Measurement of Angle-correlated Differential (n,2n) Reaction Cross Section with Pencil-beam DT Neutron Source

S. Takaki, K. Kondo, S. Shido, H. Miyamaru, I. Murata, K. Ochiai* and T. Nishitani*
Division of Electric, Electronic and Information Engineering,
Graduate School of Engineering, Osaka University, Suita, Japan
*Japan Atomic Energy Agency, Tokai-mura, Ibaraki, Japan
e-mail: takagi@ef.eie.eng.osaka-u.ac.jp

Angle-correlated differential cross-section for ^{9}Be(n,2n) reaction has been measured with the coincidence detection technique and a pencil-beam DT neutron source at FNS, JAEA. Energy spectra of two emitted neutrons were obtained for azimuthal and polar direction independently. It was made clear from the experiment that there are noise signals caused by inter-detector scattering. The ratio of the inter-detector scattering components in the detected signals was estimated by MCNP calculation to correct the measured result. By considering the inter-detector scattering components, the total ^{9}Be(n,2n) reaction cross-section agreed with the evaluated nuclear data within the experimental error.

1. Introduction

^{9}Be(n,2n) reaction cross-section is quite important value in order to design fusion reactor. However, because ^{9}Be(n,2n) reaction makes no radioactive isotopes, the foil activation method cannot be used. The cross-section can be measured by the detection of α-particles. But it is impossible by the method to obtain emitted neutron energy spectrum of emitted neutron directly, which is very important in the case of light nuclei because the evaporation process may not be directly applied to evaluate the spectrum. Up to now, the method using coincidence detection technique was established.[1] In the present study, this method was applied to measure energy and angular dependent distributions of ^{9}Be(n,2n) reaction.

2. Experimental procedure

In present experiment, we used a pencil-beam DT neutron source of Fusion Neutronics Source (FNS) in Japan Atomic Energy Agency (JAEA). It is the only existing pencil-beam DT neutron source in the world, which supplies an excellent experimental condition, i.e., 10^{6} n/cm^{2}/sec inside the beam and several hundred n/cm^{2}/sec outside. One can thus arrange neutron detectors very close to the sample to get a very good signal to noise (S/N) ratio.

The schematic experimental arrangement around detectors is shown in Fig.1. The distance between the neutron source and a beryllium sample (2cm in diameter, 2cm long) was 485cm. Two spherical

NE213 (4cm in diameter) detectors to detect neutrons emitted simultaneously by the (n,2n) reaction were used and located at 18.8cm from the beryllium sample. An ^{238}U fission chamber was located on the beam line behind the sample to monitor the neutron flux. As shown in Fig.2, three angular parameters (θ_0,θ,ϕ) with respect to the detector position were defined in which θ_0 and θ are polar angles of emitted two neutrons and ϕ is the azimuthal angle of detector 2 from detector 1. Measurement points were determined by the combination of these angle parameters.

