Experimental study on breakup reaction of beryllium and carbon induced with 14-MeV neutrons based on emitted charged-particle measurements

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Abstract. Detailed measurements of α-particle emission double differential cross section for beryllium and carbon with 14-MeV incident neutrons were carried out. In order to identify contributing reaction channels to the ^{9}Be(n, 2n + 2α) and ^{12}C(n, n' + 3α) reactions, we attempted to reproduce energy distributions of emitted particles by Monte Carlo calculations according to reaction kinematics of a lot of channels which contribute to the reactions. As for the ^{9}Be(n, 2n + 2α) reaction, a contribution of the ^{9}Be(n,α)^{6}He* channels and the simultaneous breakup channel was suggested to account for the energy and angular distribution of emitted α-particles and neutrons. As for the ^{12}C(n,n'+3α) reaction, the ^{12}C(n,α)^{9}Be* channels were largely contributed and well reproduced the experimental data.

1 Introduction

Beryllium and carbon are important candidate materials of a fusion reactor. The ^{9}Be(n,2n + 2α) and ^{12}C(n,n'+3α) reactions have a relatively large cross section around neutron energy of 14 MeV. Double-differential cross section (DDX) of these reactions for emitted neutrons is indispensable to calculate various nuclear properties of the reactor. DDX for emitted α-particles is also needed to estimate nuclear heating, material damage and gas production. Mechanism of these reactions is complex because of existence of a lot of reaction channels to reach the 4-body final states of 2n + 2α or n + 3α, which are sequential decays accompanied with several intermediate nuclei. Simultaneous breakup further complicates the reaction processes. DDX for emitted neutrons and α-particles are closely related with each other because both the particles are emitted through the same reaction. Knowledge for the reactions is hence important in order to evaluate these DDX accurately from engineering requirements. Understanding of the reaction mechanism is also interesting from a viewpoint of nuclear physics.

However, few measurements of DDX for emitted α-particles for beryllium and carbon have been carried out so far. Previous analyses for the reaction process were based on insufficient experimental information for emitted α-particles, and consistent analyses with emitted neutrons and α-particles have been limited [1–3]. We recently developed an improved spectrometer for secondary emitted charged particles using a pencil neutron beam in the Fusion Neutronics Source (FNS) facility in Japan Atomic Energy Agency (JAEA) [4]. Using the spectrometer, we have carried out detailed measurements of α-particle emission DDX for beryllium and carbon. The measured α-particle DDX data and previous neutron DDX data measured by Takahashi et al. [5] were consistently analyzed considering reaction kinematics in order to investigate channels involved in these reactions.

2 Experiment

2.1 Charged-particle spectrometer using a pencil neutron beam

All the present measurements of DDX for emitted α-particles were carried out with the pencil DT neutron beam available at FNS/JAEA. The use of the neutron beam is essential in order to reduce background neutrons around an experimental apparatus extensively. The details of the measurement technique are described in ref. [4].

A schematic view of the facility and the experimental setup is shown in figure 1. The facility is an accelerator-based intense neutron source. Generated DT neutrons are collimated by a 2-m thick shielding structure with a narrow hole of 2 cm in diameter. The mean energy of the neutron beam is 14.2 MeV. A vacuum chamber was set at the outlet of the neutron beam, and a sample material was fixed at the center of the chamber. The sample materials used in the present study are a beryllium foil of 20 μm thickness and a carbon foil of 5 μm thickness. A counter-telescope system with a pair of silicon surface barrier detectors, one for ΔE (thickness of 9.6 μm) and the other for E (thickness of 760 μm), is employed in order to distinguish kinds of emitted charged particles. The detectable minimum energy of the telescope, which depends on the thickness of the ΔE detector, is 2.5 MeV for α-particles. In order to lower the detectable energy range, anticoincidence spectra of the ΔE detector are utilized. When the ΔE detector of 9.6 μm thickness is used, the threshold energies beyond which the ΔE detector can be penetrated are around 700 keV for protons and around 1.0 MeV for tritons. The anticoincidence spectrum above those threshold energies for protons and tritons hence originates only from α-particles or particles heavier than α-particles. In the present

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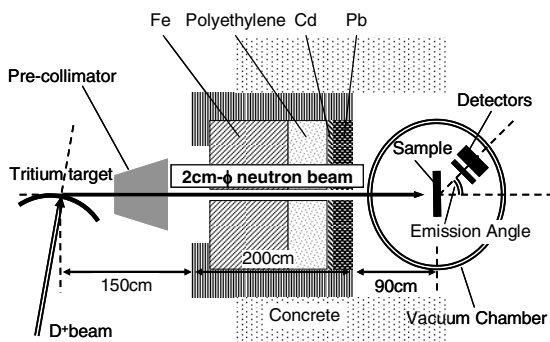
Fig. 1. Schematic view of experimental setup.

measurement, recoiling beryllium or carbon and ^{9}Be particles emitted via the ^{12}C(n,α)^{9}Be reaction cannot be negligible and their contributions are calculated and subtracted. As a result, the measurement of α-particles with a minimum energy of around 1 MeV was successfully realized.

