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Measurement of the angle-correlated neutron spectrum for the ^{9}Be(n,2n) reaction with a pencil-beam DT neutron source

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Abstract. The angle-correlated energy differential cross-section for ^{9}Be(n,2n) reaction has been measured with the coincidence detection technique and a pencil-beam DT neutron source of FNS, JAEA. Neutron energy spectra of two emitted neutrons were separately obtained as azimuthal- and axial-angle differential value, which is called TDX. From the measured TDX, double-angle differential cross sections, ADDX, angular differential cross section, ADX, and total cross section, TOX, were deduced. In the TDX, a characteristic energy spectrum for beryllium was seen. The azimuthal ADDX unexpectedly showed a 180 deg. symmetrical spectrum, not a flat one. From the result of TOX, JENDL-3.3 and ENDF/B-VI showed a little underestimation by around 10%.

1 Introduction

The (n,2n) reaction is of importance in fusion reactor development, because it is a neutron multiplication reaction and its reaction cross section shows relatively large at around several to 14 MeV. The (n,2n) reaction cross section measurements were carried out mainly by the foil activation method so far. However, for many elements the cross section cannot be measured because sometimes radioisotopes are not produced by (n,2n) reaction. Also, in principle, the energy spectrum of emitted neutrons cannot be known with this method.

A new spectrometer to measure the spectrum of neutrons emitted through the (n,2n) reaction was hence developed by the author's group [1]. With the spectrometer, precise energy and angle differential cross section data for every element can be obtained. Improvement of evaluated nuclear data and nuclear model used in the evaluation is thus expected especially for light elements, because the energy spectra of light elements may not be expressed by an evaporation spectrum and they are often spallated by a so-called breakup reaction by incidence of 14 MeV neutron.

In the present study, ^{9}Be(n,2n) was chosen as a target (n,2n) reaction. Beryllium is a well-known key element in fusion reactor. However, the (n,2n) reaction could not be directly measured because it does not produce any radioisotopes, but just two neutrons and two α particles. In the present study, angle-correlated spectra of two neutrons emitted via ^{9}Be(n,2n) reaction have been measured with the new spectrometer and with the obtained energy spectra precise angular distribution were deduced, i.e., azimuthal-angle distribution named azimuthal ADDX as well as axial ADDX. As detailed later, ADDX is a double angle differential cross section, which is deduced from TDX, i.e., a triple (double-angle and single-energy) differential cross section. Finally the total (n,2n) reaction cross section, TOX, was estimated to compare with the evaluation and other experimental data.

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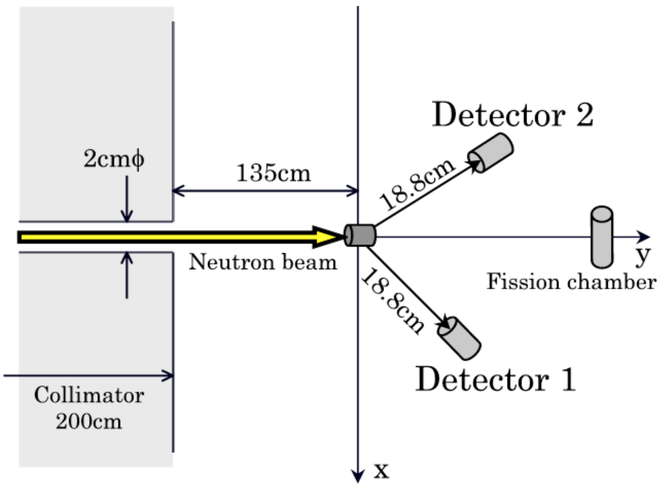

Fig. 1. Schematic experimental arrangement.

