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Benchmarking of JEFF-3.2, FENDL-3.0 and TENDL-2014 evaluated data for tungsten with 14.8 MeV neutrons

Suyalatu Zhang[1] · Yang-Bo Nie[2] · Jie Ren[2] · Fei Luo[3] · Xi-Chao Ruan[2] · Zhi-Qiang Chen[3] · Rui Han[3] · Temuerbagen Bao[1] · Si-Miao Ge[4]

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Abstract Integral experiments on tungsten slab samples were carried out on the D-T neutron source facility at China Institute of Atomic Energy. Leakage neutron spectra from the irradiated tungsten target were measured by the time-of-flight technique. Accuracy of the nuclear data for tungsten was examined by comparing the measured neutron spectra with the leakage neutron spectra simulated using the MCNP-4C code with evaluated nuclear data of the JEFF-3.2, FENDL-3.0 and TENDL-2014 libraries. The results show that the calculations with JEFF-3.2 agree well with the measurements in the whole energy range and all angles, whereas the spectra calculated with FENDL-3.0 and TENDL-2014 have some discrepancies with the experimental data.

Keywords Integral experiment · D-T neutron source · Time-of-flight technique · Leakage neutron spectrum · Monte Carlo simulation · Evaluated nuclear data

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✉ Zhi-Qiang Chen
zqchen@impcas.ac.cn

1 College of Physics and Electronics Information, Inner Mongolia University for the Nationalities, Tongliao 028000, China

2 China Nuclear Data Center, China Institute of Atomic Energy, Beijing 102413, China

3 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

4 School of Chemical Engineering, Sichuan University, Chengdu 610065, China

1 Introduction

New design concepts of nuclear reactor, transmutation of nuclear waste and spallation neutron source are investigated worldwide. For designing these facilities, accurate evaluated nuclear data are required. Compilations of evaluated nuclear data files are based on the experimental data or nuclear models. Neutron data can be obtained from evaluated nuclear data libraries, such as ADS-2.0 [1], ENDF/B-VII.0 [2], ENDF/B-VII.1 [3], JENDL-4.0 [4], CENDL-3.1 [5], JEFF [6], FENDL [7] and TENDL [8]. Integral benchmark experiments combined with Monte Carlo simulation are generally used to examine the accuracy of evaluated nuclear data [9–16].

Tungsten is considered as high heat flux handling material for fusion devices, target material for accelerator driven systems and spallation neutron sources, because of its high melting point, high heat conductivity and good neutronics performance. Integral experiments and computational analyses have been carried out for validation of tungsten in several evaluated nuclear data libraries [17–24]. The tungsten neutron data of ADS-2.0, ENDF/B-VII.0, ENDF/B-VII.1, JENDL-4.0 and CENDL-3.1 libraries were studied by the integral experiments of a tungsten slab sample of 10 cm × 10 cm × 7 cm [24]. The results show that the calculations with ADS-2.0 and ENDF/B-VII.1 agree well with the experiments in the whole energy regions except the elastic scattering peak. However, larger discrepancies are observed between the experiments and the calculated spectra using data from ENDF/B-VII.0, JENDL-4.0 and CENDL-3.1 libraries, especially around 8.5–13.5 MeV.

JEFF is an evaluated library produced under the auspices of the NEA data bank. The new JEFF-3.2 library was released on March 5, 2014, and contains 472 nuclides neutron data. FENDL was developed, updated (with the latest version of FENDL-3.0) and applied to all fusion technology. TENDL is a nuclear data library to provide the output of the TALYS nuclear model code, and TENDL-2014 was released on December 11, 2014. In this paper, accuracy of tungsten evaluated nuclear data for the JEFF-3.2, FENDL-3.0 and TENDL-2014 libraries is examined by comparing measured leakage neutron spectra with calculated ones. Leakage neutron spectra from the irradiation of D-T neutrons on tungsten slab samples (10 cm $\times$ 10 cm $\times$ 3.5 cm, and 10 cm $\times$ 10 cm $\times$ 7 cm) are measured at 60° and 120° with the time-of-flight techniques. Simulations are performed with the Monte Carlo neutron transport code MCNP-4C [25]. The comparisons are made in both the spectrum shape and the calculation-to-experiment ratio of the spectrum integrated over five energy regions.

