $\Delta E\text{-}E$ plots at $45^\circ$ from the Si telescopes. (Left) 3rd layer vs. 2nd layer; (Right) 4th layer vs. 3rd layer. The proton loci are evident.

The thick target method was applied to broaden the deuteron energy. Considering the challenges of reaction studies with radioactive nuclides, in this work we have exploited the thickness of the target to measure multiple center-of-mass energies, $E_{cm}$, with a mono-energetic incident deuteron beam which is degraded in the Li target by energy loss. In the thick-target method, the $E_{cm}$ of each reaction is kinematically reconstructed event by event, based on measurement of the angle and residual energy of each outgoing proton [10, 11, 12]. Thus, the proton energy, after the $(d, p)$ reaction, will vary depending on which depth the reaction occurred. The relation between the deuteron energy and reaction depth in the activated Li target is calculated by its energy loss [13]. With the calculated depth of each reaction, we deduced the number of $^7\text{Be}$ target nuclei in each energy slice from the energy loss calculation.
Figure 6. Example of event counting procedure. This figure shows the detected proton locus. The number of the events were counted by choosing the proton energy in the 4th layer of the Si telescope at 45°. The red dotted lines show the energy region.

The differential cross section was calculated by the following equation,

$$\frac{d\sigma}{d\Omega} = \frac{Y}{I_b N_t \Omega}.$$  \hfill (1)

Here, the $Y$ is the yield in each energy region, $\Omega$ is the solid angle of the Si telescopes, $I_b$ is the incident number of beam ions, and $N_t$ is the number of $^7$Be target nuclei. We then calculated the total cross section, $\sigma$, by assuming the angular distribution of the reaction is isotropic in the center-of-mass system.

4. Preliminary result

Figure 7. Cross section vs. incident deuteron beam energy. The triangles are the preliminary results for the $E_d=1.6$ MeV (laboratory frame) measurement, while the closed circles correspond to $E_d=0.6$ MeV. The crosses [5] and squares [7] are reference data.
The preliminary result of the cross section of the $^7\text{Be}(d,p)$ reaction is shown in Figure 7. These are preliminary data, and the magnitude may change after more thorough analysis is done. However, there is no indication of a large resonance at the BBN energy region to destroy $^7\text{Be}$ sufficiently to resolve the cosmological $^7\text{Li}$ problem. Recently, another measurement of the cross section of the $^7\text{Be}(d,p)$ reaction was published [14], and comparison with those results is ongoing. In the future, we will finalize our data analysis, and we will be able to make more firm and reliable conclusions.

5. Acknowledgments
A.I. thanks D. Kahl for useful discussions. This work was supported by JSPS KAKENHI Grant Number JP 16H03980.

References
[1] R. H. Cyburt et al., J. Cosmol. Astropart. Phys. 11, 012 (2008).
[2] M. Barbagallo et al., Phys. Rev. Lett. 117, 152701 (2016).
[3] S. Q. Hou et al., Phys. Rev. C 91, 055802 (2015).
[4] T. Kawabata et al., Phys. Rev. Lett. 118, 052701 (2017).
[5] R. W. Kavanagh et al., Nucl. Phys. 18, 493 (1960).
[6] P. Parker et al., Astrophys. J. 175, 261-264 (1972).
[7] C. Angulo et al., Astrophys. J. 630, L 105 (2005).
[8] K. K. Sekharan et al., Nucl. Instr. Meth. 133, 253-257 (1976).
[9] M. Wang et al., Chin. Phys. C 41, 030003 (2017).
[10] W. W. Daehnick et al., Phys. Rev. 133, B934 (1964).
[11] K. P. Artemov et al., Sov. J. Nucl. Phys. 52, 408 (1990).
[12] W. Galster et al., Phys. Rev. C 44, 2776 (1991).
[13] LISE++ http://lise.nscl.msu.edu/lise.html
[14] N. Rijal et al., Phys. Rev. Lett. 112, 182701 (2019).