2 Experiment

The important point of the present experiment is to utilize a pencil-beam DT neutron source at FNS facility of JAEA. Figure 1 shows the exit side of the collimator from the target room to the measuring room, which is partitioned to the target room with a 2 m thick shield. In the shield there is a narrow collimator hole to make a DT neutron beam of 2 cm in diameter. By the beam we can measure emitted secondary neutrons under a very low background condition, because detectors can be arranged very close to the sample without any shield as in figure 1. The sample is a metallic beryllium (2 cm in diameter by 2 cm long). Two spherical NE213 detectors (4 cm φ) are used as a neutron detector. Each of the emitted two neutrons is detected by each detector coincidently with the coincident detection technique. The pulse shape discrimination technique is applied to exclude gamma-ray signal. The neutron intensity is $\sim 10^{6}$ n/cm^{2}/sec inside the beam. Outside the beam the BG neutron intensity is suppressed to around several tens of n/cm^{2}/sec. To measure angle correlated neutron spectrum we arranged two detectors with three angle parameters of φ, θ_0 and θ as shown in figure 2, considering symmetrical configuration of the two detectors. As a result, from several measurements it is possible to determine the total (n,2n) reaction cross section. A ^{238}U fission chamber was located on the beam line behind the sample to monitor the relative neutron flux. The absolute value was derived by the foil activation technique with an aluminium foil attached on the upstream surface of the sample. Figure 3 shows the electronic circuit of the present measuring system. The system includes n/γ discrimination part, time-of-flight part and gate process part for the coincidence detection. Nine ADCs accumulate signals, one of which is for time of flight (TOF) and the remaining eight of which is for pulse height spectra (PHS). The eight ADCs are divided into foreground detection (including coincidence peak in the TOF spectrum) and background detection (outside the foreground) as detailed in figure 4, each four of which are divided into low and high gains and for detectors 1 and 2. Adopting two gains enables to extend the measurable energy over one decade by setting 10 times larger gain than the other. The lower measurable neutron energy of the present measurement is 1.2 MeV.

Because two detectors are positioned very close with each other, there exists a particular event that a neutron passes through the two detectors one after another to yield a faked coincident signal, named inter-detector scattering. Practically, one neutron enters one detector, and can be detected by an elastic scattering with hydrogen in the detector. The scattered neutron hardly goes toward the other detector because of scattering angle limitation due to neutron-hydrogen scattering reaction kinematics. However, via multiple-scattering, the scattered neutron may go to the other detector to make a signal. We expected there should be very few events creating such an inter-detector scattering. But in fact the contribution cannot be neglected and was corrected by a Monte Carlo code. A polyethylene block up to around 10 cm in thickness was placed between the two detectors to suppress the inter-detector scattering contribution.

3 Data processing

The measured raw pulse height spectra were first transformed into light output spectra. The position of Compton edge formed by the 1.275 MeV gamma ray emitted from ^{22}Na was used for the light unit calibration. The light output spectra were unfolded using FORIST[2]. The necessary response function was calculated with SCINFUL[3]. For correcting the experimental values, two effects were taken into consideration, i.e., attenuation/multiple-scattering of incident/emitted neutrons, and the inter-detector scattering event. Both effects were estimated separately by Monte Carlo calculations with MCNP [4]. From the results of the MCNP calculation, the rate of the inter-detector scattering component was estimated to be about 5 to 40% depending on the scattering angle. The estimated correction factor increases as the distance between two detectors becomes closer. And it was confirmed that the component could effectively be suppressed by the polyethylene shield. The correction factor of the attenuation and multiple-scattering effects was found to be very small also from the MCNP calculations, since the both effects are compensated with each other.

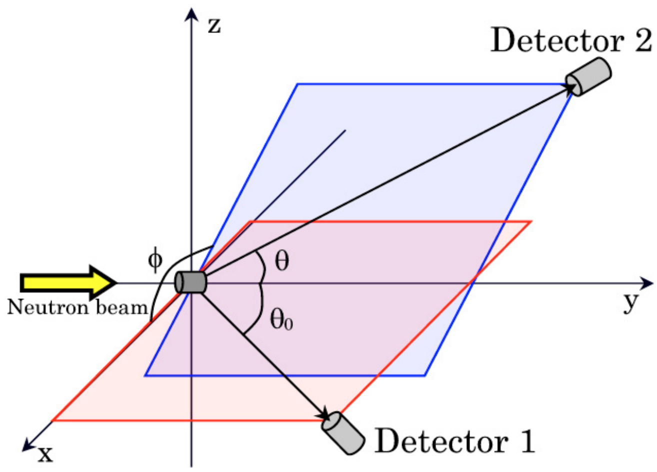

Fig. 2. Angles for setting-up of two NE213 detectors.