2 Measurements and simulations

2.1 The TOF measurements

The experiments were carried out on the integral experiment facility at China Institute of Atomic Energy (CIAE). The experimental details were reported in Refs. [14, 24, 26], so a brief description is given here. The 14.8-MeV mono-energetic neutrons were generated with the T(d, n)^{4}He reaction. The deuteron (D^+) beam was bunched about 2.5 ns width in FWHM with a repetition rate of 1.5 MHz. The beam current was about 20 μA, and the average neutron yield was about 1.3×10^9 n/s. Intensity and time structure of source neutrons were recorded by a Au–Si surface barrier detector and a stilbene crystal scintillation detector, respectively. Two tungsten samples (10 cm $\times$ 10 cm $\times$ 3.5 cm and 10 cm $\times$ 10 cm $\times$ 7 cm) were used, with the sample purity of 99.9% and density of 18.1 g/cm^3. The leakage neutron spectra at two angles (60° and 120°) were measured with a BC501A (Φ5.08 cm $\times$ 2.54 cm) liquid scintillation detector by the time-of-flight (TOF) technique. The neutron detection efficiency was calculated by NEFF Monte Carlo code [27], using a calibrated light output function. The pulse shape discrimination (PSD) property of BC501A detector was used to separate γ-rays from neutrons. Figure 1a shows typical results of PSD. Neutrons appear in higher rise time channels than gamma rays for having pulses with a long fluorescence tail. High foreground-to-background ratio was achieved using a heavy shielding and collimating system. Background measurements were taken without the sample to subtract neutrons produced from the upstream devices such as the sample holders. Examples of TOF spectra of the sample-in and sample-out measurements for the tungsten slab sample at 60° are shown in Fig. 1b, where the spectra just include neutron events.

The flight time of neutrons was analyzed after the selection of pure neutron events. The TOF spectrum consists of a peak due to the elastic scattering and other components due to the (n, inl), (n, 2n), (n, 3n) and (n, np) reaction channels. The neutron elastic peak was taken as the time reference for the neutron TOF. The energy spectrum of neutrons is converted from the TOF spectrum with consideration of the neutron detection efficiency. The calculation results of the neutron detection efficiency with 0.8 MeV bias were used for the present work. Gamma rays from ^{137}Cs (0.662 MeV) and ^{22}Na (0.511 MeV, 1.275 MeV) standard sources were used to calibrate the neutron detector.

2.2 The MC simulations

The benchmarking calculations were performed with the Monte Carlo neutron transport code MCNP-4C [25] using the tungsten data in JEFF-3.2, FENDL-3.0 and TENDL-2014 libraries. As the libraries contain no natural element of tungsten, appropriate combinations of isotopic data were used in the calculations. The characteristics of the experiment were modeled as accurately as possible, such as the T–Ti target, source neutron and neutron detection efficiency. The TARGET code [28] was used to calculate both angular distribution and angle dependent energy distribution of the source neutrons, considering the deuteron beam energy and the T–Ti target geometry.

A simplified MCNP model used in the simulation is shown in Fig. 2. Neutron transportation was limited in Regions 1 and 2. Region 2 was a cylindrical tube in the same radius as aperture size of the experimental collimator system. The outside of Regions 1 and 2 had no importance. The experimental target setup was well described and employed to define the value of source CEL variable where the particle started in the MCNP code. The time response of the source neutron, which was measured by a stilbene scintillation crystal detector, was utilized to define the TME variable. A point detector estimator was used to tally the leakage neutron time of flight spectra. The calculations for 60° and 120° were performed. The left sample was filled with air in the simulation for 60°, while the right sample was filled with air for 120° simulation.

