(n,2n) Reaction Cross Section Measurement with A Beam DT Neutron Source

-Measurement Method-

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The method has been established to measure (n,2n) reaction cross section with the coincidence detection technique using a newly developed beam-type DT neutron source at FNS, JAERI. A cylindrical manganese, the (n,2n) cross section of which was measured precisely with the foil activation method, was used to check the experimental method. It was confirmed from the experimental results that the present new method was basically functioning to measure only two neutrons emitted through (n,2n) reaction. Also, for manganese not so strong angular dependence was observed though the statistical accuracy was not sufficient. Consequently, it is expected that complete measurement for stable-isotope producing element by (n,2n) reaction would become possible by several measurements.

1. Introduction

The (n,2n) reaction plays a very important role in the design of fusion reactor, because it is a neutron multiplication reaction and has a large cross section value over 1 barn except for light and heavy nuclides in the energy range of several to 14 MeV. In the previous experiments, the (n,2n) reaction cross sections were measured mainly by the foil activation method. Thus, the measurement became difficult unless appropriate radioisotopes were produced by the reaction. Even now, there are many natural elements left the experimental values of which are not obtained[1]. Also, especially for light elements measurements of the neutron energy spectrum and the angular distribution for the (n,2n) reaction are important, however, they were not carried out so far.

In the present study, using a newly developed beam-type DT neutron source at fusion neutronics source (FNS), JAERI, the method is established to measure (n,2n) reaction cross section and its energy and angular distribution of simultaneously emitted two neutrons with the coincidence detection technique for elements having no experimental data.

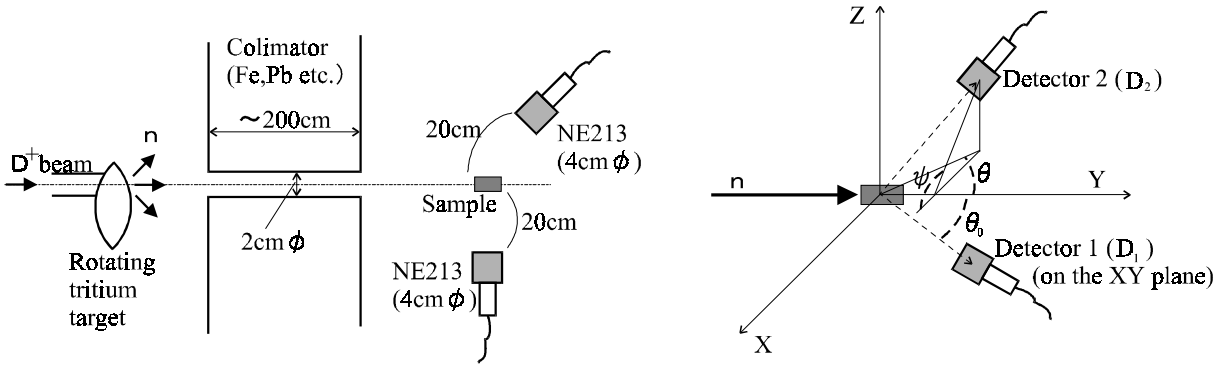
2. Experimental

Measurement of (n,2n) reaction cross section is possible in principle with the coincidence detection technique for two neutrons emitted simultaneously. However, an acceptable signal to noise (S/N) ratio could

not be obtained 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. The newly developed beam-type (2 cm ϕ-collimated) DT neutron source at FNS can realize the measurement by using the coincidence detection technique. The beam DT neutron source was developed by making a narrow (2cmϕ) hole (collimator) through the very thick shield (～2m) between the target room and the measurement room. The intensity of neutrons is ～1×10^6 n/sec/cm^2 at the exit of the collimator. The neutron flux rapidly decreases outside the beam region, therefore detectors can be arranged near the beam line. For this reason, differential cross sections which were difficult to be measured can be measured.

The schematic experimental arrangement is shown in Fig. 1. A small sample was positioned on the beam line at ～60 cm from the collimator, that means the sample was placed at ～350 cm from the neutron source. The dimensions of the sample are 1.5 cmϕ×3 cm long. The neutron flux intensity at the sample, determined by Al foil, was 1×10^6. Two NE213 (4cmϕ spherical) detectors were arranged at several positions (20 cm from the sample).