In the present measurement, the incident neutron fluence was determined by the aluminum foil activation method. For a standard cross section, 122.0 mb for the ^{27}Al(n,α) reaction evaluated in JENDL-3.3 [6] was used.

2.2 Data analysis

In order to obtain an actual energy spectrum of emitted charged particles, the measured spectrum must be corrected for energy loss in the sample. A relationship between the actual spectrum and the measured spectrum was calculated by the Monte Carlo code SRIM-2003 [7] combined with pre- and post-processing codes we made. Then the spectrum unfolding was carried out with our original code based on the spectrum type Bayes estimation method [8] to obtain the actual spectrum.

3 Results

3.1 Measurement for beryllium

DDX data for the ^{9}Be(n,xα) reaction were obtained at 9 emission angles from 15 deg to 135 deg. There has been an only previous measurement by Ferenc et al. [9], which was, however, a relative measurement and measured energy range was not so wide. Hence, our data is the only existing detailed experiment. Figures 2 and 3 show the obtained DDX at 20 and 40deg and comparison with evaluated nuclear data taken from JENDL-3.3 and ENDF/B-VI.8 [10]. In the measured DDX, two peaks corresponding to the ^{9}Be(n,α_0)^{6}He$_{(ground\,state)}$ and ^{9}Be(n,α_1)^{6}He*$_{(1.8\,MeV)}$ reactions are identified. The evaluated libraries significantly underestimate the higher energy part of DDX at 20 deg while these well agree with each other at 40 deg. We should investigate the mechanism to account for this strong α-particle emission of higher energy at forward angles.

3.2 Measurement for carbon

DDX data for the ^{12}C(n,xα) reaction were obtained at 10 emission angles from 15 deg to 150 deg. Figure 4 shows the
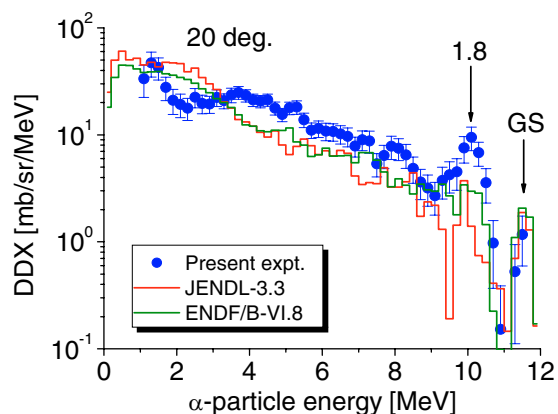

Fig. 2. Measured DDX for ^{9}Be(n,xα) reaction at emission angle of 20 deg and comparison with evaluated nuclear data.
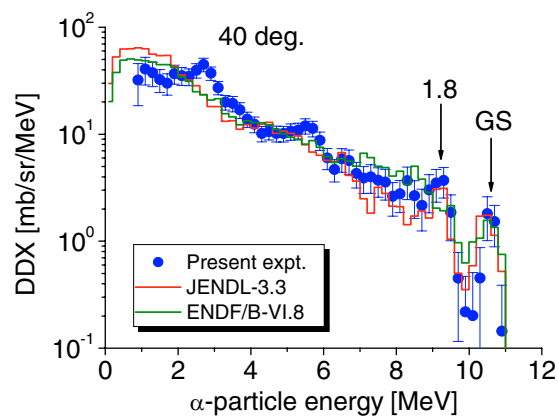

Fig. 3. Measured DDX for ^{9}Be(n,xα) reaction at emission angle of 40 deg and comparison with evaluated nuclear data.
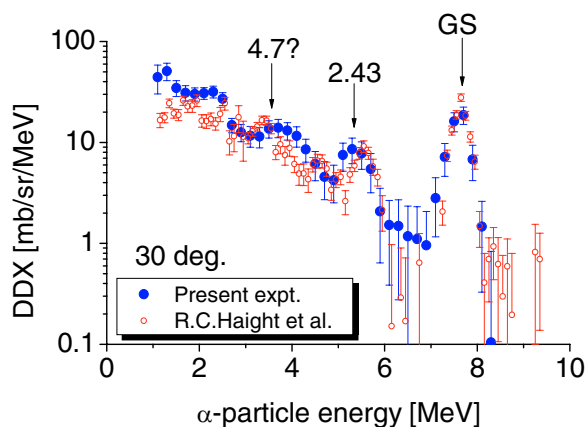