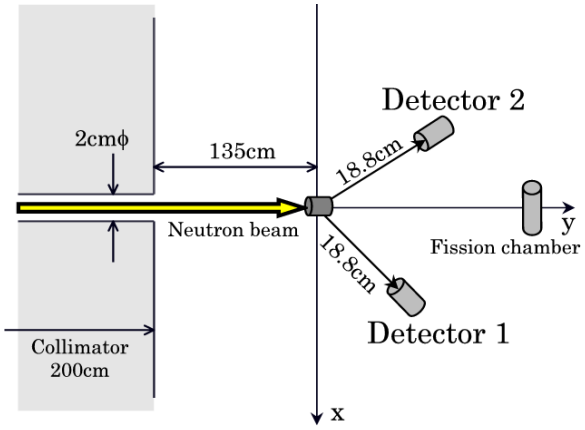

Fig.1 Schematic experimental arrangement

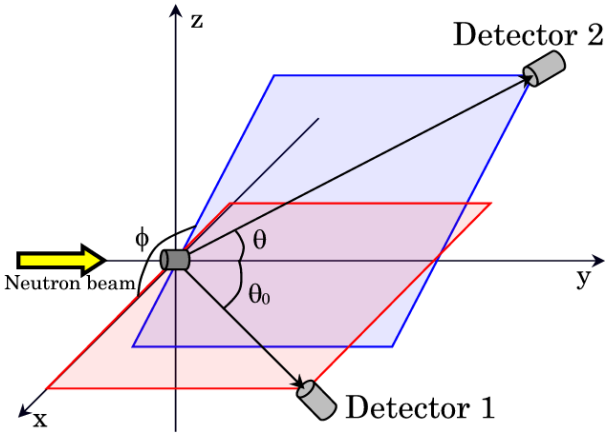

Fig.2 Arrangement around sample and detectors

Because two detectors are positioned very close with each other, there are neutrons, which can pass through both detectors in turn by inter-detector scattering. The existence of such a signal was confirmed by the measurement with a carbon sample, in which (n,2n) reaction cannot take place with 14MeV neutron, and could not be neglected. A polyethylene shielding block up to 10.16cm in thickness was located between two detectors depending on the measurement points to prevent inter-detector scattering components.

Because NE213 detectors are sensitive also to gamma ray, n/γ discrimination was applied by the pulse shape discrimination technique. Two amplifiers with different gains were used to cover a wider measurable energy range. Timing difference spectrum of anode signals of the two detectors was used to extract the coincidence signals. In the time difference spectrum, time-dependent signals, i.e., coincidence signals make a peak on a flat spectrum of time-independent signals, i.e., chance coincidence signals. The region including the peak was gated and defined as Foreground (FG), and the region of time-independent signals was defined as Background (BG). Eight pulse height spectra were measured for one case considering two detectors (1/2), two gains (high/low) and FG and BG. Details of the electric circuit of the measurement is described in ref.[1].

3. Data processing

Obtained pulse height spectra were transformed into light output spectra. Examples of measured pulse height spectra are shown in Fig.3. The position of Compton edge made by 1.275MeV gamma ray emitted from ^{22}Na was used in the light unit calibration. The BG spectra (y_{BG}) were subtracted from FG spectra (y_{FG}) by following equation.

$$y = y_{FG} - \alpha y_{BG} \qquad (1)$$

where, α is the ratio of the gate widths between FG and BG spectra.

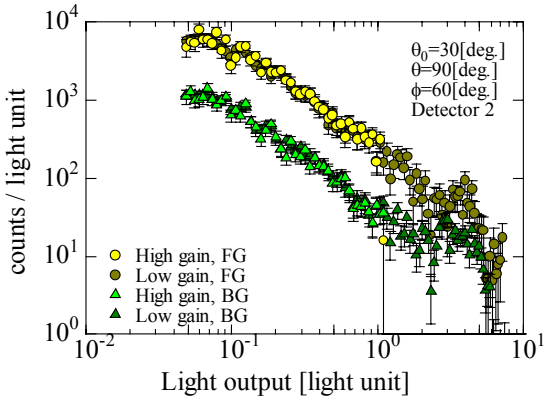

Fig.3 Measured light output spectra at described measurement point

The net light output spectra were unfolded using FORIST[2] unfolding code. Necessary response function was calculated with SCINFUL[3]. And the energy spectra were obtained by the following equations,

$$y(\theta_0,\theta,\phi,E) = R \cdot x(\theta_0,\theta,\phi,E) \qquad (2)$$

$$\sigma_i(\theta_0,\theta,\phi,E) = \frac{x_i(\theta_0,\theta,\phi,E)}{N \cdot FC \cdot C \cdot d\Omega_i \cdot d\Omega_j \cdot f_j} \qquad (3)$$

where, subscript in eq.(3) represent either detector 1 or detector 2, R is the response matrix of the NE213 detector, x_i is the unfolded spectrum, σ_i is the energy spectrum, N is the number of nuclei of the sample, FC is the integrated counts of the fission chamber monitor, C is the conversion factor of FC into the neutron flux at the sample, $d\Omega_i$, $d\Omega_j$ is the solid angle of each detector, f_j is the efficiency of detector j. The efficiency of the other detector was considered in the response matrix. The conversion factor C was determined by the activation method using aluminum foil. The angle-correlated differential cross-section was obtained by integrating the energy spectrum.

As for the correction of the inter-detector scattering effect, the detection rate of inter-detector scattering component was estimated by Monte Carlo calculation with MCNP[4] and a precise model of the experimental arrangement.