4 Results and discussion

Figure 5 shows several measured energy spectra. Those are a so-called triple differential cross section (TDX) having a unit of mb/sr/sr/MeV, because a signal is detected only in the case that two neutrons are detected coincidently by the two detectors. The spectra seem to fluctuate due to oscillation in the unfolding process. However, clear similarity is seen in every TDX spectrum and observed peaks could thus be expected to correspond to one of the excited states of ^{9}Be. For instance, the highest energy peak can be originated from the excited state of 2.4 MeV of ^{9}Be. It should be also noted that evaporation spectrum is not seen in the TDX unlike a heavy element case. Anyway, this is the first angle-correlated neutron spectrum measurement for ^{9}Be(n,2n) reaction.

The error bar in the figure contains only statistical error. Since there are no evaluated data, which can be compared with the measured spectra directly, it is difficult to discuss the validity of the nuclear data. But these data will be helpful to study the mechanism of ^{9}Be(n,2n) reaction in the future.

Figure 6 shows the azimuthal distribution at $\theta_0 = 90$ deg. This is a double-angle differential cross section (ADDX) as a function of azimuthal angle, φ. As well known, there should be no azimuthal angle dependence in differential cross section. However, in the present study since angle correlated measurement was carried out, a gentle 180 deg-symmetrical distribution can be seen. Surprisingly, the strength of angular dependence is not the same for each axial angle of θ. Their absolute values also vary substantially. The former is quite a curious result, which indicates the strength of correlation on the azimuthal angle can vary depending on the axial angle. The reason why peaks appear at $\varphi = 180$ deg. is easily interpreted, that is, momentum conservation tends to emit two neutrons in opposite directions. These trends have preliminarily been confirmed to be consistent with our own kinematics analysis results based on the measured result of α emission spectrum by Kondo et al. [5]. The present ADDX is anyhow the first measured result over the world.

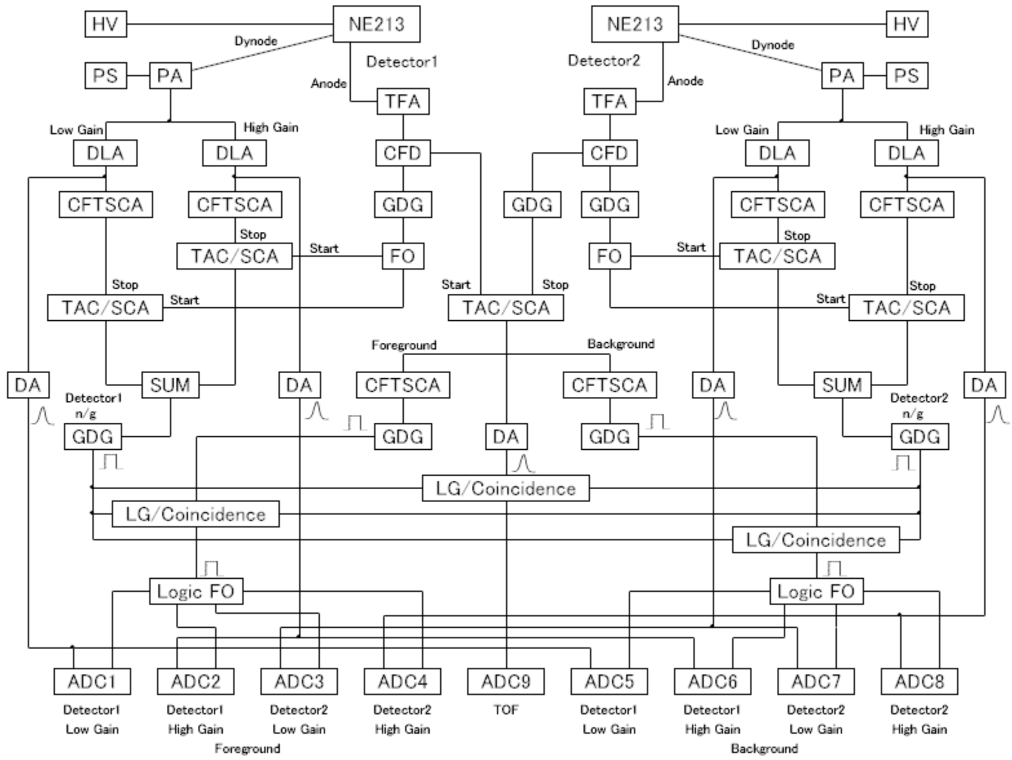

Fig. 3. Electronic circuit for neutron spectrum measurement for (n,2n) reaction with two NE213 detectors.