The measurement was carried out with the coincidence detection technique and n/γ pulse shape discrimination technique. The former is a technique to measure selectively two neutrons emitted simultaneously from (n,2n) reaction by coincidence detection. The (n,3n) reaction can be detected by this method, but it can be neglected because the threshold energy is mostly larger than 14 MeV. The latter technique was employed to exclude coincident signals of nγ pairs through (n,n'γ), (n,2nγ) and so on by discriminating the rise time spectrum of dynode signals. Two delay line amplifiers with different gains were used to extend the dynamic range of the detector from 100 keV to 10 MeV. The electronic circuit used in the present experiment is shown in Fig. 2. Foreground (FG) and background (BG) indicated in the figure correspond to coincident and time-independent signals as shown later in Fig. 3, respectively. As for the neutron angular distribution, 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 should be taken into account to yield the cross section because the two neutrons are measured separately with two detectors. Thus several measurements were carried out for one sample considering the symmetrical arrangement of the detectors. As the sample, a cylindrical manganese (1.5 cmϕ×3 cm long), the (n,2n) cross section of which was measured precisely with the foil activation method, was used to check the experimental method. Also, sample-out measurements were carried out to remove time-dependent background.



(a) Schematic arrangement of the detectors. (b) Details of the detector arrangement.

Fig. 1 Experimental arrangement.

3. Data processing and correction

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

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

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 spectra obtained by both detectors. Then the cross section can be obtained by the next equations:

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

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

where, N is the number of manganese 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. Also, f_1' and f_2' are calculated by the equations,

$$f_1'(E_2) = \Sigma_1 \xi_{2\to1}(E_2,E_1) f_1(E_1) \quad (4)$$

$$f_2'(E_1) = \Sigma_2 \xi_{1\to2}(E_1,E_2) f_2(E_2) \quad (5)$$

where, $\xi_{2\to1}$ is a normalized spectrum of correlated neutrons to be detected at detector 1 when a neutron with the energy of E_2 is detected at detector 2. $\xi_{1\to2}$ has a similar meaning as $\xi_{2\to1}$. Σ_1 and Σ_2 mean summations over E_1 and E_2, respectively. In the present study, a simple condition was assumed that there was no angle dependence in energy spectrum, and the EDX spectrum data in the nuclear data file were used to deduce the conditional efficiencies, f_1' and f_2'. The terms, $y_1R_1^{-1}$ and $y_2R_2^{-1}$, in eqs. (2) and (3) were calculated by the FORIST[2] unfolding code with the detector response matrix evaluated by the SCINFUL[3] code.

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 coincidence signal. Neutrons coming from materials other than the sample can be also scattered at two detectors sequentially, however their contribution can be removed by using the sample-out measurement. These correction calculations were carried out with the Monte Carlo code MCNP-4B[4] and

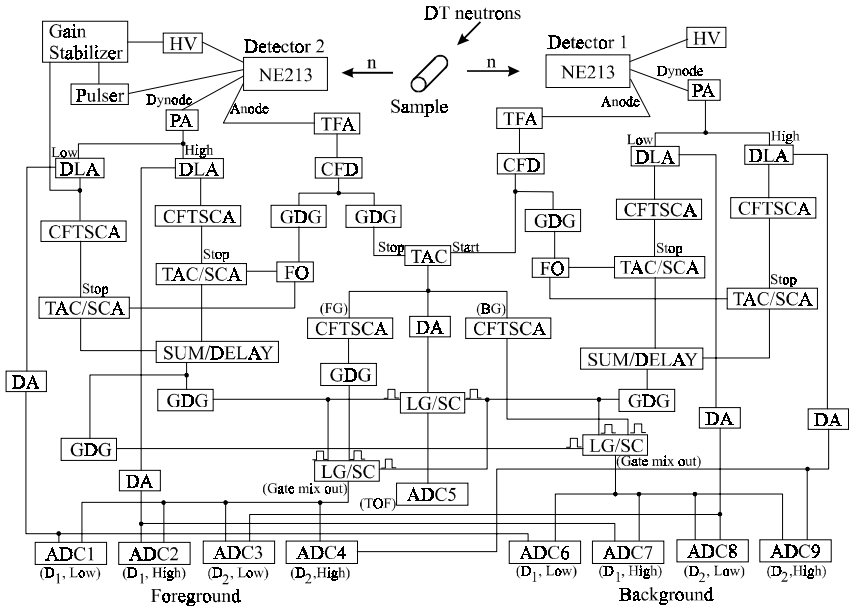


Fig. 2 Electronic circuit of the measurement.

the correction factor was estimated to be about 10%.

4. Results and discussion

Figure 3 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. Also the BG counts are successfully suppressed and a good S/N ratio is therefore achieved.