4. Results and discussion

Figure4 shows the obtained energy spectra. In the spectra, the inter-detector scattering

components are included. The error bar in Fig.4 contains only statistical error. As show in the figure, the oscillation due to poor statistics is observed especially in the high energy region above 7MeV. Since there are no evaluated data, which can be compared with the spectra in Fig.4, 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.

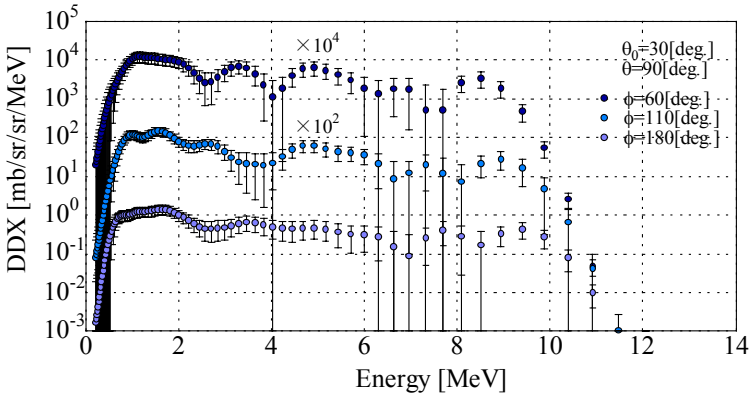

Fig.4 Obtained energy spectra at each angle

From results of the MCNP calculation, the rate of the inter-detector scattering component in the angle-correlated differential cross-section was estimated to be about 5 to 40% as shown in Fig.5. The rate increases as the distance between two detectors becomes closer. And it was found that the component was effectively suppressed by the polyethylene shield.

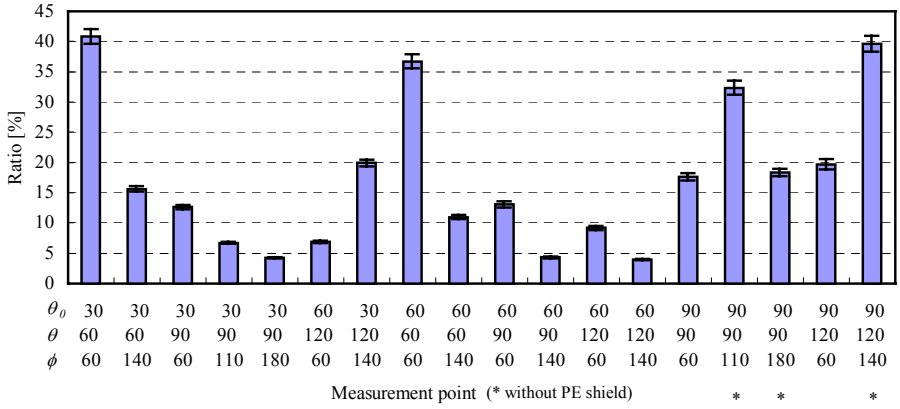

Fig.5 The ratio of the inter-detector scattering component

Figure 6 shows the azimuthal distribution at θ=90 deg. and Fig.7 shows the polar distribution at each scattering angle (θ_0 and θ) of the angle-correlated differential cross-section after subtraction of the inter-detector scattering component.

There was some azimuthal structure although it is not taken into consideration in the evaluated data. And there was a strong forward oriented polar distribution. These distributions would mainly reflect reaction kinematics according to many reaction processes included in ^{9}Be(n,2n) reaction.

The angular differential cross-section for the polar angle θ_0 was obtained by integrating the distribution over the polar angle θ. Figure8 shows the comparison of the angular distribution of cross-section with JENDL-3.3[5]. The angular distribution measured by Takahashi et al.[6] is also shown in Fig.8. It was measured by the TOF method. And it agrees well with this experiment. Especially in forward scattering angle, agreement between this experiment and the evaluated data was excellent, although there was underestimation in the JENDL-3.3 at a backward angle. Obtained total cross-section is 418±5.4mb, which is a little larger than the value evaluated in JENDL-3.3 of 380.85mb (lower energy limit was 800keV). This deference would results from the underestimation at the backward angle. Therefore further detail measurements at back scattering angles are needed.

