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DOUBLE-DIFFERENTIAL NEUTRON EMISSION SPECTRA FOR Al, Ti, V, Cr, Mn, Fe, Ni, Cu, and Zr

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Abstract: The angle-dependent neutron emission spectra have been measured for nuclides cited above at the incident neutron energy of 14.1 MeV. For aluminum, iron, nickel, copper and zirconium, the measurements were performed as well at 18 MeV incident energy. The data were obtained at 7-12 laboratory angles for secondary neutrons down to 0.6 MeV. The emission neutrons show systematic angle dependence and their angular distribution were compared favorably with the calculation based on the Kalbach-Mann systematics.

(neutron, emission spectra, Al, Ti, V, Cr, Mn, Fe, Ni, Cu, Zr, 14.1 MeV, 18 MeV)

Introduction

The neutron emission spectra of fusion reactor structural materials are of prime importance for the neutronics study and shielding design of fusion reactor/1/. They are also needed for the assessment of radiation damage and nuclear heating caused by the recoil particles produced via the neutron bombardment.

The neutron emission spectra produced by the high energy neutrons are known to be angle dependent at higher emission energy because of the contribution of pre-equilibrium and/or direct reaction process. These angle dependent neutron emission is shown to affect the neutronic behavior such as neutron spectra and neutron penetration/2/. The spectra of recoil particles will be influenced by the anisotropic neutron emission. Therefor detailed data are required for energy-angular distribution for neutron emission from structural materials. Despite of the requirement, only limited experimental data have reported the high energy part of emission spectrum.

We have been studying energy-angular double-differential neutron emission cross sections (DDX) for fusion reactor candidate materials using a time-of-flight technique/3-6/. This paper presents the results for structural materials in the mass range from aluminum to zirconium at the well-specified incident energy of 14.1 MeV. Measurements at 18 MeV incident energy were also performed for 5 elements. The data were obtained 7 to 12 laboratory angles for secondary neutrons down to 0.6 MeV; the data for wide range of secondary energy is needed for study of the competition between equilibrium and pre-equilibrium process.

We derived the angular distribution of emission neutrons, angle-integrated emission spectra, partial scattering cross sections for prominent levels, and discussed the angular distributions in comparison with the calculation based on Kalbach-Mann systematics/7/.

Experiments

The experiments were carried out using Tohoku University Dynamitron Time-of-Flight neutron spectrometer. The procedure of experiments and data processing are almost identical with those reported previously/3-6/, and described briefly here.

The mono-energy primary neutrons of 14.1 MeV and 18.0 MeV were obtained via the (d,n) reaction on tritium-loaded titanium targets at the emergent angle of 90- or 97.5-degree, and 0-degree with respect to the deutron beam axis, respectively. The energy dispersion of primary neutrons was about 300 keV in FWHM. The scattering samples, which were right cylinders of 2.5 to 3.5 cm in dia. and 4 to 5 cm long, were placed vertically about 12 cm from the target at the angles noted above. Powder samples of vanadium, chromium and manganese were encased in thin-walled aluminum cans.

The secondary neutrons were detected by a NE213 scintillator, 14 cm in dia. and 10 cm long coupled to Hamamatsu R1250 photomultiplier tube and fast timing divider base. It was placed in a hydrogenous massive shield on turning table. The detector was equipped with two separate neutron-gamma discriminator with bias setting about 0.3 and 2 MeV. The timing and pulse-shape discriminator had pulse-height dynamic ranges over 400 to cover the entire energy range from 0.3 to 20 MeV. Flight path length was 4 to 8 m.

The absolute values of cross sections were determined relative to the hydrogen scattering cross section by measuring scattering yields from a small polyethylene scatterer.

Relative neutron detector efficiency was determined by calculation and measurements of Cf-252 fission neutrons and hydrogen-scattered neutron yield of 14.1 and 18.0 MeV neutrons.

A smaller NE213 scintillator, 2" in dia. and 2" long, monitored the source neutrons directly for flux normalization between sample-in and sample-out run.

The scattering angle was varied by turning the detector around the sample. For 14.1 MeV measurements, another arrangement was adopted as well/4-6/; the neutron detector was fixed at 90-degree direction, the scattering samples were placed horizontally and rotated around the neutron producing target in the plane perpendicular to the deutron beam to vary the scattering angle.