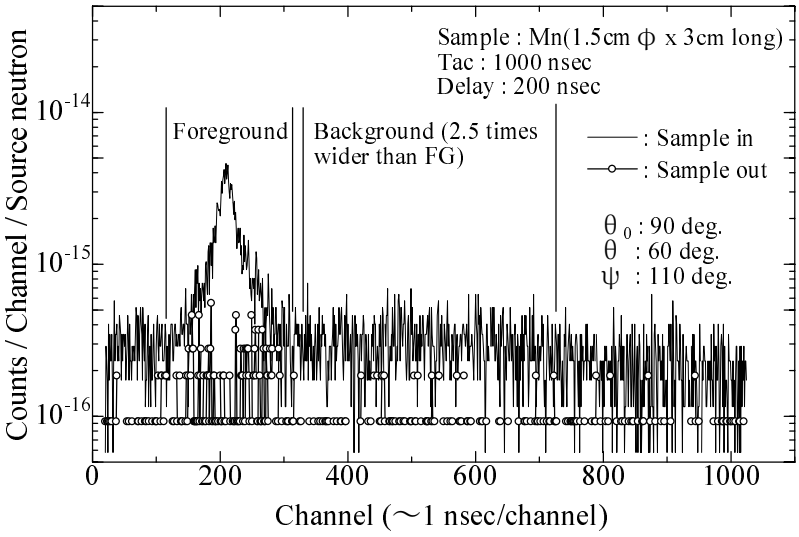


Fig. 3 Time spectrum between anode signals of two NE213 detectors.

Figure 4 shows raw neutron pulse height spectra in FG and BG measurements. It is confirmed that the FG spectrum is sufficiently larger than that of BG. Also, two spectra for high- and low-gain modes smoothly overlapped each other around 1～2 MeV. This means that the two-gain method is successfully functioning.

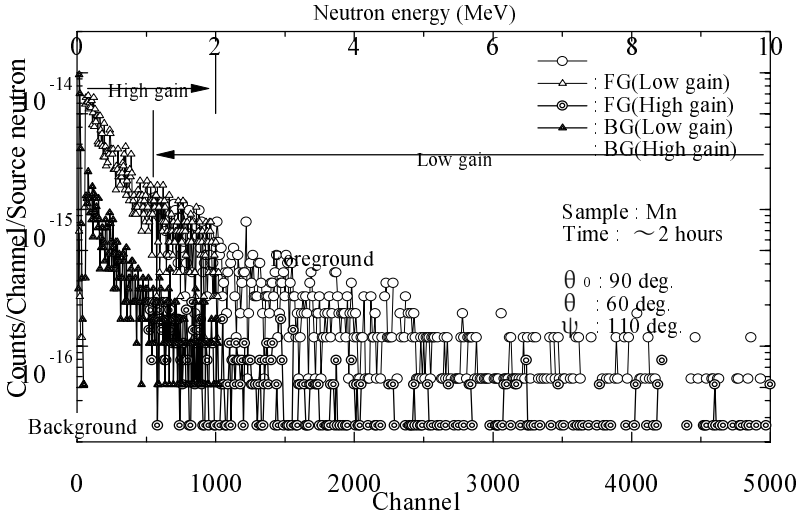


Fig. 4 Raw neutron pulse height spectra in FG and BG measurements.

Figure 5 shows neutron spectrum obtained by unfolding the pulse height spectrum with FORIST. In the figure, the error bars are not specified because the error value is so large that the spectra become not legible if specified. The values are around several tens percentages. A slight fluctuation is observed in each spectrum. However, a fairly good agreement between experiment and JENDL fusion file is seen except for low energy region. Large discrepancies in the low energy region are thought to be caused by the detector response matrix, which is to be re-evaluated.

Figure 6 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 even if considering the discrepancy observed below 1 MeV in Fig. 5. This indicates that the present new measurement method is significantly successful. Figure 7 shows angular distribution for circumferential direction. It seems that there is no angular dependence. However, this cannot be concluded because the accuracy is not so good. From the results, it was confirmed that the angular dependence was, if any, very weak. Thus, it is expected that one complete measurement for a medium-heavy element would become possible by several measurements.

5. Conclusion

Using a newly developed beam-type DT neutron source at FNS, JAERI, the method was 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 was measured precisely with the foil activation method, was

