Measurements of Double-Differential Neutron Emission Cross Sections of Nb, Mo, Ta, W and Bi for 14 and 18 MeV Neutrons

Mamoru BABA, Shigeo MATSUYAMA, Takuya ITO†, Takeshi OHKUBO and Naohiro HIRAKAWA

Department of Nuclear Engineering, Tohoku University*

(Received October 8, 1993)

Double-differential neutron emission cross sections have been measured for Nb, Mo, Ta, W and Bi at 14 MeV incident energy, and for Nb and Bi at 18 MeV using Tohoku University Dynamitron TOF spectrometer. The experimental results indicated problems in current evaluations both for energy spectra and angular distributions. Angle-integrated neutron emission spectra and angular distributions of secondary neutrons were analyzed, respectively, by the statistical multi-step model code EXIFON and the systematics by Kalbach-Mann and by Kalbach. The energy spectra were reproduced successfully by EXIFON except for Bi, and the angular distributions were followed by the systematics over wide range of outgoing energy and target mass if the emission spectra calculated by EXIFON were employed for generation of angular distributions.

KEYWORDS: double-differential cross sections, neutron emission, niobium, molybdenum, tantalum, tungsten, bismuth, 14 and 18 MeV, measurements, TOF method, pre-equilibrium neutrons, energy spectra, angular distribution, statistical multi-step model, code EXIFON, Kalbach-Mann systematics, Kalbach systematics

I. INTRODUCTION

Energy and angular doubly-differential neutron emission cross section (DDX) for fast neutron induced reactions is of great importance both in applied and basic nuclear science. DDX data are indispensable in neutronic designs of fusion and accelerator-based reactors since secondary neutrons from fast neutron induced reactions distribute over wide energy range and high energy neutrons have strong anisotropy via the direct and the pre-equilibrium processes\(^{(1)}\). They are required also for assessment of radiation effects, i.e. radiation damage and heating, due to recoil atoms induced by fast neutron scattering. In addition, experimental DDX data are very useful for validation of models and parameters adopted in nuclear reaction theories\(^{(2)}\)\(^{(3)}\). In particular, angular distribution of pre-equilibrium neutrons is of interest concerning the quantum mechanical effect\(^{(2)}\)\(^{(3)}\).

For the reasons, experimental DDX data are required for various nuclides over wide energy range of incident and outgoing neutrons. However, most of previous DDX measurements were confined to 14 MeV incident energy and there have been only very few experiments for incident energies higher than 14 MeV\(^{(4)}\)\(^{(5)}\). Furthermore, even in the case of 14 MeV data, experimental data measuring wide range of emission spectrum with sufficient energy resolution are very limited\(^{(6)}\), and discrepancies existing among experimental data make it difficult to derive definite information on models and parameters\(^{(4)}\).

In order to provide systematic experimental DDX data, we have been conducting a series of experiments for 14, and 18 and 1~6 MeV incident neutrons on light to medium-
heavy elements including U and Th using Tohoku University Dynamitron time-of-flight (TOF) spectrometer\(^{(7)-(11)}\). Following the previous studies, we extended the measurements to medium-heavy and heavy elements. We carried out measurements for Nb, Mo, Ta, W and Bi at 14.1 MeV incident energy, and for Nb and Bi at 18.0 MeV. These elements are expected as structural, shielding materials or neutron multipliers\(^{(1)}\) in fusion reactors, and of interest as the reference for nuclear reaction theory\(^{(2)}\)(\(^{(3)}\)). In the present experiments and data analyses, in particular for 18 MeV measurements, cares were taken for source-related backgrounds to obtain the data over the almost whole range of emission spectrum.

In addition to DDX data, we deduced angle-integrated neutron emission spectrum (Energy Differential Cross Section; EDX) and angular distribution (Angular Differential Cross Section; ADX) of secondary neutrons. Deduced EDXs were analyzed using a statistical multi-step model code EXIFON\(^{(12)}\) which enables parameter-free calculations for overall emission spectrum on the basis of quantum mechanical concept. Then, ADXs were compared with the semi-empirical systematics by Kalbach-Mann\(^{(13)}\) and by Kalbach\(^{(14)}\) using the EDXs obtained by EXIFON. This method will be useful for DDX prediction because advanced quantum-mechanical models\(^{(15)}\)(\(^{(16)}\)) require sophisticated and time-consuming calculations to obtain DDXs. We applied the analyses also to the data of lighter elements\(^{(9)}\) and examined the effect of neutron spectrum on the angular distributions derived by the systematics mentioned above.