Fig. 4. Measured DDX for ^{12}C(n,xα) reaction at emission angle of 30 deg and comparison with previous measurement.

obtained DDX at 30 deg and comparison with the previous data measured by Haight et al. [11]. There is no evaluated DDX which can be compared with our data directly. In our obtained DDX, obvious peaks corresponding to the ^{12}C(n,α_0)^{9}Be$_{(Ground\,State)}$ and ^{12}C(n,α)^{9}Be*$_{(2.43\,MeV)}$ reactions are clearly identified. The contribution of ^{9}Be*$_{(4.7\,MeV)}$ might exist. Between both the measurements, agreement of the higher energy part is fairly good, while a slight discrepancy
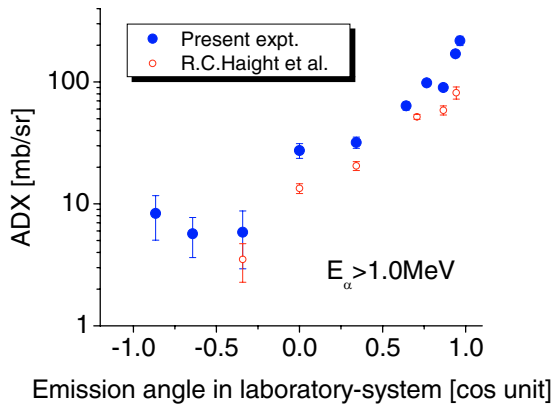
Fig. 5. Measured ADX for $^{12}C(n,3\alpha)n'$ reaction and comparison with previous measurement, where contribution of $^{12}C(n,\alpha_0)$ reaction was excluded.

was observed below 3 MeV. Figure 5 shows the angular-differential cross section (ADX) for the $^{12}C(n,n'+3\alpha)$ reaction, where the contribution of the $^{12}C(n,\alpha_0)$ is excluded. There is a strongly forward-peaked and slightly fluctuated distribution, which would suggest some direct reaction contribution. The difference between the present experiment and Haight's measurement is caused by the discrepancy of DDX below 3 MeV.

4 Analysis based on reaction kinematics

4.1 Monte Carlo calculation

We tried to identify the reaction channels which contribute to the $^9Be(n,2n+2\alpha)$ and $^{12}C(n,n'+3\alpha)$ reactions. For this purpose, emitted energy distributions of all possible channels both for α-particles and for neutrons were calculated according to reaction kinematics by the Monte Carlo method. The calculated spectra were fitted to experimental data by the least-squares method and the contributing channels were determined. For the experimental data, our measuring DDX for α-particles and DDX for neutrons measured by Takahashi et al. [5] were used. The calculation procedure was the same as that is ref. [1]. In the calculation, simply 2-body sequential decays via excited states of ^{12}C, ^9Be and ^6He and the 3-body simultaneous breakup with a pure phase space were considered. Decay modes for $^8Be^*$ and $^5He^*$ from the excited nuclei were adopted according to refs. [2,12,13]. For all the intermediate states, the density-of-states function was given by the Breit-Wigner distribution with constant level widths evaluated in refs. [12,13]. The angular distributions for the inelastic scattering of neutrons, which were given in the calculation, were cited from ref. [5] for the excited states of ^9Be at 2.43, 4.7, 6.76 and 7.94 MeV and ^{12}C at 7.65 and 9.64 MeV. For the other excited states of ^9Be and ^{12}C, isotropic distribution in center-of-mass system was assumed. In other 2-body decays, isotropic distribution in center-of-mass system was also assumed.

