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DOUBLE-DIFFERENTIAL NEUTRON SCATTERING CROSS SECTIONS OF BERYLLIUM, CARBON, OXYGEN

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Abstract: The energy-angular double-differential neutron scattering cross sections have been measured for beryllium, carbon and oxygen at the incident neutron energies of 14.1 MeV and 18.0 MeV. The measured neutron emission spectra and partial scattering cross sections are presented in comparison with the evaluated values. The neutron spectra from beryllium were analyzed on the basis of a multi-particle decay model, and were reproduced reasonably by assuming contribution of simultaneous four-body breakup process.

(neutron, emission spectrum, T-O-F, beryllium, carbon, oxygen, 14.1 MeV, 18 MeV)

Introduction

The energy-angular doubly-differential neutron scattering cross sections (DDX) of fusion reactor structural materials are basic nuclear data for neutronic design of fusion reactors/1/. The DDX data for beryllium, carbon and oxygen are of special importance since these nuclides are expected as an effective neutron multiplier, shielding and reflector material, and constituent of tritium breeder and coolant, respectively. However, the experimental data covering entire range of emission spectrum with sufficient energy resolution are very few and show disagreement each other. In addition, integral studies have pointed out problems for neutron emission data/2,3/.

This paper presents the measurement of double-differential neutron scattering cross sections of beryllium, carbon and oxygen for incident neutrons of 14.1 and 18 MeV. The data at 18 MeV were measured to study the energy dependent behavior of the cross sections. The measured data will be compared with other experiments and evaluated data concerning the emission spectra and partial scattering cross sections derived from the DDX. The beryllium emission spectra are analyzed with a multi-particle decay model.

Experiments and Data Analyses

The measurements were carried out using a time-of-flight neutron spectrometer at Tohoku University Dynamitron facility. The experimental technique have been described previously /4-7/. The present measurements were performed at 12 laboratory angles, and for secondary energy below 1 MeV with refinements in apparatuses and data analyses.

Experiment

The primary neutrons of 14.1- and 18-MeV were obtained via the T+d reactions using solid tritium-loaded titanium (Ti-T) targets at the emission angle of 97.5- and 0-degree, respectively. The energy spreads of primary neutrons were about 300 keV. The Ti-T targets were contained in thin-walled chambers and cooled by air blow to reduce neutron degradation. The effects of background neutrons due to parasitic reactions on target and to scattering around targets were taken into consideration in the data analyses.

The scattering samples were right cylinders of solid beryllium (2.0 cm in dia., 3 cm long), carbon (2.5 cm in dia., 4 cm long), and powder of MnO_2 & Al_2O_3 (3.5 cm in dia., 4.5 cm long) encased in aluminum cans and used to extract oxygen data. The samples were suspended vertically about 12 cm from the target by remotely controlled sample changer.

The secondary neutron detector was a NE213 scintillator, 14 cm in dia. and 10 cm thick, coupled to a Hamamatsu R1250 photomultiplier tube and a fast-timing divider base. It was placed in a massive shield on a turning table at the flight path length up to 6 m. The detector was incorporated with two separate neutron-gamma discriminators having bias setting of 0.3 and 2 MeV. The higher bias eliminates the uncertainty in a detector efficiency caused by carbon events in the scintillator/8/, and provides excellent neutron-gamma separation. The timing module and neutron-gamma discriminator had pulse-height dynamic ranges of 1000 and 400, respectively, to measure the neutron energy range from 0.3 to 20 MeV in a single setup. The overall timing resolution was 2.5 to 3.0 nanosecond.

The cross section scale was determined relative to the hydrogen scattering cross sections/9/ by measuring scattering yields from a polyethylene sample. The relative detector efficiency curve was determined by combining the calculation and measurements of the Cf-252 fission neutrons and hydrogen scattering yields.

A smaller NE213 scintillator was employed to monitor the source neutron intensity in T-O-F mode and used for neutron fluence normalization.

Data Analyses

The experimental T-O-F data were corrected for 1) sample-out backgrounds, 2) detector efficiency, 3) sample-size effect, and for 4) backgrounds due to parasitic and degraded neutrons.

The effects of 3) and 4) were estimated using a Monte-Carlo calculation considering the kinematics of neutron scattering and finite geometry between the target and sample. The evaluated nuclear data were employed for the simulation; however, the neutron emission spectra were to be revised for beryllium so as to make adequate correction. The fraction and spectrum of parasitic and degraded neutrons were estimated from the measurement of source neutrons and a separate Monte-Carlo calculation. The sample size correction for the polyethylene sample was made using an analytic method. The corrected data were analyzed further with a least-squares fitting program to deduce the partial scattering cross sections.

Results and Discussion

In this section, we present typical experimental results in comparison with other experiments and the evaluated data, JENDL-3T*/10/, JENDL-3PR2, ENDF/B-IV,V/11/.