The experimental and data correction method are described in Chaps. II and III, respectively. The results are presented and discussed in Chap. IV.

II. EXPERIMENTAL METHOD

The experiments were carried out using Tohoku University Dynamitron TOF facility\(^{(7)-(11)}\). The experimental apparatus and techniques were basically identical with those described previously\(^{(7)-(9),(10)}\). In the present experiments, a post-acceleration chopper\(^{(15)}\) was newly employed to improve the energy resolution by reducing the pulsed beam duration.

Primary neutrons of 14.1 and 18.0 MeV were produced via the \(d-T\) reaction by bombarding tritium-loaded titanium (Ti-T) targets with a pulsed deuteron beam with \(\sim 2.0\) ns duration provided by a 4.5 MV Dynamitron accelerator. Neutrons of 14.1 and 18.0 MeV were obtained at 97.5° and 0° emission angles, respectively. By this arrangements and employing appropriate target thickness, the energy spreads of primary neutrons were held less than \(\sim 0.3\) MeV. Besides, the chamber for neutron production target was made to be low-mass and cooled by air blowing to avoid neutron degradation. The source neutron spectra, however, were contaminated by parasitic reactions, \(D(d, n), C(d, n)\) etc., and by scattering of primary neutrons on the target. Contamination by parasitic reactions was rather serious for 18 MeV source because of higher deuteron beam energy as shown in Fig. 1: The continuum neutrons are mainly due to scattering of primary neutrons. These contaminant neutrons gave rise to sample-
dependent backgrounds through scattering by a sample. They could not be eliminated experimentally and were corrected for in data reduction as described in Chap. III.

The cross section was determined relative to the well known hydrogen scattering cross section by measuring the scattered neutron yields from a polyethylene sample.

Scattering samples were metallic right cylinders of natural element, 3 cm-diam and 5-cm long. The polyethylene sample was 1.5-cm diam and 5-cm long. These sample sizes were chosen to maintain the magnitude of sample-size effect within 30~40% to avoid the uncertainty introduced in sample-size correction (cf. Chap. III). The samples were suspended 12 cm from the neutron producing target using a sample changer controllable from the data acquisition room.

Secondary neutrons were detected by an NE213 scintillator, 14-cm diam by 10-cm thick coupled to a fast photomultiplier, Hamamatsu R1250. The anode signal was fed into a constant-fraction timing discriminator and used for TOF measurement with a time-to-amplitude convertor. The NE213 detector was equipped with two separate n-γ pulse-shape discriminators having different bias settings, ~0.3 MeV and 2~3 MeV proton. For signal processing, employed were modules having pulse-height dynamic ranges of 400. Therefore, this "two bias system" enabled the measurement of neutrons between 20 and 0.5 MeV in a single measurement with a good timing resolution and a signal-to-background ratio. Relative detector efficiency was determined by TOF measurement of fission neutrons from 235U, for \( E_n < 5 \text{ MeV} \), and by Monte Carlo calculations using the code OSS for \( E_n > 5 \text{ MeV} \). The calculated relative efficiencies agreed with the experimental values by the n-p scattering technique. The overall timing resolution was 2.0 to 2.5 ns. The flight path was around 6 m for 14 MeV measurement but was shortened to around 4 m for 18 MeV measurement because of much lower neutron intensity. The scintillator was housed in a massive shield placed on a turning table. The scattering angle was varied by rotating the neutron detector around the scattering samples.

A smaller NE213 scintillator was employed to monitor the intensity and the spectrum of source neutrons in a TOF mode, and used for the flux normalization between measurements.

In data acquisition, TOF and pulse-shape spectra for high- and low-bias systems of the neutron detector, and the TOF spectrum of the monitor detector were gathered concurrently using the Canberra S-88 pulse-height analyzer.

The DDX measurements were carried out at 7 to 11 laboratory angles between 25° and 150°. At each scattering angle, sample-in and sample-out measurements were done. In Fig. 2, shown are typical example of TOF spectra for sample-in (Bi) and sample-out runs at 18 MeV incident energy. The signal-to-background ratio is fairly good while backgrounds due to contaminant neutrons are observed around 600 channel.