4.2 Beryllium

Figure 6 shows the calculated DDX of the $^9Be(n,2n+2\alpha)$ reaction both for emitted α-particles and for neutrons at
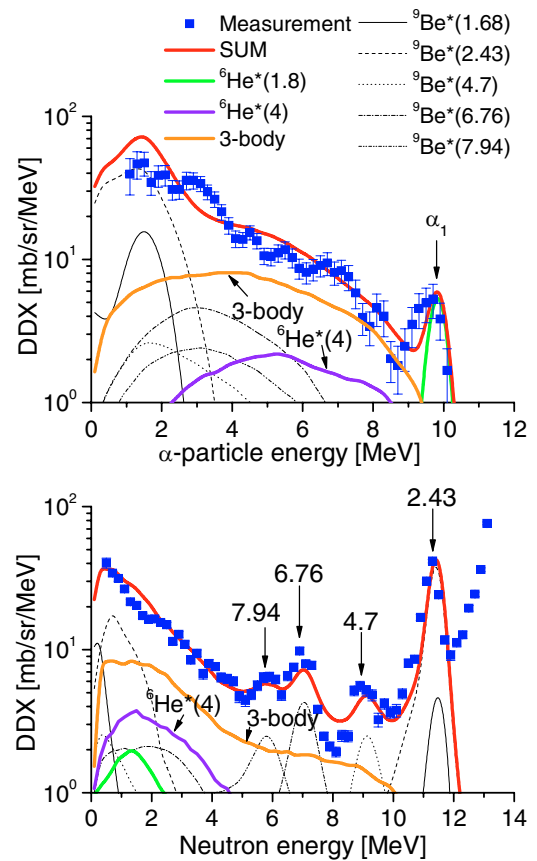

Fig. 6. Measured and calculated DDX of $^9Be(n,2n+2\alpha)$ reaction at emission angle of 30 deg both for α-particles and for neutrons.

30 deg. The component indicated as "3-body" in the figure is contribution of the $^9Be(n,n'+\alpha+^5He)$ simultaneous breakup reaction. The 3-body and $^9Be(n,\alpha)^6He^*_{(\geq 1.8 MeV)}$ channels are essential to reproduce the experimental results well. In the present study, the contribution of the $^9Be(n,\alpha)^6He^*$ channels was estimated as around 15% and the contribution of the simultaneous breakup channel was estimated as around 30%.

4.3 Carbon

Figure 7 shows the calculated DDX of the $^{12}C(n,n'+3\alpha)$ reaction both for emitted α-particles and for neutrons at 30 deg. In the present estimation, the $^9Be^*_{(2.43 MeV)}$ and $^9Be^*_{(4.7 MeV)}$ channels play an important role. The continuum in lower energy of the neutron DDX is reproduced well. These channels would be reasonable to account the strong forward-peaked distribution. The contribution of the $^{12}C(n,\alpha)^9Be^*_{(2.43 MeV)}$ and the $^{12}C(n,\alpha)^9Be^*_{(4.7 MeV)}$ channels was estimated as around 25% and 10%, respectively.

5 Summary

We have conducted detailed measurements of α-particle emission DDX for beryllium and carbon using our developed spectrometer with a pencil DT neutron beam. In order to identify the reaction channels which contribute to the
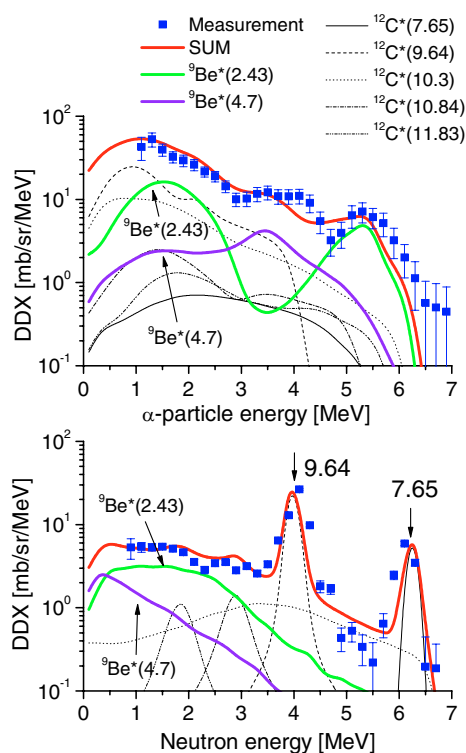
Fig. 7. Measured and calculated DDX of ^{12}C(n,n'+3α) reaction at emission angle of 30 deg both for α-particles and for neutrons.

^{9}Be(n, 2n + 2α) and ^{12}C(n, n' + 3α) reactions, emitted energy distributions of all possible channels both for α-particles and for neutrons were calculated according to reaction kinematics. The calculated spectra were fitted to our measuring DDX for α-particles and DDX for neutrons measured by Takahashi et al. As a result, the information of contributing channels was obtained. As for the ^{9}Be(n, 2n + 2α) reaction, a contribution of the ^{9}Be(n, α)^{6}He* and simultaneous breakup channels are essential to account for the measured DDX of emitted α-particles. As for the ^{12}C(n, n' + 3α) reaction, the ^{12}C(n, α)^{9}Be* channels are largely contributed and well

reproduce the lower energy continuum of neutron DDX. Significant contribution of these first-α-emission channels would suggest importance of the α-particle knock-on or stripping process. Further theoretical approaches are desired in order to investigate the direct reaction process in these nuclei.

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