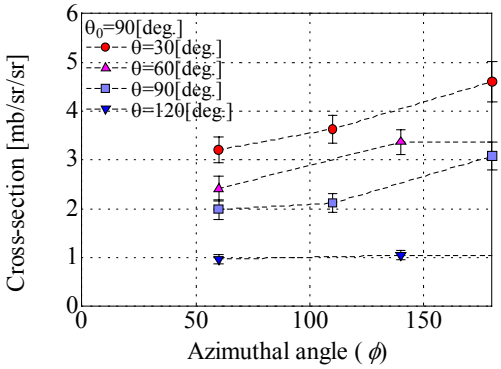

Fig.6 The azimuthal distribution of ^{9}Be(n,2n) reaction cross-section at θ_0=90 deg.

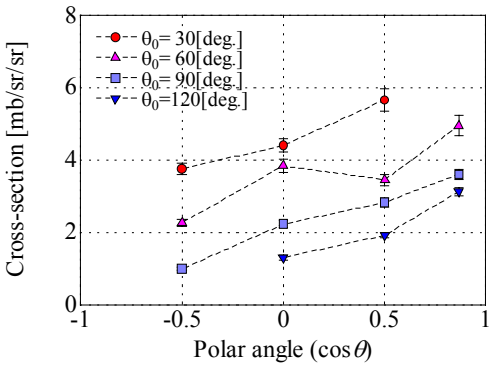

Fig.7 The polar distribution of ^{9}Be(n,2n) reaction cross-section at each scattering angle

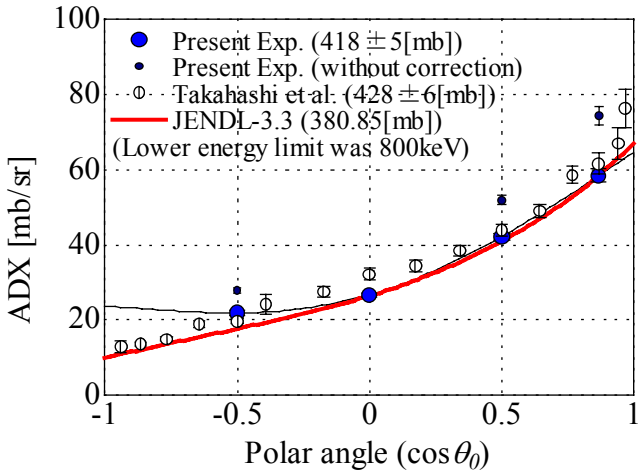

Fig.8 The angular differential cross-section for ^{9}Be(n,2n) reaction compared with JENDL-3.3

5. Conclusion

Using the pencil-beam DT neutron source and the coincidence detection technique, angle-correlated energy differential cross-section for ^{9}Be(n,2n) reaction was measured successfully. Noise signals caused by the inter-detector scattering component were taken into consideration and subtracted according to the calculation. As for in the energy spectra, measurement with better statistics is required to discuss the validity. However, the integral value of the energy spectrum, that is the total cross-section, has an acceptable accuracy, and could be compared with the evaluation to give an excellent agreement with JENDL-3.3. Since the longitudinal distribution of ^{9}Be(n,2n) reaction and its energy spectrum was quite new measurement value, which has been measured very few, more investigation will be required in order to find out the nuclear reaction of beryllium precisely.

Acknowledgements

The authors wish to acknowledge the FNS staff for their excellent operation of the FNS accelerator: Mr. Kutsukake, Mr. Tanaka, Mr. Abe, Mr. Seki and Mr. Oginuma.

References

[1] I. Murata et al., *J. Nucl. Sci. Technol.*, **Sup. 2**, 433 (2002)

[2] R. H. Johnson: “FORIST:Neutron Spectrum UnfoldingCode - Iterative Smoothing Technique”, PSR-92, ORNL/RSIC (1975).

[3] J. K. Dickens: “A Monte Carlo Based Computer Program to Determine a Scintillator Full Energy Response to Neutron Detector for En Between 0.1 and 80 MeV:User's Manual and FORTRAN Program Listing”, ORNL-6462 (1988).

[4] J. F. Briesmeister, Ed.: “MCNP – A General Monte Carlo N-Particle Transport Code, Version 4C”, LA-13709-M (2000).

[5] K. Shibata et al. “Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL-3.3”, *J. Nucl. Sci. Technol.*, **39**, 1125 (2002).

[6] A. Takahashi et al. “Double differential neutron emission cross sections at 14.1MeV –Volume-I-,” *OKTAVIAN Report*, **A-87-03**, Osaka University, Japan (1987)