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DOUBLE DIFFERENTIAL NEUTRON EMISSION CROSS SECTIONS AT 14.1 MEV FOR BE, V AND FE

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Abstract: Double differential neutron emission cross sections for Be, V and Fe have been measured with incident neutrons of 14.1 MeV, based on the pulsed neutron and TOF technique with an 8.3 m long flight path. From these data, angle-integrated neutron emission spectra were reduced. Results were compared with the latest JENDL-3T and the ENDF/B-IV data. Disagreements were consequently significant for Be and V. The analysis of the ^{9}Be(n,2n) reaction considering the direct multibody breakup process revealed good agreement with the measured data. For V, the treatment of the precompound and compound processes by the GNASH86 code gave much better emission spectra than the ENDF/B-IV data.

(14.1 MeV, neutron emission, double differential, Be, direct breakup, V, Fe, JENDL-3T)

Introduction

For many elements of the candidated fusion reactor materials, accurate measurements of double differential neutron emission data have been requested[1] At the OKTAVIAN facility, Osaka University, we have measured the data at the 14.1 MeV incident neutron energy for 15 elements[2,3,4]. In the present paper, we describe the experimental results and analyses for Be, V and Fe which are of primary interest as the neutron multiplier (Be) and the first wall materials (V and Fe).

Experimental

The experimental method is described in detail elsewhere[2]. The experiment was carried out using an 8.3 m long TOF facility. A cylindrical metal sample of ^{9}Be, natural V or natural Fe, with 3 cm diameter and 7 cm (5 cm for V) length, was set up at a position radially 17 cm distant from the tritium target center of the pulsed D-T neutron source. Emitted neutrons from the sample to the 85° direction against the deuteron beam line were measured with an NE213 detector of 25 cm diameter and 10 cm thickness. To change the scattering angle of neutrons, we rotated the sample with the 17 cm radius around the tritium target center, keeping the axial direction of the cylindrical sample parallel to the deuteron beam line. We measured double differential data for 15-16 angle-points from 15° to 160° in the LAB system[4].

Operation of the accelerator was done with the pulse width of 2 ns and the repetition frequency of 0.5 MHz (for Be) or 1 MHz (for V and Fe). The data of background time-spectrum was obtained with the same TOF system, just removing the sample. A conventional electronic circuitry was used for the measuring system. Using a ^{252}Cf neutron source and a 1.5 cm diam. 5 cm long polyethylene cylinder, the energy-dependent efficiency of the NE213 detector was calibrated. The covering energy regions for secondary neutrons are 0.2-14 MeV for Be and 0.5-14 MeV for V and Fe. The overall energy resolution was ± 0.2 MeV. The incident neutron energy was approximately[2] 14.1 MeV.

Through a conventional way of data processing, we obtained raw data of double differential neutron emission cross sections and then made the corrections[2] for the multiple scatterings, in both of the sample and the polyethylene cylinder, and for the low energy tail of the source neutron spectrum. From the thus obtained double differential data, we reduced angle-integrated neutron emission spectrum in the CM system for each element, assuming the kinematics of the inelastic scattering with pseudo-levels in 0.2 MeV intervals[3]. In parallel, we reduced angle-differential cross sections for resolved elastic and discrete inelastic scatterings[4], for each element, and for the ^{9}Be(n,2n) reaction.

With respect to the experimental error, we show the statistical error only, as seen in the following graphs. In addition, we have to take into account the 3-4 % error from the detector efficiency calibration. The multiple scattering correction for V has failed[2], because we used the double differential cross section data base from the ENDF/B-IV data which gave neutron spectra drastically different from the measured ones. We adopted therefore the raw data, for V. The corrected data at the elastic scattering peaks and in the low energy region less than about 3 MeV were however reasonable, and this fact showed that the raw, namely uncorrected V data would contain the systematic error less than 10 % at each energy bin.

