Role of the ^{7}Be$(n, p_1)^7$Li* Reaction in the Cosmological Lithium Problem Studied with the ^{9}Be$(^3$He$, \alpha)^8$Be$^*(p)^7$Li Reaction

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I. INTRODUCTION

The primordial ^{7}Li abundance predicted by the big bang nucleosynthesis (BBN) model is overestimated by a factor of three to four when compared to the observation, which is the so-called cosmological lithium problem [1]. This problem may be solved if the ^{7}Be abundance, the main source of ^{7}Li through the electron-capture decay, decreased largely during the BBN epoch. The ^{7}Be$(n, p)^7$Li reaction is of primarily importance in destruction of ^{7}Be, followed by the ^{7}Li$(p, \alpha)^4$He reaction to destroy most of the synthesized ^{7}Li. The reaction rate of the former used in the BBN calculation has been deduced based on the cross sections obtained by (1) direct measurement for the energy range from thermal to 13.5 keV neutron energy [2], and (2) the inverse reaction using detailed balance; however, the inverse reaction measurement does not provide the ^{7}Be$(n, p_1)^7$Li$^*(0.478$ MeV$; 1/2^-)$ reaction cross section. Since the relevant energy is considered up to about $E_n = 2$ MeV in the BBN calculation, investigation on the ^{7}Be$(n, p_1)^7$Li* reaction cross section is required. Recently, a direct measurement of the ^{7}Be$(n, p)^7$Li reaction was carried out at the n_TOF facility, CERN for the energy range up to $E_n = 325$ keV [3]. The cross section data showed 35% higher than that of the prior result [2] at low energy. However, the contribution of the ^{7}Be$(n, p_1)^7$Li* reaction could not be evaluated separately in their measurement.

In order to approach the ^{7}Be$(n, p_1)^7$Li* reaction cross section by using the cross section data deduced from the inverse reaction measurements, experimental determination of Γ_{p1}/Γ_{p0}, the branching ratio between the proton decays from resonance states in ^{8}Be to the ground state and to the first excited state of ^{7}Li, is desired.

II. EXPERIMENTAL

We have carried out experiment of the ^{9}Be$(^3$He$, \alpha)^8$Be$^*(p)^7$Li reaction to deduce the Γ_{p1}/Γ_{p0} ratio at the Tandem accelerator facility in Japan Atomic Energy Agency (JAEA). A 1 μm thick beryllium target was tilted by 45° relative to the beam direction and irradiated by a ^{3}He beam accelerated at 30 MeV. Resonance states populated by the $(^3$He$, \alpha)$ reaction were identified by measuring the magnetic rigidity of α particles at zero degree using the magnetic spectrograph ENMA. Along the focal plane, a wire chamber and a plastic scintillator with two photomultiplier connected to both edges were installed. The wire chamber consists of four sets of anode wires and a cathode plate operated in isobutane gas at a pressure of 150 mbar. The horizontal position information of particle trajectories were obtained by the resistance dividing method at the first and fourth sets of wires. The second and third wires provided the ΔE information so that the particle identification was performed using the ΔE-E technique together with the plastic scintillator. Decay-protons were measured in coincidence with α particles by three silicon strip detectors surrounding the target for the angular range from 49° to 150°.

III. RESULTS AND DISCUSSION

The excitation energy spectrum of ^{8}Be including 7 resonances of interest (E_X = 18.91, 19.07, 19.235, 19.4, 19.86, 20.1 and 20.2 MeV) was deduced by magnetic rigidity measurement of α particles as shown in Fig. 1. The correlations between E_X and the kinetic energies of decay-protons measured in coincidence are shown in Fig. 2(a) and (b) for the measurement angles of 65-70° and 140-145°, respectively. Two curves going up to the right were observed in both diagrams. The upper corresponds to the decays of ^{8}Be$^* \to {}^7$Li$_{g.s.} + p_0$ and the lower corresponds to the ones of ^{8}Be$^* \to {}^7$Li$^* + p_1$. Therefore, we have clearly succeeded in separating the events of proton decays to the first excited state of ^{7}Li from the ones to the ground state. Angular distributions of decay-protons in the rest frame of residual ^{8}Be were deduced for every excitation energy bins of 100 keV. These an-

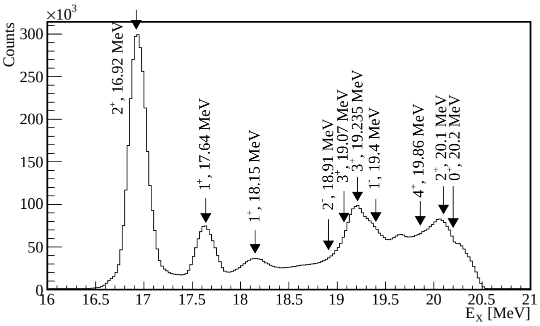

FIG. 1: Excitation energy spectrum of ^{8}Be populated by the ^{9}Be$(^3$He$, \alpha)^8$Be reaction deduced by measuring the magnetic rigidity of α particles by ENMA spectrograph. The arrows indicate the known excited states of ^{8}Be.

