Measurement of ^{nat}Zr (n,2n) Reaction Cross Section from the Angle-Correlated Neutron Spectrum with Pencil-beam DT Neutron Source

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Angle-correlated differential cross-section for ^{nat}Zr (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.

1. Introduction

The (n,2n) reaction is a neutron multiplication reaction, the cross-section data of which are crucial information to design a fusion reactor. The ^{nat}Zr (n,2n) reaction cross-section is very important because Li_2ZrO_3 is one of the fusion blanket candidate materials. However, in the previous benchmark studies it was pointed out that agreement between experiment and evaluation was not acceptable as shown in Figs.1 and 2. In the case of ^{nat}Zr (n,2n) reaction cross section measurement, the conventional foil activation method cannot be applied, because suitable radioisotopes cannot be produced by the reaction. In the present study, two neutrons simultaneously emitted by the (n,2n) reaction were detected directly by two detectors.

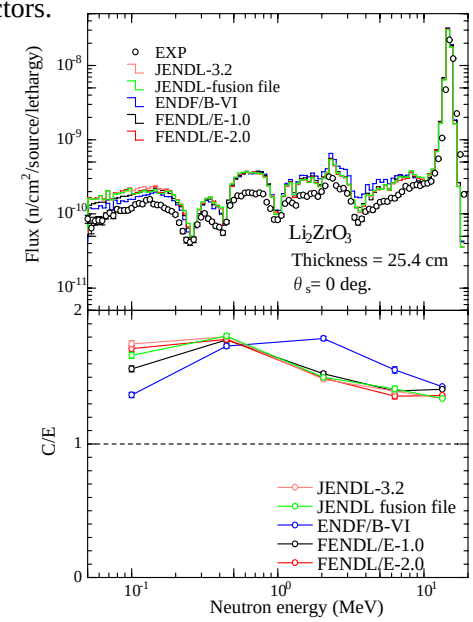

Fig.1 Comparison of measured and calculated leakage neutron spectra at 0° for 25.4 cm thick Li_2ZrO_3 assembly
I. Murata et al. Fus. Eng. Des., 51-52(2000) p.821.

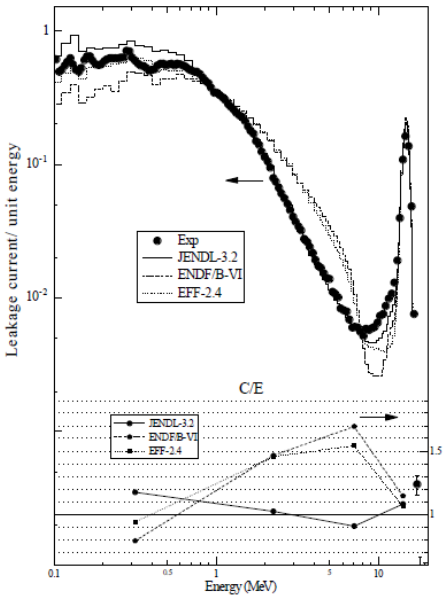

Fig.2 Measured and calculated neutron leakage spectra from the Zr pile
C. Ichihara et al. J. Nucl. Sci. Tech., 40 (2003) p.417.

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., 10^5 n/cm^2/sec inside the beam and very low neutron flux of several hundred n/cm^2/sec outside the beam.

The schematic experimental arrangement around detectors is shown in Fig.3. The distance between the neutron source and a zirconium sample (2.4cm in diameter, 2cm long) was 550cm. Two spherical NE213 (4cm in diameter) detectors to detect neutrons emitted simultaneously by the (n,2n) reaction were located at 18.8cm from the zirconium sample. An ^{238}U fission chamber was set up on the beam line behind the sample to monitor the neutron flux. As shown in Fig.4, three angle parameter (θ_0,θ, ϕ) with respect to the detector position were defined in which θ_0 and θ are the 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.