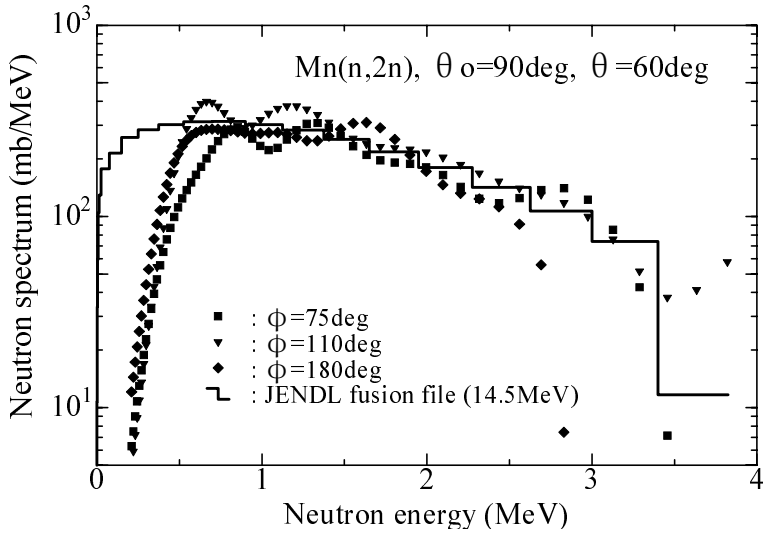


Fig. 5 Neutron spectrum obtained by unfolding the pulse height spectrum.

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, however one problem was still left that the statistical accuracy was not sufficient. Some improvement of experimental and data processing procedure are necessary to solve it. Also, it was found that for Mn not so strong angular dependence was observed. Consequently, it is 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.

Acknowledgments

The authors wish to acknowledge the FNS staff for their excellent operation of FNS.

References

[1] for example, see compiled data in EXFOR.

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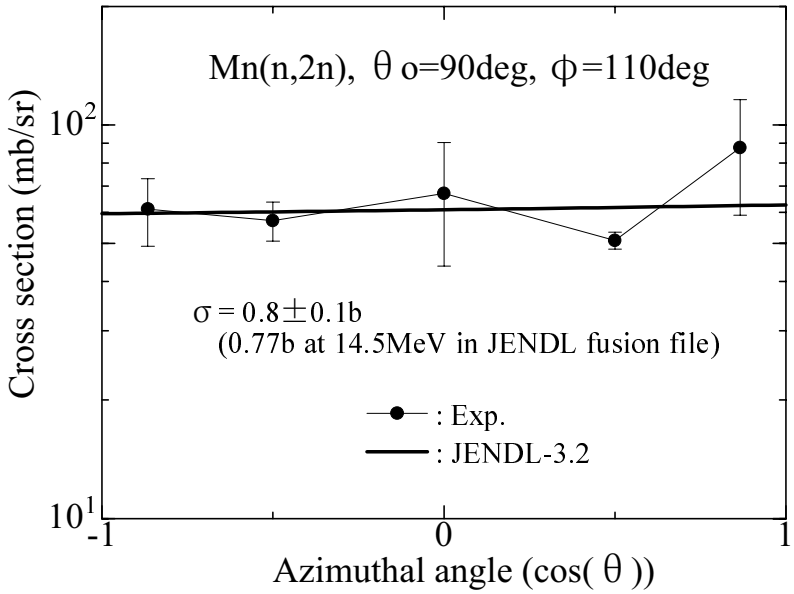

Fig. 6 Angular distribution for axial direction.

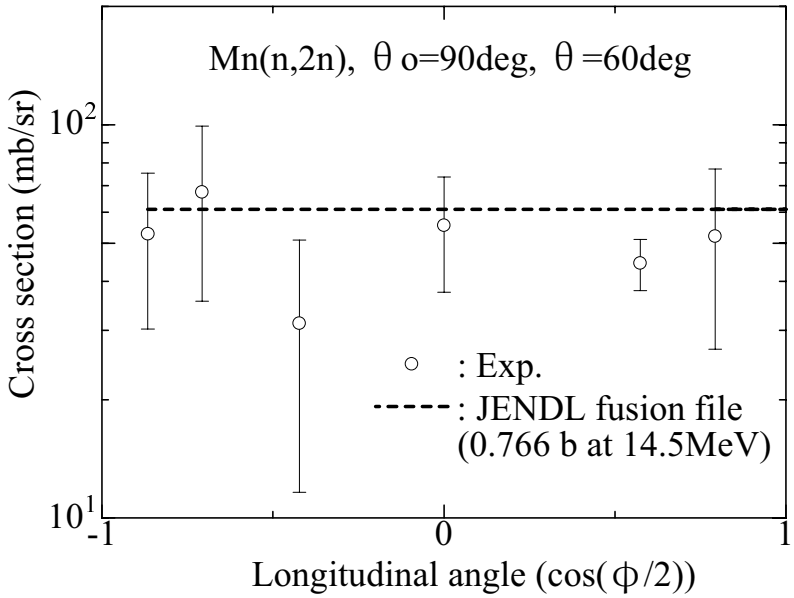

Fig. 7 Angular distribution for circumferential direction.