Measurement of alpha resonance scattering on $^7\text{Be}$

H. Yamaguchi, T. Hashimoto, S. Hayakawa, D.N. Binh, D. Kahl, S. Kubono, T. Kawabata$^a$, Y. Wakabayashi$^b$, N. Iwasa$^c$, Y. Miura$^c$, Y.K. Kwon$^d$, L.H. Khiem$^e$, N.N. Duy$^e$, and T. Teranishi$^f$

Center for Nuclear Study, Graduate School of Science, University of Tokyo
$^a$Department of Physics, Kyoto University
$^b$Advanced Science Research Center, JAEA
$^c$Department of Physics, Tohoku University
$^d$Department of Physics, Chung-Ang University
$^e$Institute of Physics and Electronics, Vietnam Academy of Science and Technology
$^f$Department of Physics, Kyushu University

A measurement of the $^7\text{Be}+\alpha$ elastic scattering was performed at CRIB [1, 2], to study the resonance structure of $^{11}\text{C}$. The excited states of $^{11}\text{C}$ above the threshold for the $\alpha$-particle decay are particularly of interest from the following points of view.

The first is on the astrophysical interest. The $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction is considered to play an important role in the hot $p$-$p$ chain and related reaction sequences [3]. Several reaction sequences including the $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction should take place in some high-temperature environments ($T_\beta > 0.2$). One of those sequences is called pp-V,

$$^7\text{Be}(\alpha, \gamma)^{11}\text{C}(\beta^+\nu)^{11}\text{B}(p, 2\alpha)^4\text{He},$$

which are reaction chains to synthesize CNO nuclei without the triple-$\alpha$ process. The $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction and these sequences are considered to be important in the explosion of supermassive objects with lower metallicity [4], novae [5] and big-bang nucleosynthesis. The $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction rate is greatly affected by the resonances. At the lowest temperature, the reaction rate is determined by the subthreshold resonance at the excitation energy $E_{\text{ex}}=7.50$ MeV and the direct capture rate. The two resonances located at $E_{\text{ex}}=8.11$ MeV and $E_{\text{ex}}=8.42$ MeV determine the rate at high temperature around $T_\beta = 0.5-1$. Higher excited states may contribute to the reaction rates at very high temperature ($T_\beta > 1$).

Resonance states above 9 MeV were previously studied via $^{10}\text{B}(p, \alpha)$ and single-nucleon transfer reactions such as $^{12}\text{C}(p, d)^{11}\text{C}$ [6–9]. The resonances have typically widths of the order of 100 keV, but their $\alpha$-decay widths are still not known with a good precision, and the spin and parity have not been clearly determined yet. The excited states at lower energies ($E_{\text{ex}}=8–9$ MeV) have narrower particle widths, and the $\alpha$ widths are unknown, except for the two resonances located at $E_{\text{ex}}=8.11$ MeV and $E_{\text{ex}}=8.42$ MeV. The $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction rate was directly measured only at the energies of these two resonances [10], and the resonance parameters including $\alpha$ widths were determined. That measurement is the only known direct measurement of the $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ reaction.

The $3/2^-_1$ state in $^{11}\text{C}$ at $E_{\text{ex}}=8.11$ MeV is regarded as a dilute cluster state [11], where two $\alpha$ particles and $^3\text{He}$ are weakly interacting. Its exotic structure is attracting much attention [12]. The cluster structure in $^{11}\text{B}$, the mirror nucleus of $^{11}\text{C}$, was studied by measuring its isoscalar monopole and quadrupole strengths in the $^{11}\text{B}(d, d')$ reaction [13, 14]. As a result, they indicated that the mirror state of the $8.11$-MeV state is considered to have a dilute cluster structure. It is also claimed that the large monopole strength for the $3/2^-_1$ state at $E_{\text{ex}}=8.56$ MeV in $^{11}\text{B}$ is an evidence of the $2\alpha + t$ cluster structure. If the $3/2^-_1$ state has a large deformation that arises from the developed cluster structure, a characteristic rotational band is expected to be formed. It is interesting to search for the rotational band built on the $3/2^-_1$ state in the present measurement.

In the present study, we used the $^7\text{Be}+\alpha$ resonant elastic scattering to observe $\alpha$ resonances. The strength of the resonances is expected to provide information on the $\alpha$-cluster structure of $^{11}\text{C}$, and on the astrophysical $^7\text{Be}(\alpha, \gamma)$ reaction rate. The measurement was performed using the thick target method in inverse kinematics [15] to obtain the excitation function for $E_{\text{ex}}$ at 8.5–13.0 MeV in $^{11}\text{C}$. The experimental setup is almost identical to the one used in the $^7\text{Li}+\alpha$ measurement [17]. A pure and intense $^7\text{Be}$ beam can be produced at CRIB using a cryogenic target [16]. In the present measurement, a low energy $^7\text{Be}$ beam at 14.7 MeV was produced using a 2.3-mg/cm$^2$-thick hydrogen gas target, and a $^7\text{Li}$ beam at 5.0 MeV/µ. The purity of the $^7\text{Be}$ beam was almost 100% after the Wien filter. The typical $^7\text{Be}$ beam intensity used in the measurement was $2 \times 10^5$ per second at the secondary target, and the main measurement using a helium-gas target was performed for 4 days.

A Micro-Channel Plate (MCP) was used for the detection of the beam position and timing. A CsI-evapolated 0.7-µm-thick alminum foil was placed on the beam axis for the secondary electron emission. The secondary electrons were
reflected by 90° at a biased thin-wire reflector and detected at the MCP with a delay-line readout.

The gas target consisted of a 50-mm-diameter duct and a small chamber. Helium gas at 800 Torr was filled and sealed with a 2.5-μm-thick Havar foil as the beam entrance window. The helium gas was sufficiently thick to stop the $^7$Be beam in it. $\alpha$ particles recoiling to the forward angles were detected by the “$\Delta E$-E detector”. The detector, consisting of 20-μm- and 490-μm-thick silicon detectors, was placed in the gas chamber. The distance from the beam entrance window to the detector was 250 mm. To measure 429-keV gamma rays from inelastic scattering to the first excited state of $^7$Be, NaI detectors were placed around the duct. We used ten NaI crystals, each with a geometry of 50 × 50 × 100 mm. They covered 20–60% of the total solid angle, depending on the reaction position.

Fig. 1 shows the energies of particles detected at the $\Delta E$-E detector, in coincidence with the $^7$Be beam at the MCP. Most of the particles measured was $\alpha$ from the elastic scattering, and a small number of protons and deuterons were observed in the measurement. A measurement using an argon-gas target of the equivalent thickness was also performed to evaluate the background $\alpha$ particles as the contamination in the beam.

The calculation of the kinematics by taking into account the energy loss in the gas target provided the excitation energy of $^{11}$C from the measured energy of the $\alpha$ particle. The obtained energy spectrum of alpha particles is shown in Fig. 2. A structure with peaks, considered to be due to alpha resonances, was observed. An excitation function for the $^7$Be+$\alpha$ elastic scattering will be obtained in the future analysis. The resonance parameters to be determined in this study, such as the spin, parity and $\alpha$ width (related with the spectroscopic factor of the $\alpha$-cluster configuration) would provide valuable information for the $\alpha$-cluster structure in the high excited states, and astrophysical reaction rates in high-temperature phenomena.

References