Beryllium

Figure 1 presents the DDX results for beryllium at 14.1 MeV, compared with the JENDL-3T evaluation. It is noted that excitation of discrete levels are much less pronounced in the experimental spectra than assumed in the evaluation, while the experimental energy resolution is sufficiently good to resolve them, if there.

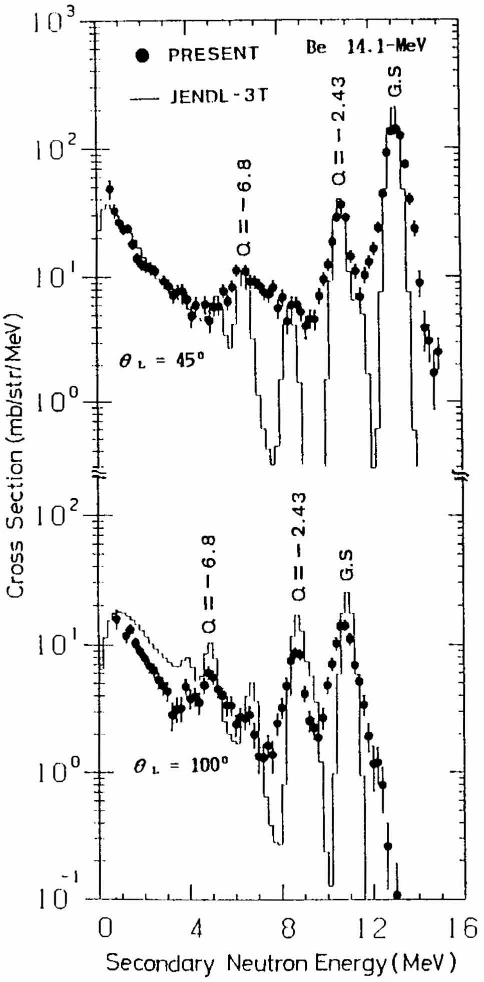

Fig.1. Neutron emission spectra of beryllium for 14.1 MeV neutrons, compared with JENDL-3T evaluation.

The experimental data by Takahashi et al. /12/, and by Drake et al. at LANL/13/ are in good agreement with the present ones and show similar trends, although LANL data are substantially larger than the present and Takahashi et al.'s ones at lower energy range.

The present value of (n,2n) cross section (492±30 mb), obtained by integrating the nonelastic neutrons over energy and angle, is about 15% smaller than LANL and JENDL-3T data, but agrees with lower values by Takahashi et al. and LLNL evaluation/14/. The inelastic scattering cross section for 2.43 MeV level (161±10 mb) is also in agreement with that by Hogue et al./16/ and JENDL-3T, LLNL evaluation.

The fact that the experimental emission spectra indicate only a few discrete levels excited suggests significant contribution of simultaneous breakup process in the neutron emission. Figure 2 shows the results of model calculation of emission spectra. The calculation assumes contribution of 1) simultaneous four-body breakup process (isotropic in C.M. system), as well as the 2) sequential decay of the exited levels at 2.43 and 6.7 MeV in Be-9, and 3) that of the first level in He-6; the excitation cross sections of Be-9 and neutron spectrum for 3) were taken from the present data, and JENDL-3T respectively. The sequential process 2) was assumed to result in three-body phase-space distributions in their C.M. system. An artificial continuum levels were assumed as well to compensate slight underprediction of the calculation.

The magnitude of four-body breakup process, estimated by fitting the phase-space distribution to the experimental spectra, accounts for about one third of (n,2n) cross section. This is in contrast to the case of lower incident energy/4/, where sequential process dominates the spectra.

It should be noted that present calculation reproduces satisfactorily the shape and angular dependence of the emission spectra, without introducing so many reaction channels as in ref.14 and 17.

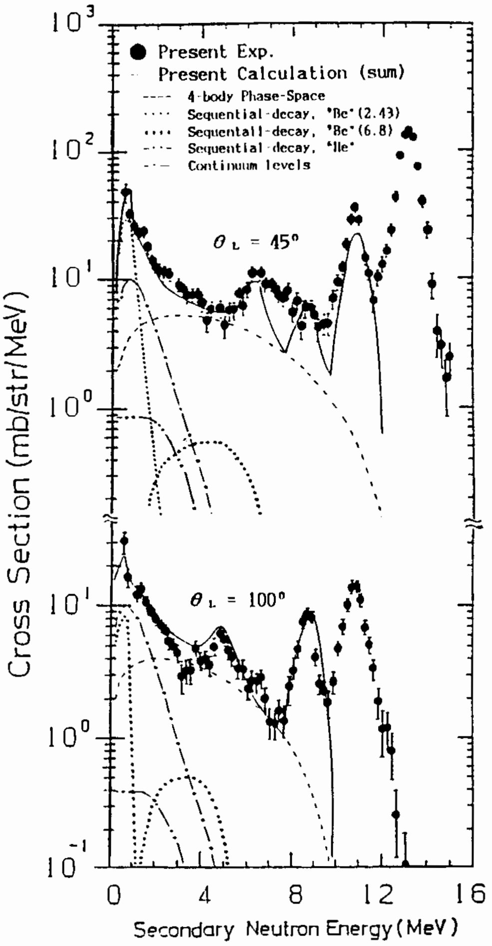

Fig.2. Analysis of beryllium neutron emission spectra for 14.1 MeV neutrons.