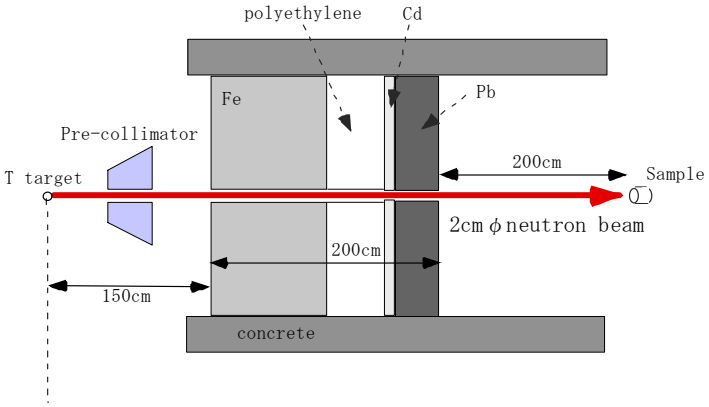

Fig.3 Schematic experimental arrangement

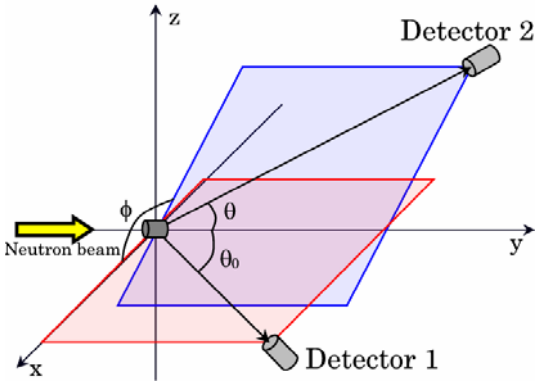

Fig.4 Arrangement around sample and detectors

Because two detectors are positioned very close with each other, there exists a neutron, which can be detected in both detectors by passing through them in turn. This is a troublesome background called “inter-detector scattering” in this paper. A polyethylene shielding brick up to 10.16cm in thickness was thus arranged between two detectors to prevent the inter-detector scattering components.

Because NE213 detectors are sensitive also to gamma ray, n/γ discrimination was carried out by the pulse shape discrimination technique. Two amplifiers with different gains were used to cover a wider measurable energy range from 800 kev to around 10 MeV. Time difference spectrum of anode signals of the two detectors was used to extract the coincidence signals. The region including the peak was gated and defined as Foreground (FG), and the flat 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.5. The position of Compton edge made by 1.275MeV gamma ray emitted from ^{22}Na and 0.834MeV gamma ray emitted from ^{54}Mn was used in the light unit calibration. The BG spectrum (y_{BG}) was subtracted from the FG spectrum (y_{FG}) to derive the net FG spectrum by the following equation.

$$y = y_{FG} - \alpha y_{BG} \tag{1}$$

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

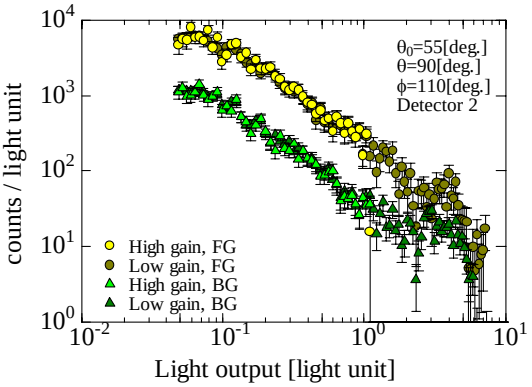

Fig.5 Measured light output spectra.

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

$$y(\theta_0, \theta, \phi, E) = R \cdot x(\theta_0, \theta, \phi, E) \tag{2}$$

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

where subscripts 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 obtained energy and angle differential cross section, N is the number of nuclei of the sample, FC is the integrated counts of the fission chamber, 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. As for the correction of the inter-detector scattering, the detection rate of inter-detector scattering was estimated by Monte Carlo calculation with MCNP[4] taking into account precise model of each experimental arrangement.