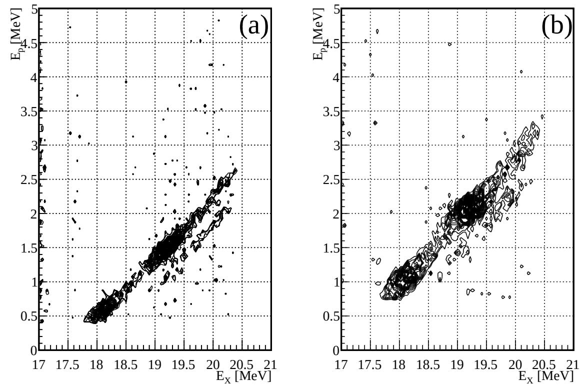

FIG. 2: Correlation diagrams between the excitation energy of ^{8}Be and the kinetic energies of decay-protons measured in coincidence for the angular domains of (a) 65-70° and (b) 140-145°. The upper and lower curves correspond to the proton decays to the ground and the first excited state of ^{7}Li, respectively.

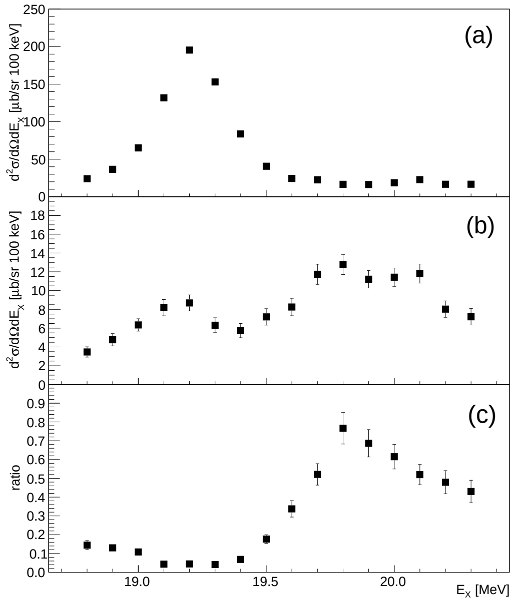

FIG. 3: The differential cross section as a function of the excitation energy of ^{8}Be for (a) the $^{9}\mathrm{Be}(^{3}\mathrm{He},\alpha)^{8}\mathrm{Be}^{*}(p)^{7}\mathrm{Li}_{\mathrm{g.s.}}$ reaction and (b) the $^{9}\mathrm{Be}(^{3}\mathrm{He},\alpha)^{8}\mathrm{Be}^{*}(p)^{7}\mathrm{Li}_{\mathrm{1st}}$ reaction. (c) Ratio of the data in (b) to the ones in (a).

gular distributions were fitted with a series of Legendre polynomials up to third order. The differential cross sections $d^2\sigma/d\Omega dE_X$ for both $^{9}\mathrm{Be}(^{3}\mathrm{He},\alpha)^{8}\mathrm{Be}^{*}(p)^{7}\mathrm{Li}_{\mathrm{g.s.}}$ and $^{9}\mathrm{Be}(^{3}\mathrm{He},\alpha)^{8}\mathrm{Be}^{*}(p)^{7}\mathrm{Li}^{*}_{\mathrm{1st}}$ reactions were deduced from the integrals over the solid angles of protons, and the results are plotted in Fig. 3(a) and (b) as a function of excitation energy of ^{8}Be, respectively. In Fig. 3(c), the ratios of the data in Fig. 3(b) divided by the ones in (a) are plotted. The deduced ratio is about 11% around 18.9 MeV, which is much larger than the conclusions of Koehler *et al.* [2]. This may be true, but there may be also a possibility that a new resonance state in ^{8}Be exists just below 18.91 MeV resonance, which causes the enhancement of the proton decay events to the first excited state in ^{7}Li. At 19.2 MeV, near the strongest peak observed in the $^{7}\mathrm{Li}(p,n)$ reaction measurements, the ratio becomes about 5%. A peak of about 79% was observed around 19.8 MeV, which is clearly due to the 19.86 MeV resonance.

IV. SUMMARY

We have carried out experiment of the $^{9}\mathrm{Be}(^{3}\mathrm{He},\alpha)^{8}\mathrm{Be}^{*}(p)^{7}\mathrm{Li}$ reaction at 30 MeV to deduce the Γ_{p1}/Γ_{p0} ratio for the resonance states of ^{8}Be at the excitation energy from 18.9 to 20.2 MeV. Our result suggests that the p_1 decay may have strong peaks around the resonance states of ^{8}Be at 18.91 and 19.86 MeV.

As future prospects, investigation on the systematical errors in the cross section data should be done. This requires a detailed simulation on the reaction including the evaluation of performance of the ENMA spectrograph. Also, in order to determine the branching ratio for each resonance state of ^{8}Be, resonance fit using the Breit-Wigner expressions is required. The first result of the resonance fitting will be reported in the thesis.

[1] B. D. Fields, Ann. Rev. Nucl. Part. Sci. **61**, 47-68 (2011).
[2] P. E. Koehler *et al.*, Phys. Rev. **C37**, 3 (1988).
[3] L. Damone *et al.*, Phys. Rev. Lett. **121**, 042701 (2018) and Supplement Materials therein.