A cylindrical polyethylene of Φ13 cm $\times$ 6 cm was used as a standard sample. The measured leakage neutron

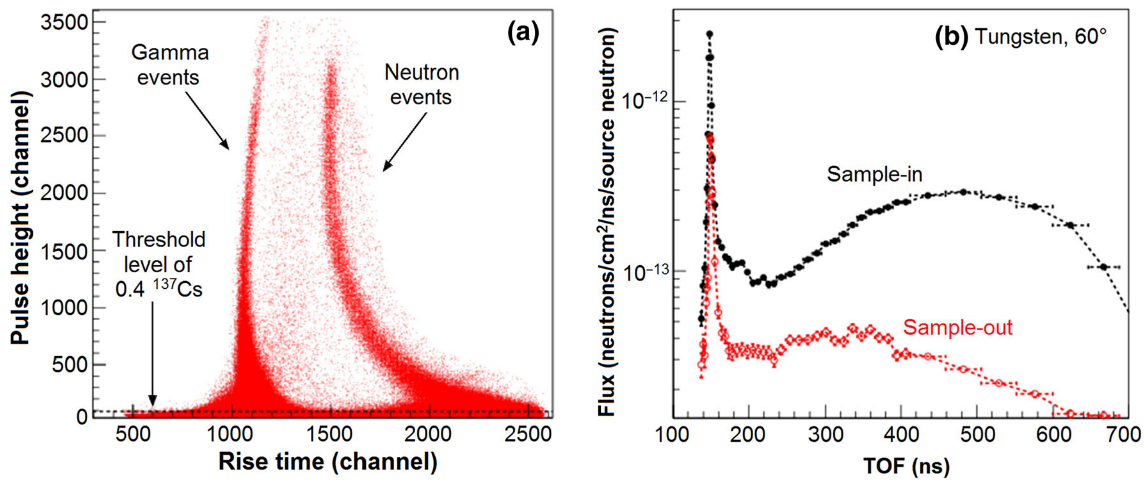

Fig. 1 (Color online) Separation of neutron and gamma with the PSD technique (**a**) and TOF spectra measured with and without W sample (**b**)

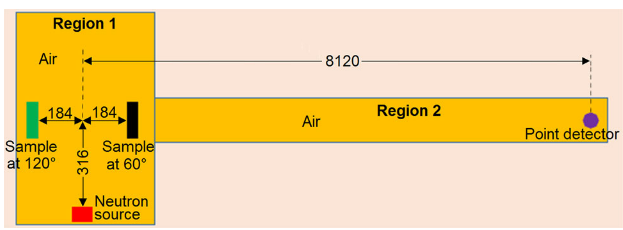

Fig. 2 (Color online) Model for the MCNP simulations (in mm)

spectra were normalized and compared with the MCNP calculated ones. The normalizations were completed by matching the areas under the spectra of n–p scattering peak. This normalization factor was then applied to the analysis of the tungsten experiment. The measured and calculated leakage neutron spectra from the polyethylene sample at 60° for 14.8 MeV neutrons are shown in Fig. 3.

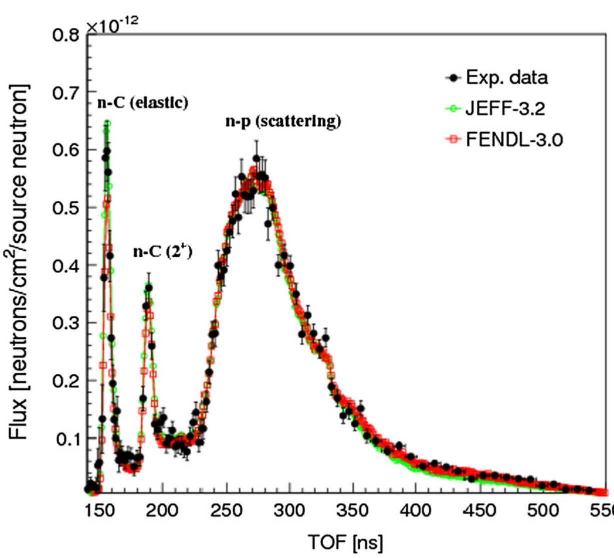

Fig. 3 Leakage neutron TOF spectra from polyethylene at 60°

The calculations with both JEFF-3.2 and FENDL-3.0 libraries predicted the measurements fairly well in the whole energy range, indicating that the experimental setup works properly and the MCNP simulations are correct.

3 Results and discussion

The leakage neutron TOF spectra from the tungsten samples of 3.5 and 7 cm in thickness were measured at 60° and 120° from the incidence of 14.8 MeV neutrons. The pure neutron energy spectra were converted from the TOF spectra after eliminating gamma and background events. In Fig. 4, the MCNP calculated leakage neutron spectra with different evaluated nuclear data libraries are compared with the measured ones. Uncertainties of the present experiment come from the statistical and systematic errors. The systematic errors were mainly caused by neutron detection efficiency ($\leq$5%) and source neutron yield ($\leq$3%). The calculation-to-experiment (C/E) values of the spectra integrated over four energy regions are given in Table 1.