Results and Discussions

Beryllium

For the multiple scattering correction, we used the JENDL-3T data[5]. The present double differential data at 100° are compared with those by Baba[6] and Drake[7], in Fig.1 where the JENDL-3T and the ENDF/B-IV data are also shown. The present data are in good agreement with the data by Baba and Drake, except the difference in energy resolutions and the data at the 2.429 MeV state peak (the second peak from right in the experiment). In the low energy region less than about 7 MeV, the JENDL-3T data overestimate the present data while the ENDF/B-IV data underestimate, significantly. In this energy region, no obvious discrete peaks are seen in the experimental spectra, although the evaluated data have discrete peaks from the inelastic scattering which is the first step of the sequential neutron emission for the ^{9}Be(n,2n).

It has been pointed out that the simultaneous direct breakups to 3 and 4 particles take place with dominant portions in the ^{9}Be(n,2n) reaction[8]. The disagreements between the experimental spectra and the evaluated data may reflect the ignoring of these direct breakup processes in evaluations. We tried therfore a calculational analysis based on the Monte Carlo method taking into account the following reaction processes:

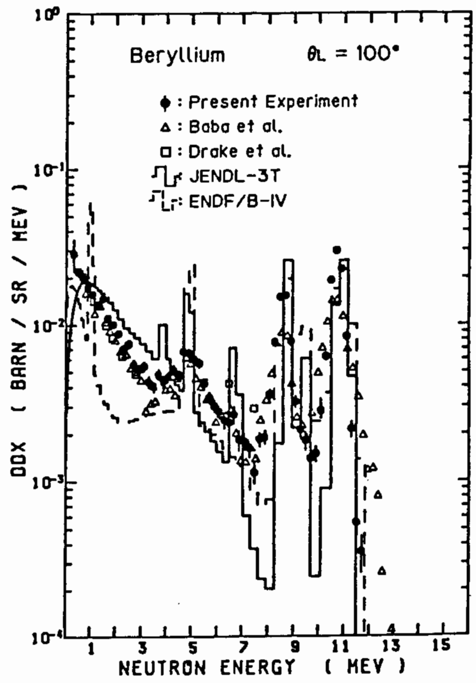


Fig.1 DDX data at 100° for Be, compared with other experiments and the evaluated data

1) $^{9}Be + n \rightarrow {}^{9*}Be + n_1$, $^{9*}Be \rightarrow {}^{8}Be + n_2$, $^{8}Be \rightarrow {}^{4}He + {}^{4}He$
2) $^{9}Be + n \rightarrow {}^{9*}Be + n_1$, $^{9*}Be \rightarrow {}^{5}He + {}^{4}He$, $^{5}He \rightarrow {}^{4}He + n_2$
3) $^{9}Be + n \rightarrow {}^{5}He + {}^{4}He + n_1$, $^{5}He \rightarrow {}^{4}He + n_2$
4) $^{9}Be + n \rightarrow {}^{4}He + {}^{4}He + n_1 + n_2$

We assumed portions to these four branches as follows:

1) There are discrete inelastic scatterings to the following excited levels for the process 1) with portions,

2.429 MeV state,	34 %
4.70 MeV state,	2 %
6.70 MeV state,	4 %

for the first neutron n_1, and the second neutron n_2 is emitted by the evaporation process.

2) We neglected the process 2).
3) For the process 3), the compound nucleus ^{10}Be breaks up to the three particles in the phase space with the portion 45 %, and then ^{5}He breaks up to ^{4}He and n_2 in the phase space.
4) For the process 4), the compound nucleus ^{10}Be breaks up simultaneously to the 4 particles in the phase space with the portion 15 %.

The choice of the portions is arbitrary and not optimized, which was guessed however taking into consideration the experimental double differential spectra. Results of the Monte Carlo analysis are shown in Figs. 2-a, b and c for three angles, in comparison with the experimental data. We can say that agreements are satisfactory in the forward angles, although the spectrum at 150° is considerably underestimated in the 1-4 MeV region. The highest energy peaks in the experimental data are from the elastic scattering, which is not included in the calculations.