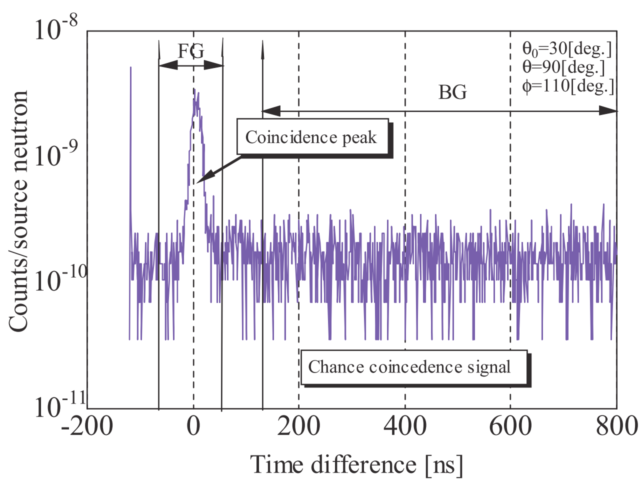

Fig. 4. Time difference spectrum made up of anode signals from the two NE213 detectors. A strong peak corresponds to the coincidence signals regarded as foreground (FG). Other flat spectrum is for time-independent coincidence signals, i.e., background (BG).

As for the ADDX as a function of axial angle of θ, there was a strong forward-oriented polar distribution as expected. The angular differential cross-section (ADX) was obtained by integrating the axial ADDX. Figure 7 shows the comparison of the measured ADX with ENDF/B-VI and JENDL-3.3 together with the previous experimental result by Takahashi et al. His data were deduced with the neutron DDX measured by the time-of-flight method [6]. The agreement among the experimental values is excellent. However, slight underestimation is seen in the JENDL-3.3 and significant underestimation is found out in ENDF/B-VI at backward angles. By integrating the ADX, the total (n,2n) reaction cross section is deduced. In the present measurement, however it is noted that the lower measurable energy is 1.2 MeV. The results are summarized in table 1. As expected from the comparison of ADX, a slight underestimation of around 10% is also observed in both nuclear data libraries. As described earlier, ENDF/B-VI showed smaller values than JENDL-3.3 in backward angles as in figure 7. This means that the ENDF/B-VI evaluation would show a little too strong forward peaked spectrum. Therefore the discrepancy with JENDL-3.3 would consequently be compensated. Reconsideration of the angle dependence is necessary in ENDF/B-VI evaluation. On the other hand, the problem for JENDL-3.3 is easily settled just by offsetting the cross section value.

Table 1. Total cross section of ^{9}Be(n,2n) reaction compared with evaluated nuclear data and the previous experimental value by Takahashi et al.

Present exp. [mb]	387 ± 11
Takahashi et al. [mb]	383 ± 6
JENDL-3.3 [mb]	344
ENDF/B-VI [mb]	340

5 Conclusion

Using the pencil-beam DT neutron source and the coincidence detection technique, angle-correlated energy differential cross-section (TDX) for ^{9}Be(n,2n) reaction has been measured for the first time. From the measured TDX, double angle

