4.4 Measurement of (n,2n) Reaction Cross Sections by Coincidence Detection of Emitted Two Neutrons with A Pencil-Beam DT Neutron Source

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4.4.1 Introduction

The (n,2n) reactions are of primary interest in the design of fusion reactor, because it is a neutron multiplication reaction and has a large cross section value in the energy range of several to 14 MeV. In the previous experiments, the cross section was measured mainly by the foil activation method. However, the measurement often became difficult unless appropriate radioisotopes were produced by the reaction. In other words, if a sample element includes isotopes of which the difference of the neutron number between any two isotopes is unity, the measurement is impossible in principle. To overcome this difficulty, there are some other methods available to obtain the cross section value. The most famous method is to measure neutron multiplication using a very large schintillator [1]. However, at present the accuracy of the method is not better than the foil activation method. Also the method is normally available for elements, i.e., an enriched sample should be prepared for measuring an isotope. Nevertheless, it can be said that mostly the cross sections of (n,2n) can be measured with this somewhat old method, unless minding the accuracy.

The focused point in the present study is the differential cross section, i.e., energy spectrum and angular distribution. With the above method, it is not possible to measure the neutron spectrum and angular distribution of neutrons emitted through (n,2n) reaction. Fortunately, the energy spectrum of the two neutrons is mostly predicted by an evaporation spectrum. But, for light elements, the energy spectrum might become complicated because the evaporation process may not be assumed for small cluster nuclei. For 14 MeV neutrons, it is generally known that there is weak angular dependence, i.e., forward oriented distribution on the angular differential cross section. However, for lights elements the detailed angular dependence is not yet found out. It must be crucial information to find out the nuclear reaction mechanism. The problem is that it is quite hard to extract and measure only the two neutrons emitted from (n,2n) reaction out of all the measured signals including strong background neutrons and other particles.

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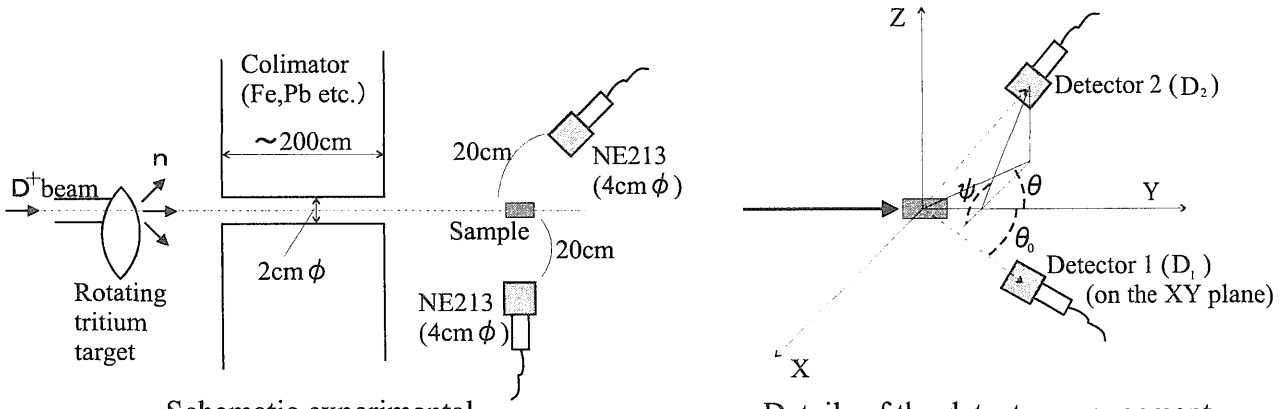
In the present study, using a newly developed pencil-beam DT neutron source at fusion neutronics source (FNS), JAERI [2], a method was established to accurately measure the energy and angle dependent neutron spectrum of only the emitted two neutrons as well as its cross section with the coincidence detection technique, especially for light elements to examine their (n,2n) reaction mechanism. The method was at first validated by an experiment with a manganese sample [3,4], because the emitted neutron spectrum from ^{55}Mn(n,2n) reaction can be assumed to be an evaporation spectrum and the cross section value was well known by various experimental studies carried out so far. In the present paper a preliminary result of measurement for beryllium was also described. Beryllium is known to be the most



Schematic experimental arrangement.

Details of the detector arrangement.

important neutron multiplication material for the fusion reactor.