Angular distributions of the $^{9}Be(n,2n)$ neutrons are shown in Fig.3. The present Monte Carlo calculation agrees very well with the experiment, while the JENDL-3T data overestimate significantly in backward angles. For the $^{9}Be(n,2n)$ cross section at 14.1 MeV, the present experiment gave 478 ± 14 mb, which is in agreement with the value of 492 ± 30 mb by Baba[6] and however 13 % smaller than the JENDL-3T data of 542 mb.

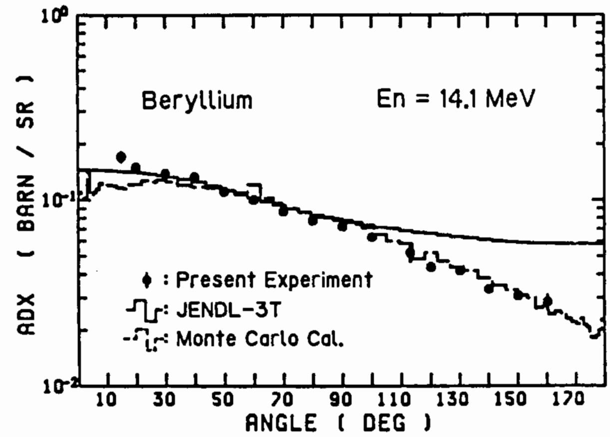
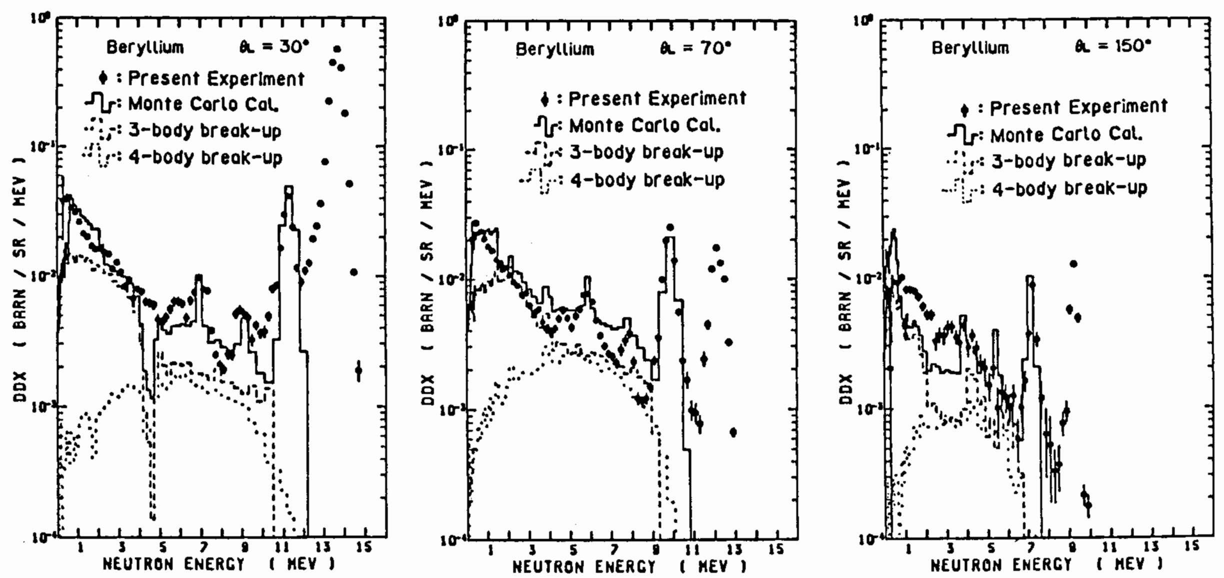
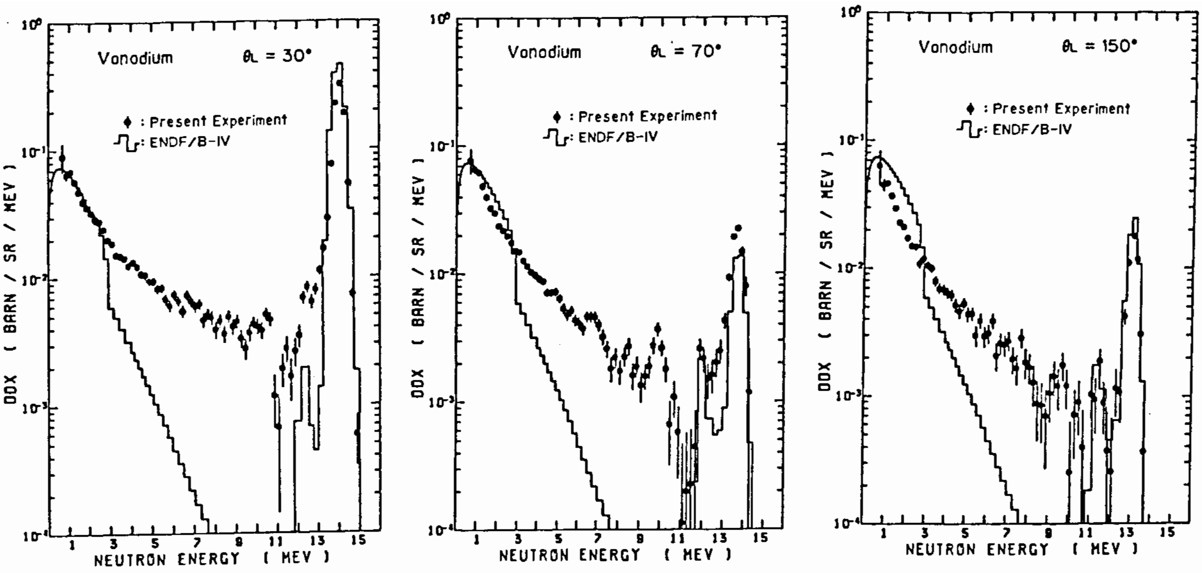


