REVIEW

Measurements of Double Differential Cross Sections at OKTAVIAN

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This is a brief review of the measurements of double differential neutron emission cross sections, which have been done at the OKTAVIAN facility of Osaka University since 1981, for many elements of fusion reactor materials. In the phase-1 experiments, double differential cross sections with high energy resolution and good counting statistics were accumulated for D, Li, Be, B, C, N, O, F, Na, Al, Si, Cl, Ti, Cr, Mn, Fe, Ni, Cu, Zr, Nb, Mo, W and Pb. The ring geometry TOF spectrometer was used in the phase-1, a drawback of which was due to the considerable variation of incident energy. In the phase-2 experiments, a new TOF spectrometer was installed for fixing the incident neutron energy to be 14.1 MeV and keeping the energy resolution and counting statistics. We can then obtain angle-integrated emission spectra and partial differential cross sections from measured double differential neutron emission cross sections. In the phase-2, measurements have been done for Be, C, 12B, 14B, F, Mg, Al, Si, V, Cr, Fe, Ni, Cu, Pb and Bi. All the data in the two phases have been efficiently utilized to improve evaluated neutron cross sections in JENDL-3, EFF-1 and ENDF/B-VI.

KEYWORDS: double differential cross sections, energy resolution, statistical data, 14 MeV, OKTAVIAN, ring geometry, fixed incident energy, emission spectra, partial cross section, fusion reactors, fusion-reactor materials

I. INTRODUCTION

Double differential neutron emission cross sections are of primary interest in the application for fusion reactors. They are basic nuclear data to predict accurately the tritium breeding performances in blankets and to carry out the shielding calculations for complicated geometries\(^{(1)}\). Double differential particle emission data are also of particular importance for the analysis and estimation of neutron-induced material damage\(^{(2),(3)}\), since we can at present deduce the data of primary knockon atom spectra only from these particle emission data. The accumulation of accurate double differential cross sections (DDX) has therefore been requested for many elements and isotopes which are candidates for breeder, structure and shielding materials.

At the OKTAVIAN facility of Osaka University, we have measured DDX data since 1981 for more than 20 elements of candidate materials. The measurement has been done in two phases. In the phase-1 experiments, we used a ring geometry TOF spectrometer which could provide us many DDX data with excellent energy resolution and good counting statistics for incident neutron energies around 14 MeV\(^{(4)}\). In the ring geometry method, however, there exists a drawback; the incident neutron energy changes considerably as we vary the scattering angle by moving a ring sample along the accelerator target tube. This drawback was overcome by the installation of a new TOF spectrometer in the phase-2 experiments\(^{(5)}\). Measured DDX data in the phase-1 and phase-2 experiments have been intensively compared with the evaluated data

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in ENDF/B-IV(6), JENDL-3T(7)*, etc., by many investigators in the world, and have made significant contributions to update evaluations toward JENDL-3 and ENDF/B-VI. This paper reviews briefly the DDX measurements at OKTAVIAN.

II. RING GEOMETRY EXPERIMENT

The phase-1 experiments using the ring geometry TOF spectrometer were done in the period 1981∼1986. The experimental method is written in detail elsewhere(4). Ring samples with about 1 cm in minor radius and 10 cm in major radius were used in these experiments. The neutron flight path was 9.5 m, which was very long compared with 2∼3 m flight paths used in many other laboratories for the DDX measurement at that time. In addition, a powerful operation of the OKTAVIAN Pulse Line(4) has been available to provide pulsed D-T neutrons with 1.5∼2 ns pulse width and 2∼5 x 10^3 neutrons generated per pulse. An NE213 detector of 5 inch in diameter was used as the main neutron detector with two parallel circuits for the neutron-γ-ray pulse shape discrimination, which enabled us to cover a relatively wide dynamic range, for instance 0.3∼15 MeV, of secondary neutron energy. These experimental conditions attributed to the significantly good energy resolution and counting statistics of the obtained DDX data.