III. DATA REDUCTION AND CORRECTION

1. Cross Section Derivation
For deduction of DDXs, experimental data were corrected for the effects of (1) sample-out backgrounds, (2) detector efficiency, (3) finite sample-size and (4) sample-dependent backgrounds. Firstly, the experimental TOF data were subtracted with the sample-out

![Fig. 2 Typical TOF spectra for foreground (sample-in) and background (sample-out) runs in 18 MeV measurements](image-url)
backgrounds and transformed into energy spectra using relative detector efficiency\(^7\). The absolute DDX was determined using the differential n-p scattering cross section\(^7\).

Then, the data were corrected for distortion by the sample-size effects, i.e. multiple-scattering and flux attenuation, and by the sample-dependent backgrounds.

2. Data Correction for Sample-dependent Effects

The sample-size correction for polyethylene could be made precisely by the simple analytic formula\(^{19}\) because only the peak yields for n-p scattering were needed. For sample-size correction of DDX, on the other hand, a Monte Carlo program SYNTHIA\(^{20}\) was employed because the fraction of multiply-scattered events should be evaluated for each outgoing energy and emission angle. This is also the case for sample-dependent background correction.

This program simulates neutron scattering, reaction and attenuation within the sample and provides three tabulated data for neutron spectrum to be observed in the neutron detector: 1. \(I(E, \theta, E')\), 2. \(N_n(E, \theta, E')\) (\(n = 1 \sim 5\)) and 3. \(R(E, \theta, E')\), where \(E\) and \(E'\) are, respectively, the incident and outgoing neutron energies, and \(\theta\) is the emission angle; \(I(E, \theta, E')\) is the neutron spectrum expected for an infinitely-dilute sample, and \(N_n(E, \theta, E')\) is the spectrum for the \(n\)-th collision, and \(R(E, \theta, E')\) is the sum of \(N_n(E, \theta, E')\) over \(n\) and corresponds to the program-predicted spectrum for the real sample. The \(R\)-spectrum should agree with experimentally observed one if the data employed in the simulation are proper.

The correction was made by multiplying the following correction factor to the uncorrected data. We obtained the sample-size correction factor \(A_s\) by

\[
A_s(E, \theta, E') = \frac{I(E, \theta, E')}{R(E, \theta, E')} \tag{1}
\]

and overall correction factor \(A_T\) including sample-dependent backgrounds by

\[
A_T(E, \theta, E') \tag{2}
\]

where \(E_i\) and \(f_i\) are, respectively, the energy and relative intensity to the primary neutrons of the \(i\)-th contaminant, and \(R(E, \theta, E')\) is the simulated secondary neutron spectrum for the \(i\)-th neutrons by SYNTHIA. The spectrum and intensity of parasitic neutrons were determined by the source spectrum measurement while those of target-scattered neutrons were estimated by Monte Carlo calculations using the code MCNP\(^{21}\). For 18 MeV data, the time-dependence of \(f_i\) was also considered to take account of slight increase of the D(d, n) neutrons during the experiment.

Actually, as stated in Ref. (20), the data employed in the simulation, in particular the neutron emission data for sample nuclides, should be examined carefully to obtain reasonable correction factor. For most nuclides presently studied, the correction factors obtained by use of the evaluated data, JENDL and ENDF/B, were doubtful because the simulation resulted in \(R\)-spectra largely differing from the measured ones. As shown in Sec. IV-1, such differences were attributed mainly to the inadequacy of evaluated DDX for continuum neutrons. Consequently, we reconstructed the DDX data of continuum neutrons by the procedure described in Chap. IV or by calculations using EXIFON\(^{12}\) and employed in the simulation. As for the uncertainty of the correction, we assigned around 10% of the correction according to the sensitivity of resulting correction factors to the data employed in the simulation\(^{22}\).

3. Derivation of EDX and ADX

The laboratory DDX data corrected for sample-dependent effects were transformed into the center-of-mass system (CMS) assuming two body reaction kinematics\(^{23}\) to derive EDXs and ADXs in CMS. The EDXs were obtained by fitting the DDX in CMS with the Legendre polynomials. It should be noted that the present EDXs for the elastic-scattering do not include the contributions from the angles between 0° and 25° because of too steep angular distributions to make angle-
integration.

The error of the experimental data was estimated by a quadratic sum of each error source, (1) counting statistics \((1\sim30\%)\), (2) absolute normalization \((5\%)\), and (3) data correction for sample-dependent effects \((10\%\) of the correction).