4. Results and discussion

Figure 6 shows the obtained energy spectra. This is a triple-differential cross section, i.e., double-angle and single energy differential cross section, called TDX. Hence, there are no evaluated data, which can be compared with the present measured data. The spectra seem to be an evaporation spectrum. Estimated error contains statistical error and unfolding process error evaluated by FORIST. Figure 7 shows the detection ratio between the inter-detector scattering component of a neutron and the coincident signal of two neutrons emitted from (n,2n) reaction calculated by MCNP. The results were used to evaluate correction factors. The ratio increases as the distance between two detectors becomes closer. A 10 cm polyethylene shield, arranged between the detectors, effectively suppressed the inter-detector scattering.

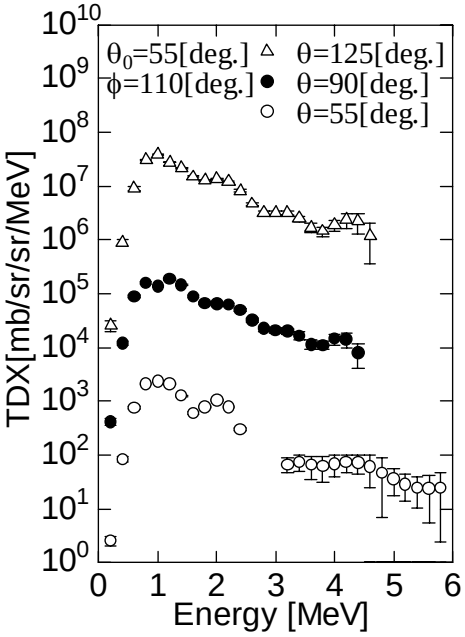

Fig.6 Measured energy spectra at each angle.

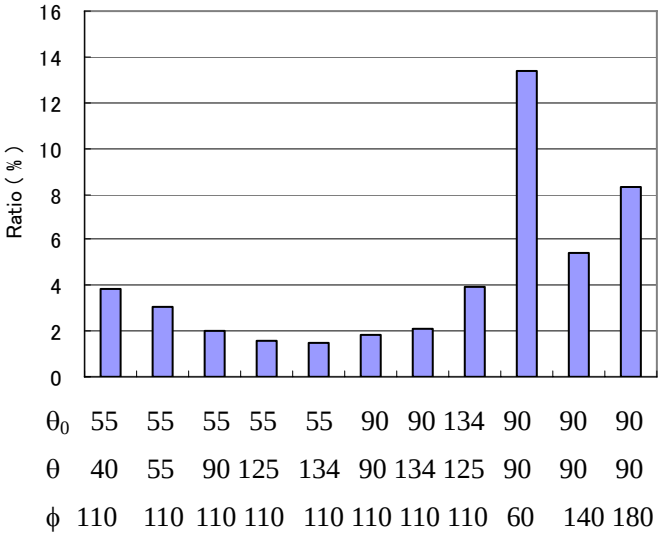

Fig.7 Ratio of inter-detector scattering component at each angle.

By integrating TDX over energy, two kind of angular distributions named ADDX are obtained, i.e., one is as a function of azimuthal angle (Fig. 8) and the other is for polar angle (Fig. 9). It seems no angular dependence azimuthally within the error bar as shown in Fig. 8. A gentle forward oriented polar distribution was observed for axial ADDX as in Fig. 9. The ADX is obtained by integrating ADDX over angle. It shows also a slight forward peaked distribution. The obtained total cross-section (TOX) over the minimum measurable energy of 800 keV was fairly larger than the one evaluated in JENDL-3.3 as described in Table 1. Unexpectedly, the result shows an opposite trend to the suggestion pointed out by the previous benchmark studies.

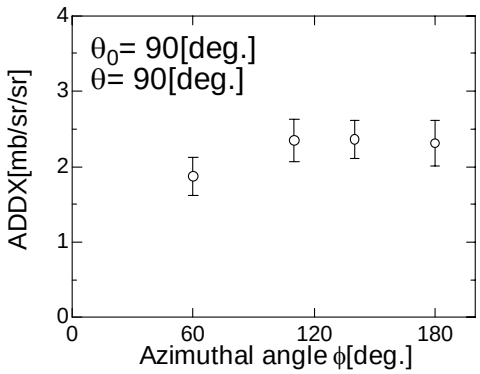

Fig.8 The azimuthal distribution of ^{nat}Zr (n,2n) reaction cross-section.