From these comparisons, the following observations are found.

(1) JEFF-3.2

The leakage neutron spectra calculated with JEFF-3.2 (red solid line in Fig. 4) agree well with the measured spectra in the whole neutron energy range at 60° and 120° for the both sample thicknesses. Therefore, JEFF-3.2 is considered as precise enough within this energy range.

(2) FENDL-3.0

As shown in Fig. 4, the leakage neutron spectra simulated with cross-sectional data of FENDL-3.0 (blue circle) can predict the experimental data within error fairly well

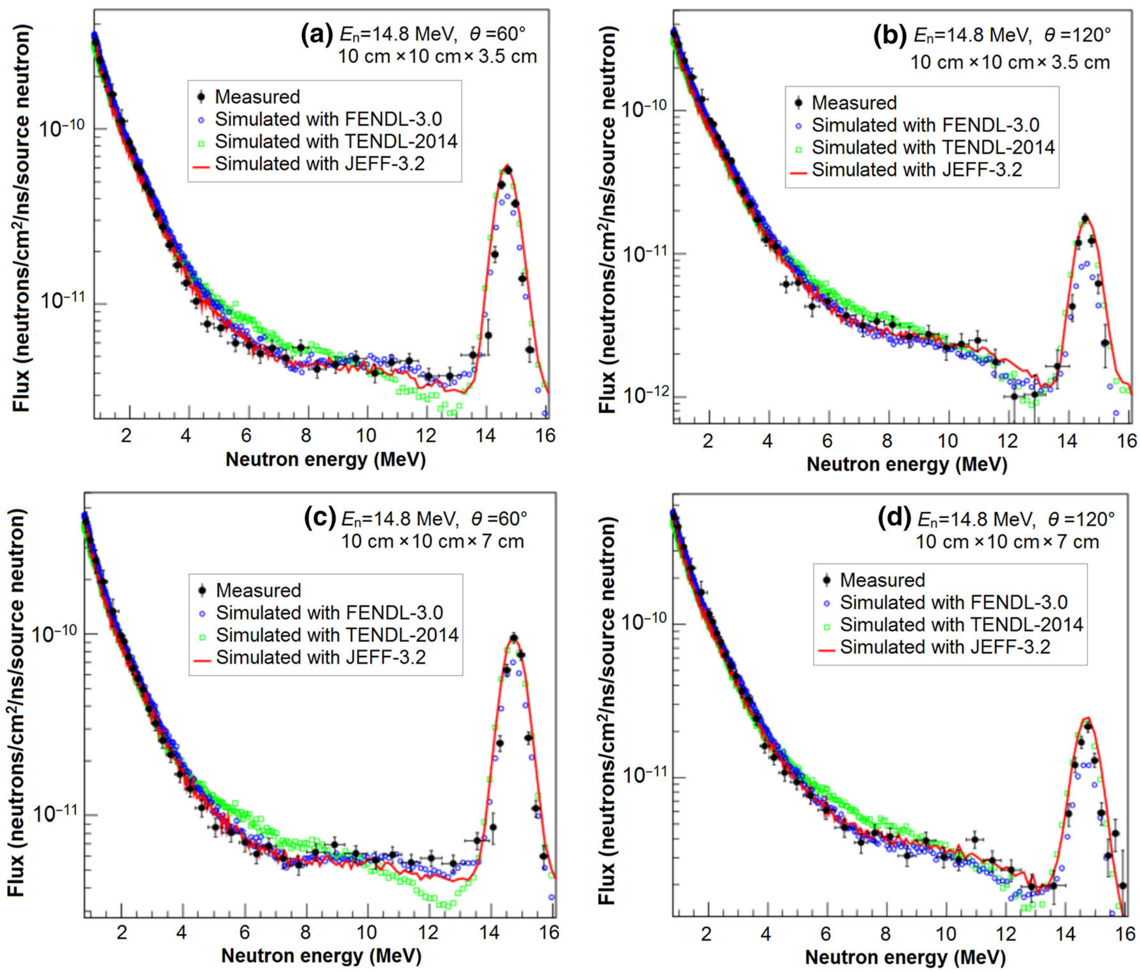

Fig. 4 (Color online) Measured and simulated leakage neutron spectra from tungsten sample of 3.5 and 7 cm in thickness at 60° and 120°