Fig.3 Angle-differential cross sections of $^{9}Be(n,2n)$



(a) (b) (c)

Fig.2 DDX data for Be, in comparison with the Monte Carlo calculation



(a) (b) (c)

Figs.4-a, b, c DDX data for V, compared with the ENDF/B-IV data, at En = 14.1 MeV

Vanadium

Typical measured data of double differential neutron emission cross sections are shown in Fig. 4 for three angles, in comparison with the ENDF/B-IV data. We can see drastic disagreements at all angles, in the intermediate energy region of 3-11 MeV. The reason of these disagreements is of course due to the fact that some of direct discrete inelastic scatterings and the precompound process are ignored in the ENDF/B-IV evaluation. Agreement is good at the elastic scattering peaks. In the low energy region less than 3 MeV, the experimental data show slight enhancement of neutron emission in forward angles, compared with the isotropic data of ENDF/B-IV.

To fill up the disagreements in the 3-11 MeV region, we tried an analysis with the precompound process using the GNASH86 code[9]. The optical potential by Wilmore and Hodgson[10] was used. We adopted the level density parameter a = 8.1 MeV^{-1}, which was considerably different from the value given by Grimes et al.[11], and the Kalbach constant K = 1.1. The result is shown in Fig.5, for angle-integrated emission spectra, in comparison with the measured data and the ENDF/B-IV data. Agreement is good as a whole, although a considerable overestimation is seen in the low energy region less than 3 MeV where the contribution of the (n,2n) reaction may be significant. In the experimental data, we observe peaks at the 1.8, 3.8 and 5.0 MeV excited states from the discrete (direct) inelastic scattering which is not included in the present analysis. The charged particle spectra from the V(n,xp) and V(n,xα) reactions, measured by Grimes et al.[11], were also analysed using the similar a and K parameters close to those for neutrons, with the Perey potential[12] for proton and the McFadden and Satchler potential[13] for α-particle. We could find consistent agreements for the three kinds of particle emissions.