The DDX data around 14 MeV for several scattering angles have been accumulated for D, Li, Be, B, C, N, O, F, Na, Al, Si, Cl, Ti, Cr, Mn, Fe, Ni, Cu, Zr, Nb, Mo, W and Pb(4)(8)(9), and numerical data tables and graphs are given(10)(11). These DDX data were compared with the ENDF/B-IV(6) data which were the most popular nuclear data for the fusion neutronics analysis at that time, and we consequently found(4)(8)(9) significant (in some cases, drastic) discrepancies between the experiments and the evaluated data. In particular, discrepancies were drastic for important material elements like natural-lithium (tritium breeder in fusion blanket), Be and Pb (neutron multipliers), C (first wall and reflector), Ti, Cr, Ni and Cu (structural materials) and W (shield). The DDX data taken in the phase-1 experiments at OKTAVIAN have been compared with other evaluated nuclear data (JENDL-2, ENDF/B-V, EFF-1, etc.) and with theoretical analyses by many investigators in the world, to improve evaluations. We have obtained consequently the following statements:

1) The direct simultaneous breakup process plays a significant role for the 14 MeV neutron reaction with light nuclei, e.g. D(n, 2n), ^7Li(n, n'), ^9Be(n, 2n) and ^1C(n, n'3α).

2) For heavier nuclei, a considerable number of discrete inelastic scatterings take place by the direct reaction, as seen in the measured DDX spectra as resolved peaks.

3) In the secondary neutron energy region of 5~10 MeV for heavy nuclei, the neutron emission by the precompound process plays a dominant role and its angular dependence is not negligible.

As an example of many obtained results, typical DDX data for natural lithium are shown in Fig. 1, in comparison with two evaluated data (JENDL-3T(7) and ENDF/B-IV(6)). It is obvious that the ENDF/B-IV evaluation gives quite different emission spectra from the experimental ones. The ENDF/B-IV data at backward angles (for instance, 135°) are non-physical, since the neutron emissions are observed in the higher energy region than that of the elastic peak. A drastic improvement has been made in the JENDL-3T evaluation, which gives the DDX spectra close to the experimental ones as seen in Fig. 1 where we notice a relatively strong excitation of the 4.63 MeV state that leads to the following breakup of ^7Li to an α-particle and a triton.

Although we have had accurate DDX data around 14 MeV in the phase-1 experiments, it was difficult to reduce angle-integrated and partial differential cross sections since the incident neutron energy changed from 14.8 MeV at 0° to 13.5 MeV at 160°. To update the

* JENDL-3T is a temporary file for testing the evaluated data for JENDL-3. The data in JENDL-3T will be partly revised in JENDL-3.
evaluated nuclear data files by improving analyses with nuclear theory codes, we needed in many cases partial differential (angle-differential) cross sections of elastic and discrete inelastic scatterings and angle-integrated neutron emission spectra. The DDX measurement with a fixed incident energy has been therefore required.