IV. RESULTS AND DISCUSSION

In this chapter, the present experimental results are presented in comparison with other experiments, evaluations, and with model calculations based on EXIFON\(^{(12)}\) and systematics\(^{(13)}(14)\). The effect of neutron spectrum on the angular distributions derived by the systematics and the variation of angular distributions \(v.s.\) the mass number of nuclides are also discussed. Data comparisons are presented only for typical cases, since detailed comparisons have been shown elsewhere\(^{(23)}(24)\).

1. Data Comparison

Firstly, the present EDX results are compared with the experimental data by Takahashi et al.\(^{(6)}\) and the evaluation by Pavlik & Vonach\(^{(36)}\) to examine the data status; the latter data are based on experimental data and given for EDX alone.

Figure 3 illustrates the EDX for Nb and Bi at 14 MeV. The experimental spectra consist of continuum neutrons and bumps due to direct excitation of low-lying vibrational levels. The structures due to discrete states are more enhanced in Bi because it is close to the magic nuclide \(^{208}\)Pb. In comparing with others, the present results are in good agreement both in shape and magnitude even for the structures. The deviations among three data are estimated to be within \(~15\%\). Comparable agreement was also confirmed for Mo, Ta and W\(^{(23)}(24)\). As for DDX, the present data show agreement again with those by Takahashi et al.\(^{(6)}\) within around 30\% except for some cases.

For 18 MeV data, no other data are available for direct comparison.

Then, the present DDX data of Nb and Bi for 14 and 18 MeV incident neutrons are shown in Fig. 4(a), (b) and Fig. 5(a), (b), respectively, together with the evaluations of JENDL-3\(^{(24)}\) and ENDF/B-VI\(^{(37)}\). The experimental data show marked anisotropy in the energy region above several MeV because of increasing contributions of pre-equilibrium and direct processes. Both evaluations show marked

---

Fig. 3 Data comparison of EDX for Nb and Bi at 14.1 MeV

Fig. 4 Comparison of present DDX results for Nb with evaluations
disagreement with the present data both in spectrum and angle-dependence. In particular, the ENDF/B-VI data show remarkable discrepancies at backward angles because they treat the angular distribution of continuum neutrons as isotropic even for pre-equilibrium neutrons. The JENDL-3 data are in better agreement than ENDF/B-VI by considering the angular distribution and the direct process; however, they underestimate the low energy part especially for 14 MeV data, and show discontinuity between the equilibrium part and the pre-equilibrium part. Similar problems in the evaluated data were observed for Mo, Ta and W(23)(24). In the case of JENDL-3, the problems are partly due to the limitation of the data format (ENDF-5) in describing DDX(28). Revision of the evaluation and data format is now in progress for JENDL-3(28).

2. Neutron Emission Spectra (EDX) and Angular Distribution (ADX)

Figure 6(a)~(c) shows EDXs obtained by the present experiment. The solid lines in the figures show the EDXs calculated by EXIFON(12). This code provides EDX by a sum of the contributions from the statistical multi-step-direct (MSD), multi-step compound (MSC) and the multi-particle emission (MPE) processes. It takes account of the direct reaction (DR) to collective phonon and single-particle states as a part of the MSD process. In EXIFON, sets of standard model parameters are provided for major nuclides on the basis of global potential values and of nuclear structure data(12). Global values are given for the strength of two-body interaction, mass-dependent radius parameter, Fermi energy, potential depth, pairing shift and phonon width. The optical model potentials by Wilmore-Hodgson for neutron, Perey et al. for proton and Huizenga-Igo for α-particle are adopted for calculation of reaction cross sections. The nuclear structure data are also given for the energy, multipolarity and deformation parameters of phonon states and for the binding energy. In the present version, the shell-correction for the state-density is also considered for the MSC process. These parameter values have been applied successfully for description of particle emission data over wide range of nuclides and incident energy(12). To examine the applicability of them to the present data, the present calculations were performed using these builtin parameters without any adjustment. For simplification, EXIFON provides only EDX theoretically by ignoring the effects of angular momentum and nuclear spin, and it derives DDX using the systematics for angular distribution mentioned above(13)(14).