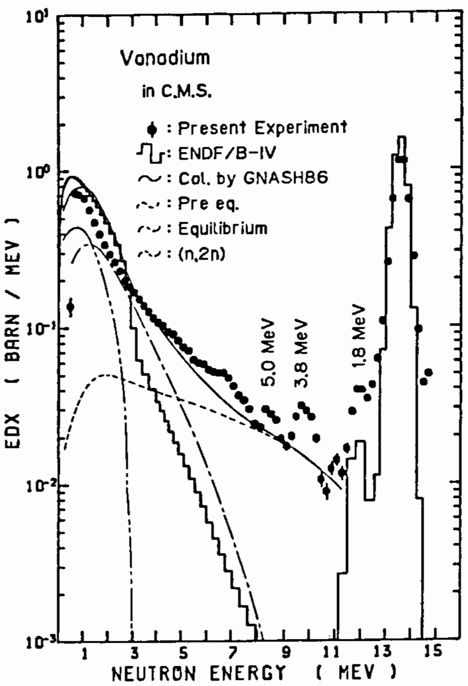
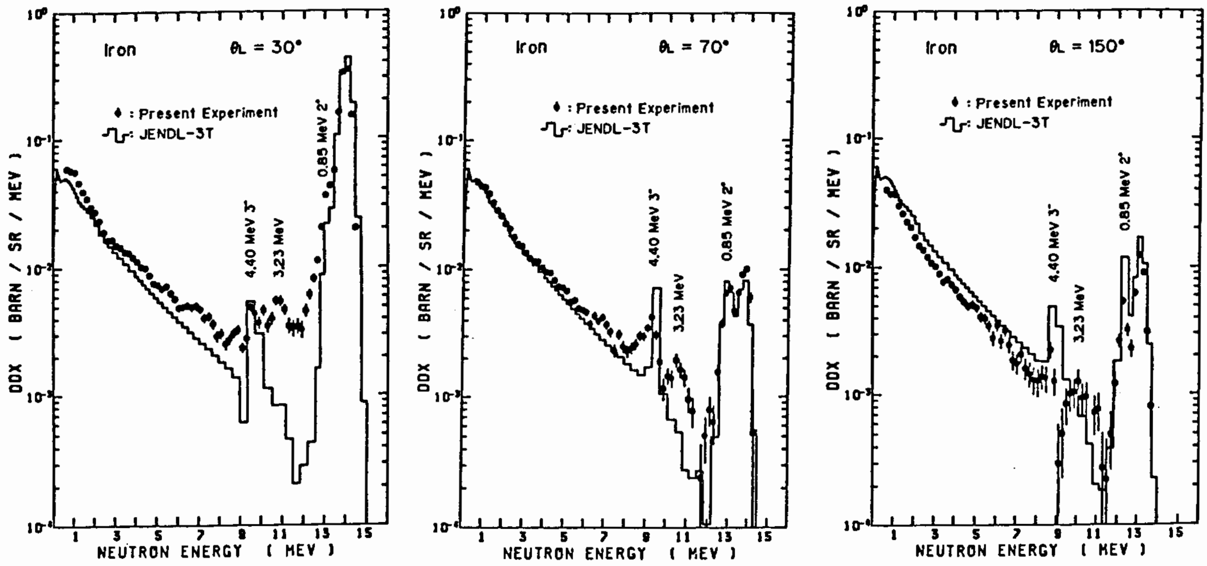