Data Analyses

The time-of-flight data were corrected for sample-out background and detector-efficiency, then transformed into energy spectra of 0.2 MeV energy bin. Further data correction was made for the finite sample-size effect and for backgrounds caused by parasitic and degraded neutrons. A Monte-Carlo code was used for the correction employing evaluated nuclear data library for simulation. The code simulates neutron emission spectra for both cases with and without the effects; the ratio of the spectra provides correction factor. The correction factor obtained by the method dose not depend very strongly on the initial guess of the emission data. However, in the cases that evaluated neutron emission data were unacceptably different from the measured ones, they were to be replaced with realistic ones obtained by the analyses shown in later section.

After the correction, the laboratory energy spectra were translated into the center-of-mass (C.M.) system. Then angular distribution of emission neutrons and angle-integrated spectrum were deduced in C.M. system.

Results and Discussion

In this section, we present typical results of DDX, angle-integrated spectra and angular distributions of emission neutrons in comparison with evaluated values. Then, the angular distributions are compared with the calculation based on Kalbach-Mann systematics.

Data Comparison

Figure 1 shows the DDX data for iron in comparison with the evaluated data of JENDL-3T* /8/ and ENDF/B-IV/9/. The present experimental data agree fairly well with the high resolution data by Takahashi et al./10/ both in shape and magnitude. The experimental data indicate anisotropy of continuum neutrons and excitation of low lying levels; which are not traced consistently by the evaluated data. Such angular dependences of emission neutrons were observed systematically for a series data of the present study. In turn, the angle-integrated spectrum shown in Fig.2 is in good agreement with the evaluations. Therefor the disagreement in laboratory emission spectra are largely attributable to the lack of energy-angle correlation in the evaluated data files. Same feature is also found for 18 MeV data.

Then, we compare the experimental data with the evaluated ones in the angle-integrated form. Figure 2 and 3 show the angle-integrated neutron emission spectra for 14.1 MeV neutrons in comparison with evaluated values. The present data of angle-integrated spectra are generally close to the corresponding data by Vonach et al./11/.

The experimental neutron emission spectrum for aluminum is between JENDL-3T and ENDF/B-IV data in the middle energy region, and close to lower value of the latter in low energy region, while it appears to overemphasize high-lying levels excitation. Same observation was found for 18.0 MeV.

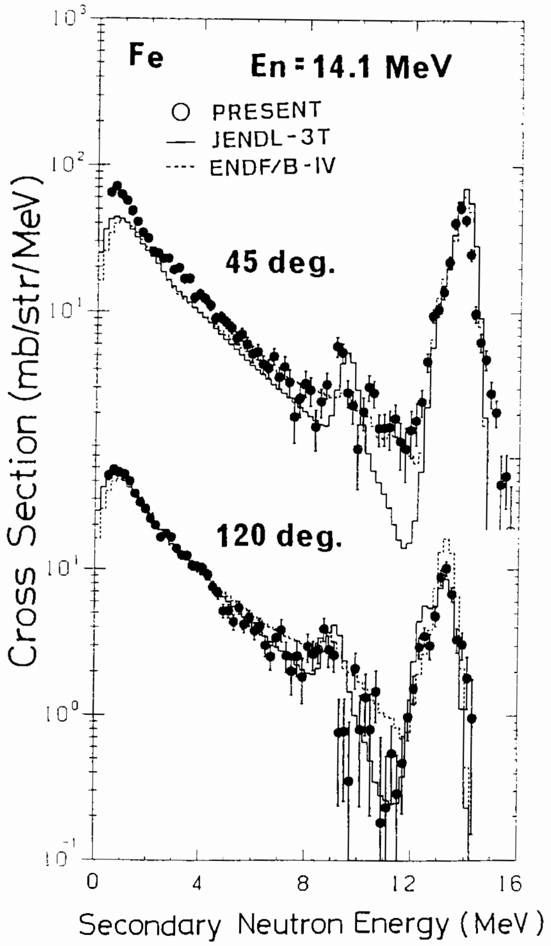

Fig.1. Neutron emission spectra of iron.

For titanium and vanadium, the evaluated values of ENDF/B-IV are far from realistic due to lack of pre-equilibrium and/or direct process, while new version is much improved/12/.

The present data for chromium and manganese are in agreement with the JENDL-3T evaluation, while they are slightly higher in the case of chromium, and indicate stronger excitation of discrete levels for manganese. The deficiency of ENDF/B-IV is clear.