Fig. 4.4-1 Experimental arrangement.

4.4.2 Experimental

Measurement of (n,2n) reaction cross section is possible in principle with the coincidence detection technique for two neutrons emitted simultaneously. However, it is not easy to attain an acceptable signal to noise (S/N) ratio, because isotropically produced source neutrons, the great majority of which does not bombard the sample, act as a large amount of background signals in the measurement. One must shield detectors to prevent such neutrons from bombarding the detectors directly and/or indirectly. Thus it means that detectors cannot be arranged close to the sample. This is a significant problem to realize efficient coincidence detection of the two neutrons. The newly developed pencil-beam (2 cmϕ-collimated) DT neutron source at Fusion Neutronics Source (FNS) [2] of Japan Atomic Energy Research Institute (JAERI) can realize the measurement. The details of the experimental procedure can be found elsewhere [3,4]. A brief description is hence given here.

The schematic experimental arrangement is shown in Fig. 4.4-1. A small sample was positioned on the beam line at ~60 cm from the collimator, meaning that the sample was

placed at ~350 cm from the neutron source. The dimensions of the sample are 1.5 cmϕ3 cm long, so that the sample can be arranged just inside the neutron beam region. The neutron flux intensity at the sample, determined by Al foil, was 1×10^6n/sec/cm^2. Two spherical NE213 (4cmϕ) detectors were arranged on a spherical shell, the center of which is the sample, in order to measure simultaneously emitted two neutrons. The distance between the sample and the detector is 20 cm.

The measurement was carried out with the coincidence detection technique and n/γ pulse shape discrimination technique to exclude other pairs of simultaneously emitted particles than the two neutrons of (n,2n) reaction. The former is a technique to selectively measure two neutrons emitted simultaneously through the (n,2n) reaction by coincidence detection. The latter technique was employed to exclude coincident signals of n γ and γ γ pairs through nuclear reactions such as (n,n' γ), (n,2n γ) by discriminating the rise time spectrum of dynode signals.

As for the angular dependence, it is known that a slightly forward oriented distribution can be obtained if simultaneously emitted two neutrons are not distinguished. However, in the present measurement, the angular correlation of the two neutrons could be taken into account to yield accurate (n,2n) cross section because the two neutrons are measured separately with two detectors.

4.4.3 Data processing and correction

The net raw neutron spectrum is deduced by the following equation:

$$y=(y_{in,FG}-\alpha \cdot y_{in,BG})-\beta\,(y_{out,FG}-\alpha \cdot y_{out,BG}), \qquad (1)$$

where, y is the net raw FG spectrum, $y_{in,FG}$ and $y_{in,BG}$ the raw FG and BG spectra in sample-in measurement, $y_{out,FG}$ and $y_{out,BG}$ the raw FG and BG spectra in sample-out measurement, α the ratio of the gated width in the time difference spectrum of two anodes signals of the detectors, and β the normalization factor between the sample-in and -out measurements, respectively. This equation can be used for both detectors. Then the cross section can be obtained by the next equations:

$$N\sigma\,\phi\,\eta\,(d\Omega_1/4\pi)(d\Omega_2/4\pi)f_1 f_2' R_1 = y_1, \text{ for detector 1,} \qquad (2)$$
$$N\sigma\,\phi\,\eta\,(d\Omega_1/4\pi)(d\Omega_2/4\pi)f_2 f_1' R_2 = y_2, \text{ for detector 2,} \qquad (3)$$

where, N is the number of sample atoms, σ the (n,2n) cross section, ϕ the neutron flux at the sample, η the neutron multiplicity of (n,2n) reaction, = 2, $d\Omega_1$ and $d\Omega_2$ the solid angles of the detectors (1 and 2), f_1 and f_2 the efficiencies of the detectors, f_1' and f_2' the conditional

efficiencies of the detectors, R_1 and R_2 the response functions of the detectors, y_1 and y_2 the pulse height spectra of the detector (identical to y in Eq.(1)), respectively.

The obtained cross section should be corrected for the following problems. One is neutron multiple-scattering in the sample. Multiple-scattering due to incident neutrons as well as emitted neutrons through (n,2n) reaction should be taken into consideration. And the other is inter-detector scattering of neutrons produced in the sample. This means that sequential detections of a neutron in the two detectors can be recognized as a coincidence signal. These correction calculations were carried out with the Monte Carlo code MCNP-4B[5] and the correction factor was estimated to be about 10%.