The solids lines show the spectra summed over MSD, DR, MSC and MPE components, and dashed lines MSD and MSC components. EXIFON reproduces fairly well the experimental EDX data over the nuclides presently studied even in the region of direct excitation, except for marked underestimation for the Bi data at 14 MeV. Similar under-
Fig. 6 Comparison of present EDX with calculation by EXIFON

(a) Nb at $E_n=14.1$ and 18.0 MeV

(b) Mo, Ta, W at $E_n=14.1$ MeV

(c) Bi at $E_n=14.1$ and 18.0 MeV
estimation of EXIFON for $^{209}$Bi and $^{208}$Pb was observed by the calculation using the previous version without shell correction for particle-state density(12). Inclusion of shell-correction enhances the MCS contribution and gives better description; however, improvement seems modest. This is not likely to be due to model parameters alone. The difficulty for magic nuclei of the multi-step model was also discussed by Marcinkowsk(4) and seems still to be an open question. Apart from this problem and slight underestimation for Nb, EXIFON follows very successfully the continuum spectra and collective excitations. In addition, the calculation indicates the importance of the direct processes (single- and multi-step) for proper description of high energy parts of neutron emission spectra.

Then, the experimental ADXs are compared with those derived from the systematics by Kalbach-Mann(13), and by Kalbach(14). These systematics represent the DDX for particle emission reaction by superposing the forward-peaked distribution for MSD process on the isotropic or the 90° symmetric distribution for MSC process with the weight of MSD fraction:

$$\frac{d^2\sigma}{d\Omega dE} = a_0 (\text{MSD}) \sum_{l=0}^{l_{\text{max}}} b_l P_l (\cos \theta)$$

Kalbach-Mann,

$$\frac{d^2\sigma}{d\Omega dE} = \frac{a_0 (\text{Total})}{4\pi} \cdot \frac{b}{\sinh(b)} \cdot \left[ \cosh(b \cos \theta) + f (\text{MSD}) \right]$$

Kalbach,

where $a_0 (\text{total}) = a_0 (\text{MSD}) + a_0 (\text{MSC})$, $f (\text{MSD}) = a_0 (\text{MSD})/a_0 (\text{MSC})$, $a_0 (\text{MSC})$ and $a_0 (\text{MSC})$ are, respectively, the cross section for MSD and MSC processes, and $P_l$ is the Legendre polynomial of order $l$. The parameters $b_l$ and $b$ which represent the angular dependence have been deduced semi-empirically from the nuclear reaction data in tens to hundreds MeV projectile energies. Kumabe et al. proposed a modified version of Kalbach-Mann systematics(28) to get better fits; it provides angular distribution close to the Kalbach systematics(28).

To derive the angular distribution from the systematics, we obtained $a_0 (\text{MSD})$ and $a_0 (\text{MSC})$ by EXIFON, including DR and MPE components into MSD and MSC, respectively. This modeling is referred as MSD/MSC method hereafter.

In Fig. 7(a)~(c), the experimental ADX data for typical outgoing energies are compared with the systematics deduced by the MSD/MSC method. The experimental data exhibit stronger anisotropy with increasing outgoing energy as suggested from the DDX data (Fig. 4 and 5). This trend in experimental data is reproduced consistently by both systematics with comparable quality for all elements and both incident energies.

Then, the analyses were applied as well to the data of lighter elements by our experiments(9)(30) to examine the applicability of the systematics. Typical results for 14 and 18 MeV neutrons are presented in Fig. 9(a) and (b), respectively; the solid lines show the Kalbach-Mann systematics derived by the MSD/MSC method. The ADXs for these lighter elements are also reproduced fairly well by the systematics for both incident energies, while our previous analyses using the conventional method (cf. Sec. IV-3) resulted in overemphasis of forward rise of angular distribution(9).

In summary of the above results, Kalbach-Mann and Kalbach systematics reproduce satisfactorily the neutron DDXs over wide mass range so long as the MSD and MSC spectra by EXIFON are employed for $a_0 (\text{MSD})$ and $a_0 (\text{MSC})$. This is also indicated from the comparison of the reduced Legendre coefficients described in the next subsection.

3. Effect of MSD, MSC Spectrum on Angular Distribution

In applying the systematics, a conventional modeling was often adopted(9)(18)(28)(31) by replacing the MSD and MSC spectra with the phenomenological exciton(32) and the evaporation(33) spectra, respectively (EXC/EVA method). In this method, the relative magnitude of
the exciton and evaporation spectra were determined by fitting the experimental EDX with the superposition of them. The fitting results are shown in Fig. 8 together with the spectra obtained by EXIFON.