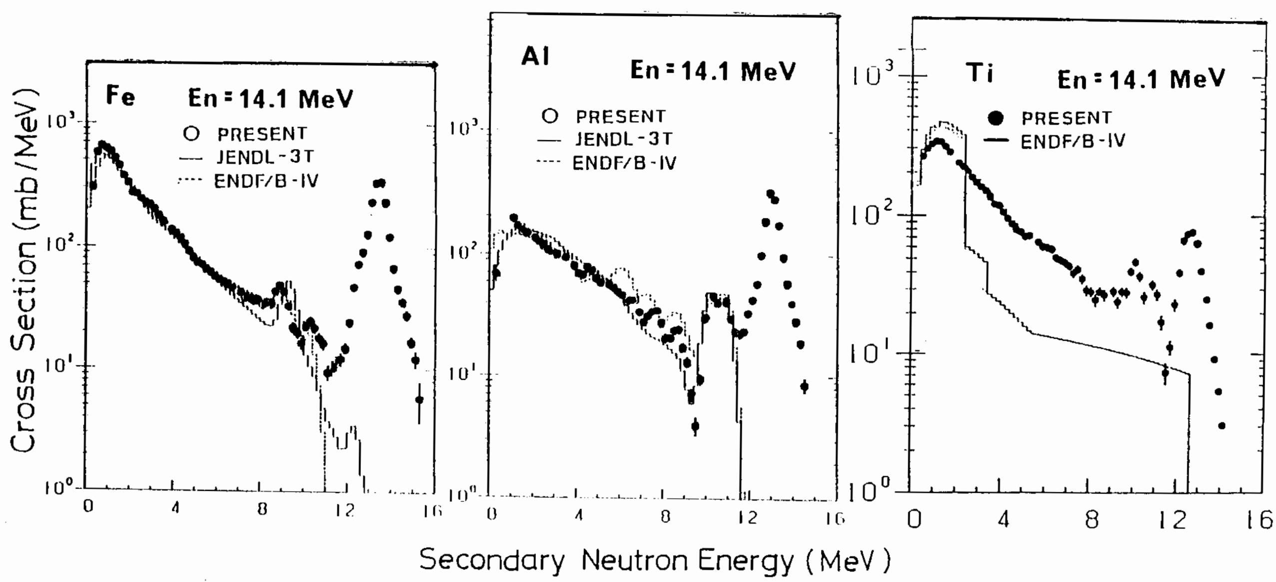

Fig.2. Angle-integrated neutron emission spectra from Fe, Al and Ti.