More details about the data processing and correction are given in Refs. [3,4].

4.4.4 Results and discussion

4.4.4.1 Validation of the method with the result of Mn [3,4]

Figure 4.4-2 shows time difference spectrum between anode signals of the two NE213 detectors. A large peak corresponding to the FG signals is found at around 200 ns in the sample-in spectrum. Since correlated signals are detected almost simultaneously, a 200 ns delay is artificially added to one anode signal. In the sample-out spectrum, a very small peak around the same position as the FG peak is seen. This corresponds to detection of two coincident neutrons due to (n,2n) reaction induced at materials surrounding the sample and detectors or inter-detector scattering of neutron between the two detectors. The BG counts are successfully suppressed and a good S/N ratio is therefore achieved.

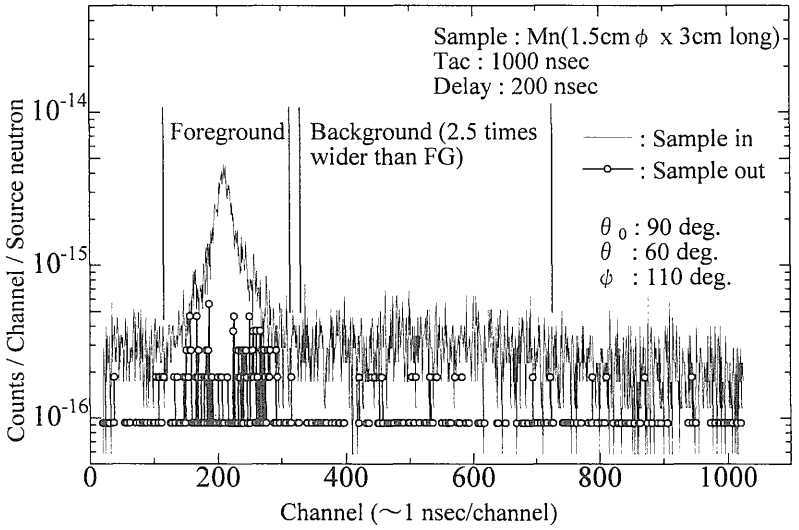


Fig. 4.4-2 Time difference spectrum between two NE213 detectors.

Figure 4.4-3 shows angular distribution for axial direction compared with the nuclear data of JENDL fusion file. It seems that one can see a slightly forward oriented distribution.

However, the accuracy is not so good as to conclude it. Nevertheless, the integral value, that is (n,2n) reaction cross section, is acceptable. This indicates that the present new measurement method is significantly successful. From the result of angular distribution for circumferential direction, it seems that there is no angular dependence. From these results, it is confirmed that the angular dependence is, if any, very weak. Thus, it is expected that one complete measurement for a medium-heavy element would become possible by several measurements.

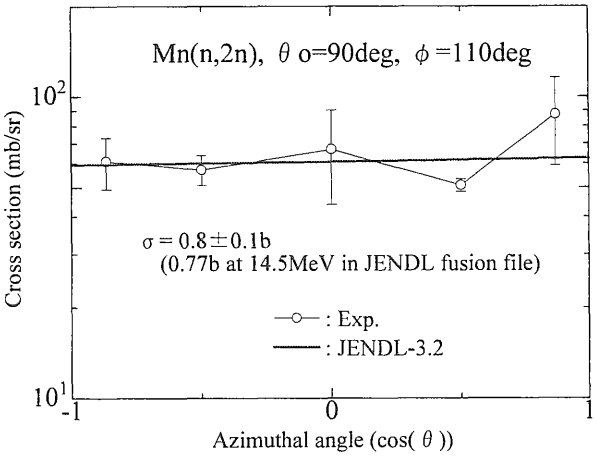


Fig. 4.4-3 Angular differential cross section of Mn(n,2n).