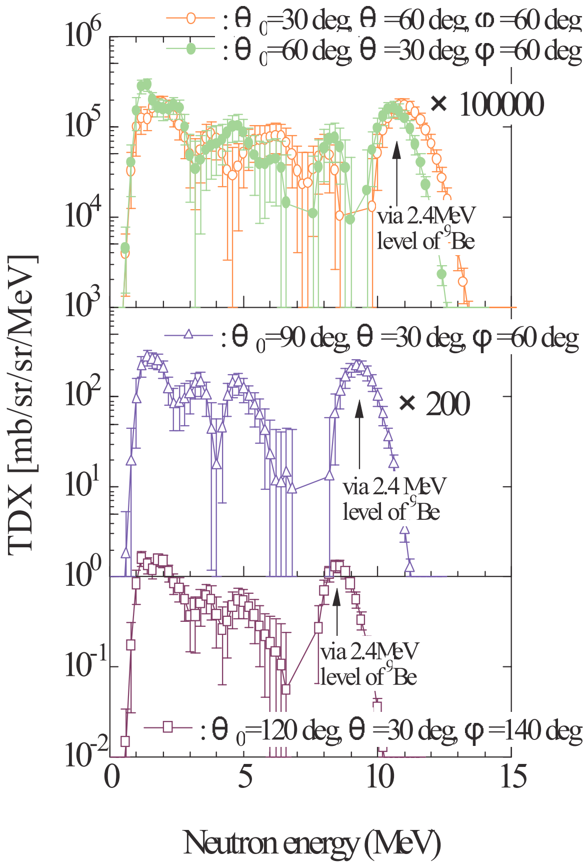

Fig. 5. Measured triple differential cross section (TDX) of ^{9}Be(n,2n) reaction for several emission angles.

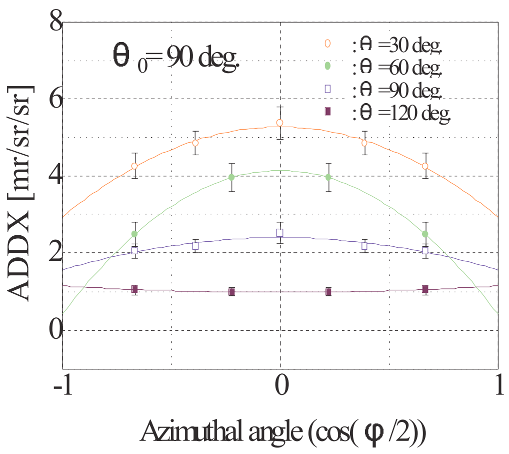

Fig. 6. Measured double-angle differential cross section (ADDX) of ^{9}Be(n,2n) reaction for azimuthal angle.

differential cross sections, ADDX, were deduced and the ADX and TOX were finally obtained. In the experimental data,

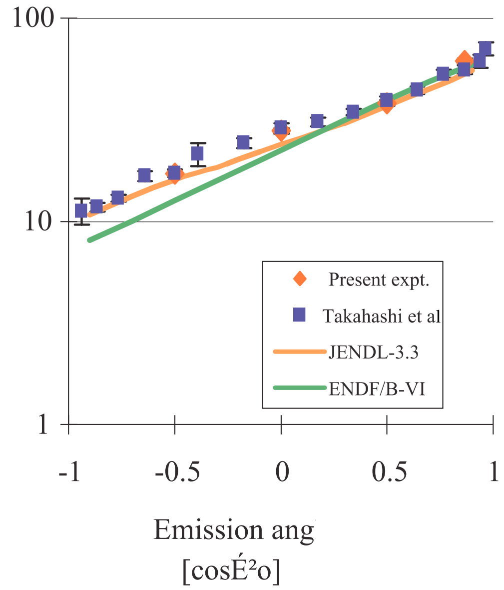

Fig. 7. Measured angular differential cross section (ADX) of ^{9}Be(n,2n) reaction compared with evaluated nuclear data and the previous experimental data by Takahashi et al.

noise signals caused by the inter-detector scattering event were corrected with the numerical analysis carried out by a Monte Carlo code. In the TDX, a characteristic energy spectrum corresponding to beryllium was seen. The azimuthal ADDX showed unexpectedly not a flat distribution, but a 180 deg. symmetrical spectrum. From the result of TOX, the evaluated nuclear data of JENDL-3.3 and ENDF/B-VI showed a little underestimated value by 10%, though the lower measurable energy should be noted to be 1.2 MeV. It was found that more precise and consistent analysis with measured α emission DDX data would be indispensable to improve the evaluated nuclear data.

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