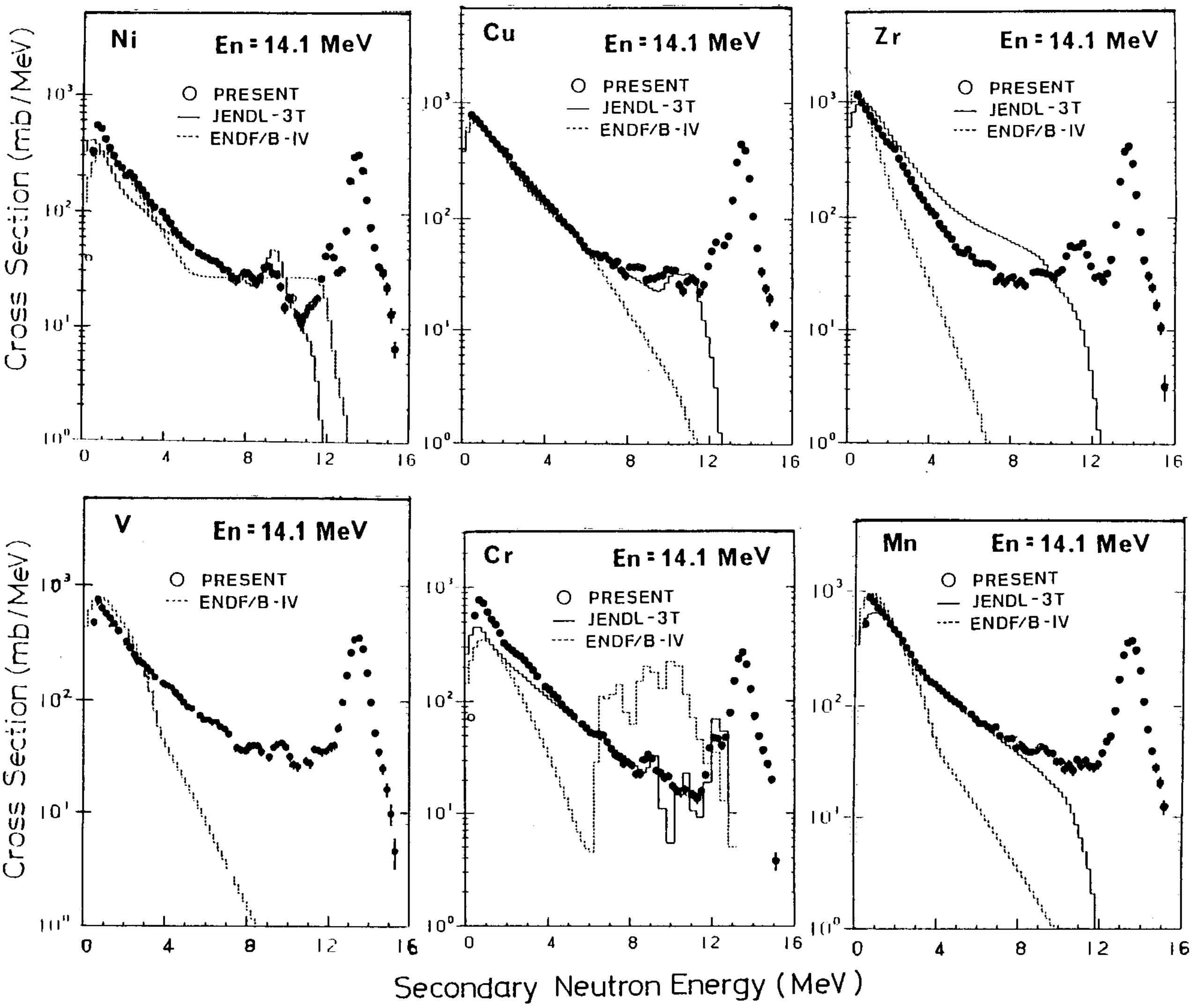

Fig.3. Angle-integrated neutron emission spectra from V, Cr, Mn, Ni, Cu and Zr.

The data of nickel agree with JENDL-3T much better than ENDF/B-IV at high energy region; however the experimental values are significantly larger than JENDL-3T in lower energy region.

The present data of copper agree very well with the JENDL-3T evaluation in whole the energy region. Such good agreement is seen also for 18 MeV incident neutrons.

For zirconium, the ENDF/B-IV data lack pre-equilibrium part of emission neutrons and underpredict drastically high energy neutrons. To the contrary, JENDL-3T appears overemphasize that component.

Neutron Angular Distributions

As shown above for iron, the emission neutrons show marked anisotropy above few MeV. Theorical calculations do not necessarily provide very good reproduction of the distribution/13/.

We have calculated the angular distributions using Kalbach-Mann systematics. The pre-equilibrium ratio necessary for the calculation was obtained empirically by fitting the angle-integrated emission spectra with the superposition of Griffin-Blann's exciton spectrum, Weiskopf-Ewing's evaporation spectrum and LeConteur-Lang's cascade neutron spectrum. Relative amplitude and nuclear temperature were determined by the least-squares method. The compound formation cross sections needed in the exciton model were calculated by the optical model.

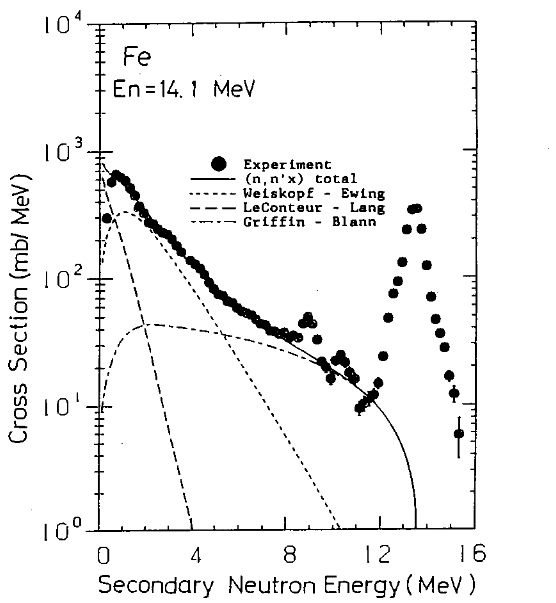

Fig.4. Angle-integrated neutron emission spectrum of iron, fitted with exciton and evaporation spectrum function.