4.4.4.2 Test measurement of beryllium [6]

A measurement for beryllium was preliminarily carried out to roughly see the angle dependence of the energy spectrum. The results will be helpful for the coming next experiment. Figure 4.4-4 shows some neutron spectra for various angle pairs under the condition that one detector is fixed at 45 deg. The energy spectra did not vary very much with respect to the scattering angle. Also the estimated angular differential cross section at 45 deg. was fairly larger than the evaluation as in Fig. 4.4-5. The latter result seems to be a serious problem. However, the circumferential angle difference, ϕ , of two detectors is 180 deg. in the measurement, meaning that the cross section may become its maximum considering the circumferential symmetry. In this case, the experimental value can be larger than the evaluation. Another problem is the extrapolation of cross section in Fig. 4.4-5. From this figure, there exists a quite strong angular dependence, i.e., strong forward angle oriented spectrum. However, no measured values are given in this experiment around

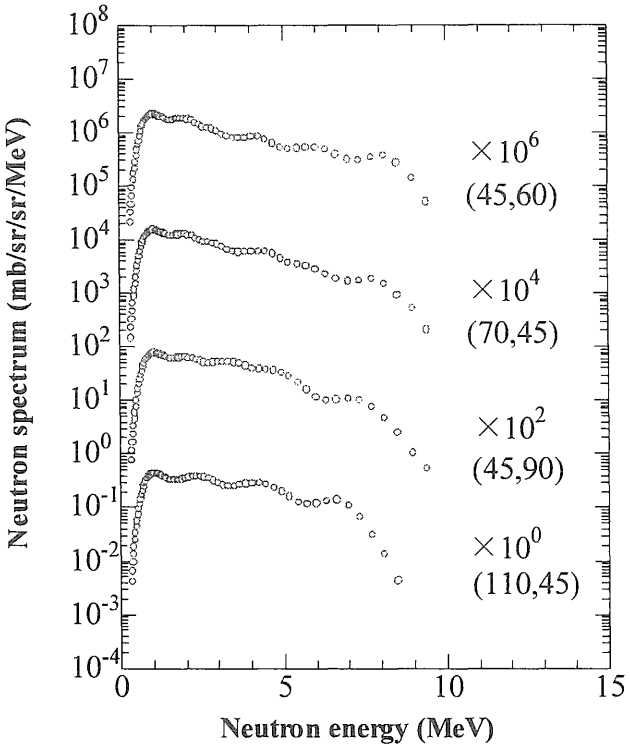


Fig. 4.4-4 Double angular differential neutron emission cross section of Be(n,2n) reaction. (θ_1, θ_2) means azimuthal angles of two NE213. detectors.

forward scattering angles. The extrapolation can thus cause a critical overestimation on the experimental value. It is concluded that more precise experiments of angular dependence are indispensable in the next machine time.

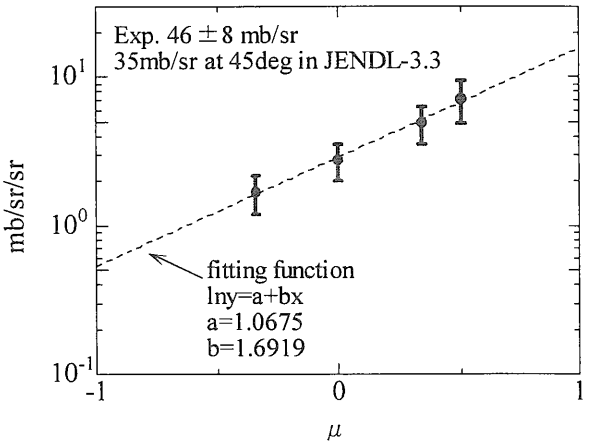


Fig. 4.4-5 Double angular differential cross section of Be(n,2n).

4.4.5 Conclusion

Using a newly developed pencil-beam DT neutron source at FNS, the method has been established to measure (n,2n) reaction cross section and its energy and angular distributions of simultaneously emitted two neutrons with the coincidence detection technique. In the present measurement, a cylindrical manganese, the (n,2n) cross section of which had been measured precisely with the foil activation method, was used to check the experimental method. From the results, it was confirmed that the present new method was basically functioning to measure only two neutrons emitted through (n,2n) reaction. Also, it was found that for Mn not so strong angular dependence was observed. It is therefore expected that complete measurement for a medium-heavy element and for stable-isotope producing element by (n,2n) reaction would become possible by several measurements. Also preliminary measurement was carried out for beryllium sample. As a result, the angular dependence of the cross section was quite large, however, the shape of the energy spectrum had little angular dependence. For beryllium further experiments are indispensable for more precise discussion.

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