The results for the Kalbach-Mann systematics by the EXC/EVA method are shown by dashed-lines in Fig. 9(a) and (b). It is clear that this simplification leads to stronger anisotropy than MSD/MSC method and to
disagreement with the experimental data whereas Kalbach stated that this spectrum distinction would provide close results to the MSD/MSC distinction for the case of higher incident energy(34). The reason of this feature is implied by Fig. 8; the exciton spectrum has much larger magnitudes than MSD spectrum in lower energy region, since it contains neutrons emitted from higher exciton states which will have almost isotropic angular distributions. Similar feature is observed in the comparison between MSD and exciton spectra by Kalbach(34). Consequently, the EXC/EVA method overestimates the "MSD fraction" and accordingly results in overemphasis of forward peaking. The differences between EXC/EVA and MSD/MSC methods are largest in medium outgoing energy where the MSD and MSC contributions are comparable.

It was observed that the forward rise given by the EXC/EVA method was enhanced especially in light mass elements from the comparison of the first order reduced Legendre coefficient $B_1$ which is the measure for the forward rise, where $B_1 = c_1/c_0$, $c_0$ and $c_1$ are the Legendre polynomial coefficients of order 0 and 1, respectively, for the angular distribution. In Fig. 10(a) and (b), the $B_1$-values for the experimental data and for Kalbach-Mann systematics based on the MSD/MSC and EXC/EVA methods are plotted vs. the mass number of target nuclide. The experimental $B_1$ values become larger with the increasing mass number. On the other hand, $B_1$ values by the EXC/EVA method are almost

---

**Fig. 8** EDX by present experiment and calculations by MSD/MSC and EXC/EVA methods (cf. Sec. IV-2, 3)

**Fig. 9** ADXs by present experiment and by Kalbach-Mann systematics based on MSD/MSC and EXC/EVA methods (cf. Sec. VI-2, 3)
independent of the mass number and in larger deviation from the experimental data for lighter mass. The MSD/MSC method follows the gross feature of the experimental data while it still overemphasizes the anisotropy generally. Watanabe reported similar observation\(^{(36)}\). Therefore, the conventional EXC/EVA method will not offer a consistent way unless the exciton spectrum is classified into the MSD and MSC parts as described by Kalbach\(^{(34)}\).

The mass dependence of ADXs observed in the experiments is interpreted by the increase of MSD fraction with the mass number as shown in Fig. 11. The figure shows the cross section ratio of MSD to total neutron emission calculated by EXIFON as a function of outgoing energy for 14.1 MeV incident energy. (The exceptionally lower values for Bi will be due to shell-effect as noted above.) The mass dependence of the MSD fraction was observed also by Yu et al.\(^{(28)}\) and will be attributed to the mass dependence of the level density.
From the above discussion, the MSD, MSC distinction should be made on the basis of a quantum mechanical approach or on a classification of the exciton spectrum into MSD and MSC part\(^{(34)}\) for proper utilization of the systematics in particular for light elements.

**V. SUMMARY AND CONCLUSION**

Double-differential neutron emission cross sections have been measured for Nb, Mo, Ta, W and Bi at 14 MeV incident energy, and for Nb and Bi at 18 MeV at 7~11 laboratory angles. The present experiments provided new data for wide energy range of secondary neutrons with a fairly good energy resolution. The data at 18 MeV will provide useful information on energy dependence of neutron emission mechanism since there have been no data at 18 MeV.

The angle-integrated emission spectra derived from the DDX were consistently reproduced by the code EXIFON except for underestimation for Bi which may be due to a common problem for the magic nuclides. The angular distributions of continuum neutrons were also reproduced generally by the phenomenological systematics by Kalbach-Mann and by Kalbach including lighter mass elements if the MSD and MSC emission spectra were evaluated by EXIFON. It was shown, on the other hand, the conventional treatment employing classical exciton and evaporation spectra in place of MSD and MSC spectra, respectively, led to too strong forward rise of angular distributions in particular for light elements.

The present experimental data and findings by the analyses will be useful for the refinement of data base on double-differential neutron emission cross section.

**ACKNOWLEDGMENT**

The present work was supported by Japan Atomic Energy Research Institute (JAERI). The authors are grateful to Drs. Y. Nakajima and Y. Kikuchi of JAERI for their cooperation. They wish to thank Dr. Y. Watanabe of Kyushu University and Dr. Kalka of Technical University of Dresden for providing us with the code EXIFON and valuable information. They also acknowledge F. Huang (Peking University), N. Ito, T. Akiyama, M. Fujisawa, R. Sakamoto and T. Iwasaki for their helps in the experiments.

---

**REFERENCES**

(18) TEXTOR, R. E., VERBINSKI, V. V.: ORNL-4160, (1965).