An example of the fitting is shown in Fig.4, reproducibility is fairly good. The pre-equilibrium ratio obtained was found to show systematic mass dependence of target nuclides.

Figure 5 shows the comparison of the experimental angular distribution with calculated ones. The experimental angular distributions are nearly isotropic below a few MeV and show forward-rise with increase of outgoing energy. The calculation traces rather well the tendency of the experimental data. However, as stated in Ref.13 , Kalbach-Mann systematics appears to overemphasize the anisotropy especially at medium energy range around 4 to 9 MeV. By the improvement, this simple model may reproduce over wide range of emission energy and elements with a single set of parameters except for low lying levels and light elements where direct reactions play dominant role.

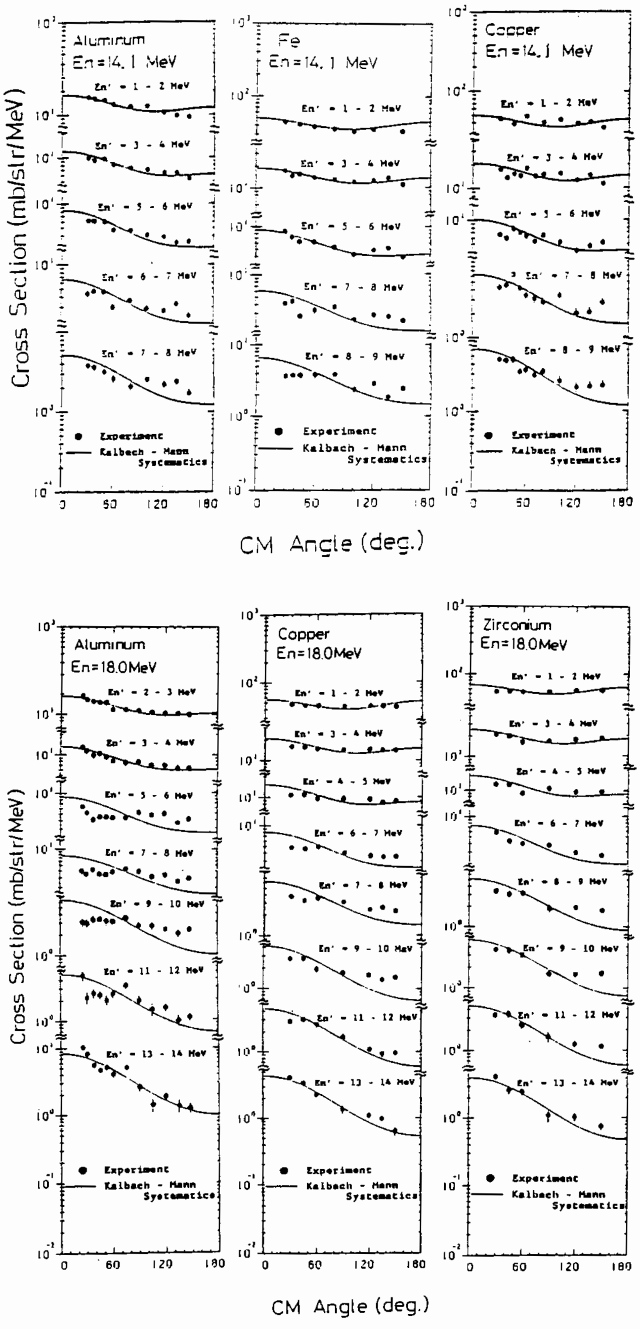

Fig.5. Angular distribution of emission neutrons, compared with Kalbach-Mann Systematics.

Summary

Double-differential neutron emission cross sections were measured for fusion reactor structural materials for 14.1- and 18.0-MeV neutrons. Measured data were compared with the evaluation. The angle-dependence of emission neutrons were compared with Kalbach-Mann systematics favorably while slight adjustment of parameters are necessary.

Acknowledgment

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* JENDL-3T is a temporary file for testing the evaluated data for JENDL-3. The data in JENDL-3T may be partly revised JENDL-3.

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