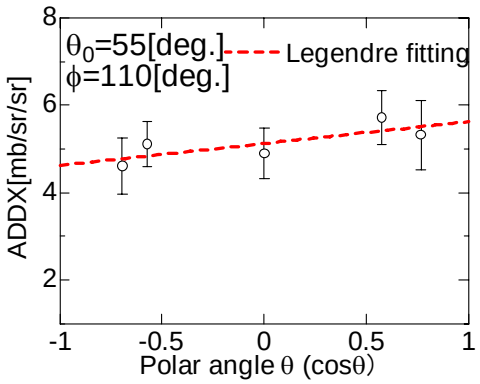

Fig.9 Example of the polar distribution of ^{nat}Zr (n,2n) reaction cross-section.

Table.1 Comparison of the obtained total cross-section (TOX) of ^{nat}Zr (n,2n) reaction

	ADX at 55 deg. [mb/sr] (En＞800 keV)	TOX. [mb] (En＞800 keV)
Present Exp.	**64±3**	**745±23**
JENDL-3.3	44.9	538.2

Next, to discuss the unexpected discrepancy of the total (n,2n) reaction cross section mentioned above, extrapolation of spectrum for energies below 800 keV was carried out with an evaporation spectrum. The nuclear temperature preferred is 1 MeV in the present study, because the evaporation spectrum for 1 MeV would fit our spectrum very smoothly. The value is the same as the one evaluated in RIPL-2. Nuclear temperatures stored in JENDL-3.3 and ENDF/B-VI are also used as references. The results are summarized in Table 2 below.

Table.2 Comparison of total cross-sections for ^{nat}Zr(n,2n) reaction, estimated by extrapolation of the measured energy spectrum below 800 keV with different evaporation spectra for several nuclear temperatures.

Nuclear temperature [MeV]	0.65 (assumed in JENDL evaluation)	1.0 (used also in RIPL-2 library)	1.73 (assumed in ENDF evaluation)
Preliminary TOX [mb]	1095±30	997±27	919±26

The result shows the agreement with JENDL-3.3 is acceptable for the total cross-section of ^{nat}Zr (n,2n) reaction obtained by extrapolating the measured energy spectrum down to zero energy. Our estimation agrees very well with the only existing measured data of Frehaut et. al., (946±67 mb at En=14.3 MeV). As a result, it is suggested that the discrepancy seen in the previous benchmark studies may be caused, not by the problem of absolute value, but by the problem of energy spectrum shape determined by the nuclear temperature. For JENDL-3.3, the absolute value is more or less acceptable, but the nuclear temperature used

may be a little small, meaning a little underestimation is seen in larger energy region and overestimation in lower energy region. For ENDF/B-VI, a slight underestimation is seen as a whole. However, from the present result and the previous benchmark study, the nuclear temperature used may be a little too high. The above results suggest examination of nuclear temperature used in the nuclear data library is worth being carried out.

5. conclusion

Using the pencil-beam DT neutron source and the coincidence detection technique, angle-correlated energy differential cross-section for ^{nat}Zr (n,2n) reaction was measured successfully. The obtained total cross-section above the emitted neutron energy of 800 keV was fairly larger than the one evaluated in JENDL-3.3. The total cross-section of ^{nat}Zr (n,2n) reaction was estimated by extrapolating the spectrum down to zero energy taking into account the nuclear temperature. The estimated value was between those of JENDL- 3.3 and ENDF/B-VI. It is suggested that the disagreement pointed out in the previous benchmark studies may be due to inappropriate nuclear temperature used in the evaluation of ^{nat}Zr (n,2n) reaction cross section.

References

[1] I. Murata et al., *J. Nucl. Sci. Technol.*, Sup. 2, p. 433-436 (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).