III. DDX AT 14.1 MeV

To fix the incident neutron energy to be 14.1 MeV without loosening the conditions for energy resolution and counting statistics, a new TOF spectrometer was designed and installed in the phase-2 experiment. The detail is written in Ref. 5. The layout of the new TOF spectrometer is shown in Fig. 2. The collimator-shield system of the spectrometer is installed in the 85° direction against the accelerator target tube line. A cylindrical sample of 2~3 cm in diameter and 5~7 cm long can be rotated around the TiT target keeping its axis parallel to the deuteron beam line, to vary the scattering angle. The flight path is 8.3 m long. A large NE213 detector with 25.4 cm diameter and 10 cm thickness is used as a main neutron detector. The TOF system of Fig. 2 is fixed to the 85° line and we do not need to rotate it. With this system, we have measured DDX data with 14.1 MeV incident energy at 15~16 angle points (15°~160°) for Be, ^10^B, ^11^B, C, F, Mg, Al, Si, V, Cr, Fe, Ni,
Cu, Pb and Bi, since 1986(12)(13)~(15). The data quality for energy resolution and counting statistics is comparable to that of the ring geometry experiment. Since the incident neutron energy has been fixed to 14.1 MeV, we can definitely observe the angular dependence of emitted neutrons, reduce partial differential cross sections for resolved elastic and discrete inelastic scatterings and integrate DDX data over scattering angles to obtain angle-integrated neutron emission spectra (energy-differential cross sections). Numerical data tables and graphs for these double and single differential cross sections are available(14)(15). The partial differential cross sections are useful for the analyses with the optical model, DWBA and coupled channel theories. The angle-integrated neutron emission spectra in the center-of-mass system(12) are useful to check the analyses with the precompound and compound theories, and powerful in particular to check directly the values of evaluated partial cross sections corresponding to specified excited states or reaction channels(12). We have obtained also angle-differential cross sections for the $^9$Be$(n, 2n)$ and $^{12}$C$(n, n'3a)$ reactions(5)(13) which are of great importance in the nuclear data applications.

In the following, we show typical results of the phase-2 experiments. In Fig. 3, the measured DDX at 70° for Be is shown in comparison with the theoretical analysis supposing the combination of the sequential and the direct breakup processes for the $^9$Be$(n, 2n)$ reaction(14). Three discrete peaks at the 2.43, 4.7 and 6.7 MeV states correspond to the sequential process. About 60% of emitted neutrons can come from the 3- and 4-body breakup processes. This shows the significant role of the simultaneous direct breakup process for light nuclei.

In Fig. 4(a), (b), we show typical DDX data for natural iron, in comparison with the JENDL-3T data which underestimate nonelastic neutrons at forward angles and overestimate at backward angles. The trend of the experimental DDX spectra that has the neutron emission enhanced at forward angles in the 3~9 MeV region is common for intermediate and heavy nuclei, which requires the treatment of angular dependence within the precompound theory analysis(12)(14). An angle-integrated neutron emission spectrum for natural Fe is shown in Fig. 5, in comparison with the one by the JENDL-3T data and the evaluated curve from experiments by Pavlik & Vonach(16). In the energy region less than about 8 MeV and at the peak around 14 MeV, the JENDL-3T data agree very well with the present experiment, while the Pavlik-Vonach evaluation seems slightly higher than the present experiment. Underestimation of the JENDL-3T data is clear in the energy range of 10~12 MeV which corresponds to excitation levels from 1.265 to 4.03 MeV(12). Angle-differential cross sections for the elastic and the three resolved discrete inelastic scatterings, 0.85, 3.23 and 4.40 MeV states, are obtained(15).
In Fig. 6 we show an angle-integrated neutron emission spectrum for natural lead. In the ENDF/B-IV evaluation, the low energy neutron emission due to the $(n, 2n)$ reaction is underestimated, compared with the present experiment. In the high energy region greater than about $5$ MeV, where the contribution of direct inelastic scatterings (for instance, 2.62 and 4.20 MeV states) and precompound neutron emission is dominant, agreement is good. In the neutron emission spectrum analysis for intermediate and heavy nuclei, good combination of the direct, the precompound and the compound process is to be searched.

A systematic DDX measurement has been done to study the pre-equilibrium $(n, n')$ cross sections on nuclei around atomic number 50\textsuperscript{17}. The recent DDX measurements at Tohoku University for a number of elements\textsuperscript{18-19} have given data in good agreement with our data\textsuperscript{5,12-15}.

We will continue the phase-2 experiment...
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(19) BABA, M., et al.: Ref.[13]

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Fig. 6 Angle-integrated neutron emission spectra in center-of-mass system, with $E_n=14.1$ MeV, for natural Pb for other elements like $^6$Li, O, N, Na, Sn, Ta, W, $^{232}$Th and $^{238}$U which are of interest in blanket and shield of fusion reactor, and for Ge, As, Ga etc. which will be used for the burning plasma diagnosis.