Carbon

Figure 3 illustrates the neutron emission spectra of carbon at 14.1 MeV, compared with the evaluated data. There observed are the "continuum" spectra resulting from carbon breakup at the energy range below the second level as well as distinct peaks corresponding to the ground state, first, second and third levels. In the "continuum" region, the experimental data show marked disagreement from both evaluations.

The data by Takahashi et al./18/ and by Drosg et al. at LANL/14/ are in general agreement with the present ones while the latter values are much higher in low energy region as seen in the case of beryllium. The solid curves in figure 3, describing a four-body phase-space distribution, isotropic in C.M. system and normalized appropriately to the experimental data, trace satisfactorily the energy angular distribution, while the reproducibility is inferior at 18 MeV.

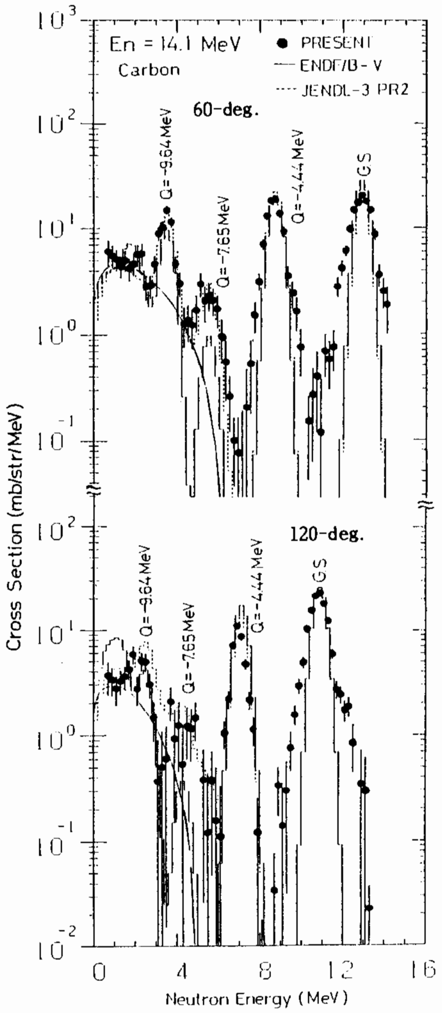

Fig.3. Neutron emission spectra of carbon for 14.1 MeV neutrons, compared with the evaluated data. The solid lines show four-body phase-space distributions.

We extracted differential scattering cross sections for prominent discrete and "continuum" levels. The (n,n′3α) reaction cross sections were also obtained by summing the cross sections for levels higher than the second level.

The present results of these cross sections agreed with our previous data/6/ except for those of "continuum" and (n,n′3α) reaction; the latter two cross sections are lower by about 30% than previous ones as a result of considering the backgrounds due to degraded neutrons. Figure 4 shows the (n,n′3α) cross sections; the present value are close to the recent measurements by Takahashi et al./18/ and Antolkovic et al./19/.

The elastic- and inelastic- scattering cross sections are generally consistent with the evaluation; however, as shown in Fig.5 marked disagreement is observed for the first and third levels at 18 MeV.

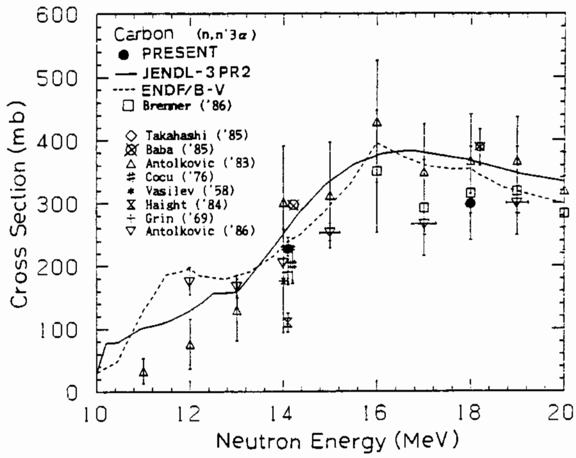

Fig.4. Carbon (n,n′3α) reaction cross sections.