Fig.5 Angle-integrated neutron emission data, V

Iron

For the multiple scattering correction, we used the JENDL-3T data[5]. Typical measured data of double differential neutron emission cross sections are shown in Fig.6, in comparison with the JENDL-3T data. We can say that agreement is good as a whole. However, significant underestimations by the JENDL-3T data are seen in the energy range between the elastic peak and the 3^- state peak of inelastic scattering, at forward angles. In the energy region lower than the 3^- state peak, the experimental data show the slightly larger enhancement of neutron emission at forward angles than those of the JENDL-3T data. At the 3^- state peaks the JENDL-3T data overestimate the experimental data in backward angles, as well as the case of the 2^+ 0.85 MeV state peaks.

Angle-integrated neutron emission spectra in the CM system are shown in Fig.7, in comparison with the JENDL-3T data and the evaluated experimental data by Pavlik and Vonach[14], who made the evaluation based on many available experimental data. The present experimental data agree well with the evaluated curve (broken), although our data seem slightly lower. The two peaks, i. e., the 4.40 MeV 3^- and the 3.23 MeV state peaks from inelastic scattering are not seen in their evaluated curve due to the broad energy bins which they applied. Underestimation of the JENDL-3T data is clear in the energy range of 10-12 MeV which



(a) (b) (c)

Figs. 6-a, b, c DDX data for Fe, compared with JENDL-3T, at En = 14.1 MeV

corresponds to excitation levels from 1.265 MeV to 4.03 MeV[5]. Partial cross sections corresponding to these levels shall be increased by several times from the values given in the JENDL-3T evaluation. It is not clarified yet what kind of the collective excitation can induce a peak at the 3.23 MeV state, and it shall be further investgated.

It seems that the experimental angle-integrated spectra in the CM system in the very low energy region less than about 1 MeV fall unreasonably, as well as the case of vanadium. Probably, the pseudo level assumption adopted in the conversion from the LAB system to the CM system does not hold in this very low energy region, since the (n,2n) process may contribute there significantly. A comparison in the LAB system is therefore more meaningful in this respect. If we look back at the double differential data in the LAB system in Fig. 6, the experimental spectral shapes in the very low energy region seem agreeable with those of the JENDL-3T data.

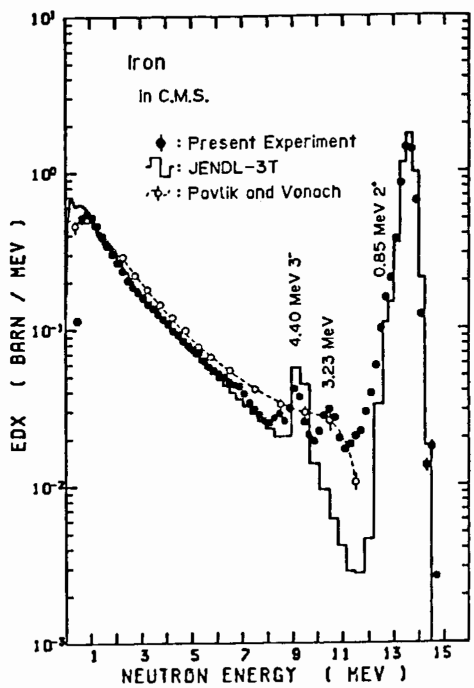


Fig.7 Angle-integrated neutron emission data, Fe

Summary

Relatively accurate data of double differential neutron emission cross sections at En = 14.1 MeV have been given in the present work, for Be, V and Fe. Through the comparisons of the measured differential emission data with the evaluated data and the supplementary theoretical analyses, the following conclusions were obtained. For the evaluation of the ^{9}Be(n,2n) data, the direct simultaneous breakup processes should be taken into account. The treatment of the precompound process for the V(n,n') reaction by the GNASH86 code could reproduce the measured angle-integrated spectrum. For iron, the JENDL-3T evaluation is satisfactory except the 10-12 MeV region of secondary energy.

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