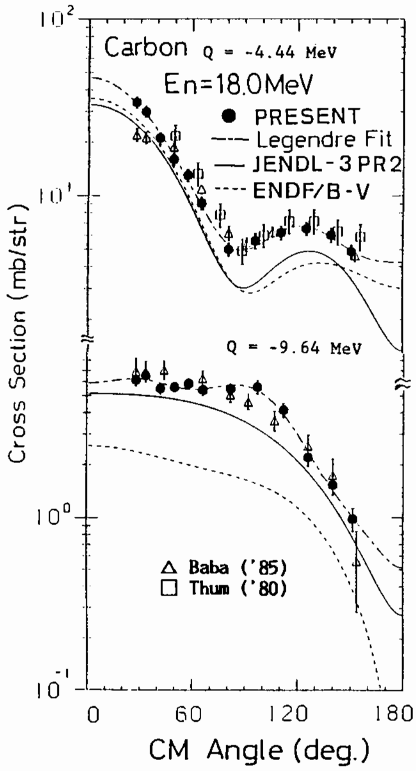

Fig.5. Neutron inelastic-scattering cross sections of carbon for 18 MeV neutrons.

Oxygen

Figure 6 illustrates the DDX of oxygen at 14.1 MeV, compared with evaluated values. The data were obtained by combining the measurements for MnO2 and Mn. For rigorous deduction of oxygen data, sample-size correction was made separately for each sample, then Mn data were subtracted from MnO2 ones.

The evaluated data reproduce satisfactorily the present ones, while JENDL-3T and ENDF/B-IV differs each other slightly. In the energy region between the ground state and first level, the experimental data show some spurious values introduced in the subtraction procedure.

The partial scattering cross sections for low-lying levels are also in agreement with our previous/7/ and evaluated ones. For higher levels, however, the present data differ from JENDL-3T and are close to ENDF/B-IV values. The example is shown in figure 7.

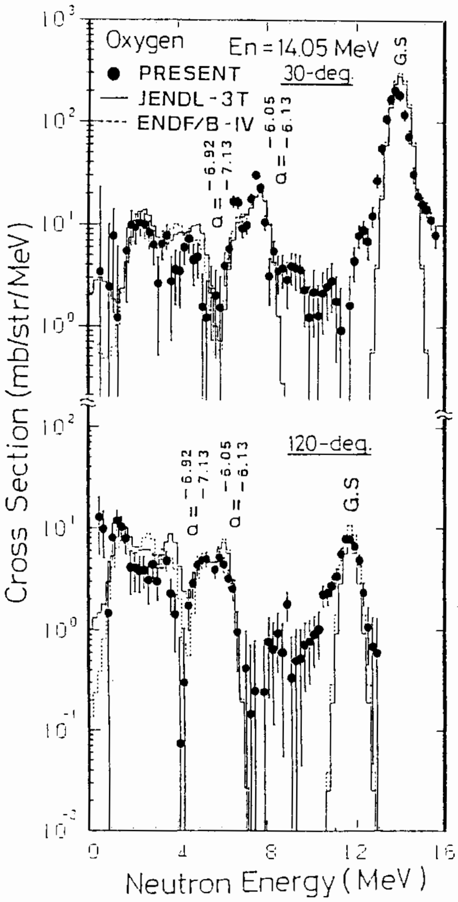

Fig.6. Neutron emission spectra of oxygen for 14.1 MeV neutrons, compared with the evaluations.

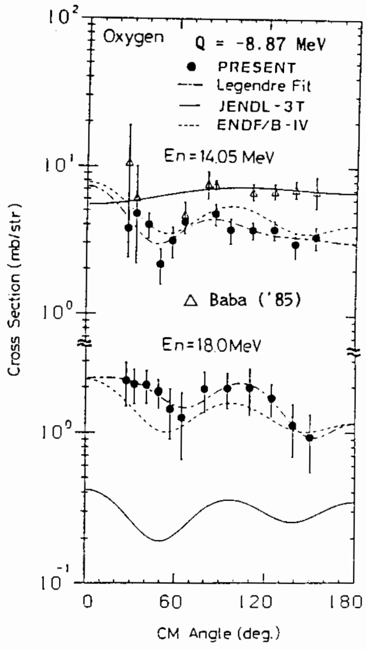

Fig.7. Neutron inelastic-scattering cross sections of oxygen for 14 MeV neutrons.

Summary

We have measured double-differential neutron scattering cross sections of beryllium, carbon and oxygen for 14.1 and 18 MeV incident neutrons and provided neutron emission spectra and partial scattering cross sections. Data comparison pointed out the deficiencies existing in the evaluated files.

For beryllium, contribution of simultaneous breakup process was suggested for interpretation of the neutron emission spectra.

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 in JENDL-3.

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