for both angles except the elastic peak. The slightly difference in elastic scattering peak may be caused by improper evaluation of FENDL-3.0 library. The angular distributions of the neutron elastic scattering for tungsten at the incident neutron energy of 14.5 MeV in the FENDL-3.0 and TENDL-2014 libraries are shown in Fig. 5. The FENDL-3.0 cross sections are lower than TENDL-2014 ones at both 60° and 120°, which caused the differences in the elastic scattering peak of the neutron spectrum.

(3) TENDL-2014

As shown in Fig. 4, the calculated spectra with TENDL-2014 match well with the experimental data in the energy ranges of <5 and 13.5–16 MeV, but largely overestimate and underestimate the measured spectra in the energy ranges of 5–9 and 9–13.5 MeV, respectively. These discrepancies are slightly larger at 60° than 120°. The contributions to the total energy spectra from the continuum inelastic and (n, 2n) for tungsten at incident neutron energy of 14.5 MeV in FENDL-3.0 and TENDL-2014 libraries are shown in Fig. 6. The contribution of the (n, 2n) reaction in the TENDL-2014 is considerably higher than FENDL-3.0 below 5 MeV and lower from 5 to 9 MeV, where the spectra calculated with TENDL-2014 differ significantly from the measured ones. The contribution from the continuum inelastic scattering in TENDL-2014 is significantly lower than that in FENDL-3.0 from 9 to 13.5 MeV, which caused the discrepancies between the measured spectra and the calculated ones at this energy range.

4 Conclusion

The leakage neutron spectra from tungsten slabs of 3.5 and 7 cm in thickness irradiated with D-T neutrons have been measured at 60° and 120° to validate evaluated nuclear data files. The MCNP calculations were performed with JEFF-3.2, FENDL-3.0 and TENDL-2014 libraries. From the comparisons between the measured and calculated leakage neutron spectra, it is found that the calculations with the evaluated data of the JEFF-3.2 fairly well reproduce the experiments in the whole energy range at

Table 1 *C/E* values of the spectra integrated over four energy regions

Samples and geometry (cm)	Energy (MeV)	*C/E* (JEFF-3.2)	*C/E* (TENDL-2014)	*C/E* (FENDL-3.0)
60° (10 × 10 × 3.5)	0.8–4.0	0.916 ± 0.060	0.953 ± 0.062	1.024 ± 0.067
	4.0–9.0	1.062 ± 0.064	1.280 ± 0.077	1.134 ± 0.068
	9.0–13.5	0.876 ± 0.053	0.809 ± 0.049	0.975 ± 0.059
	13.5–15.0	1.266 ± 0.078	1.268 ± 0.078	0.871 ± 0.054
120° (10 × 10 × 3.5)	0.8–4.0	0.843 ± 0.055	0.858 ± 0.056	0.941 ± 0.062
	4.0–9.0	1.029 ± 0.063	1.211 ± 0.074	1.081 ± 0.067
	9.0–13.5	1.044 ± 0.069	0.954 ± 0.064	0.914 ± 0.061
	13.5–15.0	1.200 ± 0.079	1.167 ± 0.077	0.610 ± 0.041
60° (10 × 10 × 7)	0.8–4.0	0.904 ± 0.061	0.927 ± 0.062	0.992 ± 0.066
	4.0–9.0	1.039 ± 0.063	1.232 ± 0.075	1.067 ± 0.065
	9.0–13.5	0.834 ± 0.051	0.756 ± 0.046	0.915 ± 0.055
	13.5–15.0	1.257 ± 0.080	1.227 ± 0.078	0.908 ± 0.058
120° (10 × 10 × 7)	0.8–4.0	0.861 ± 0.058	0.882 ± 0.060	0.958 ± 0.065
	4.0–9.0	1.071 ± 0.066	1.241 ± 0.076	1.100 ± 0.068
	9.0–13.5	0.988 ± 0.062	0.906 ± 0.057	0.852 ± 0.054
	13.5–15.0	1.269 ± 0.084	1.227 ± 0.081	0.676 ± 0.045

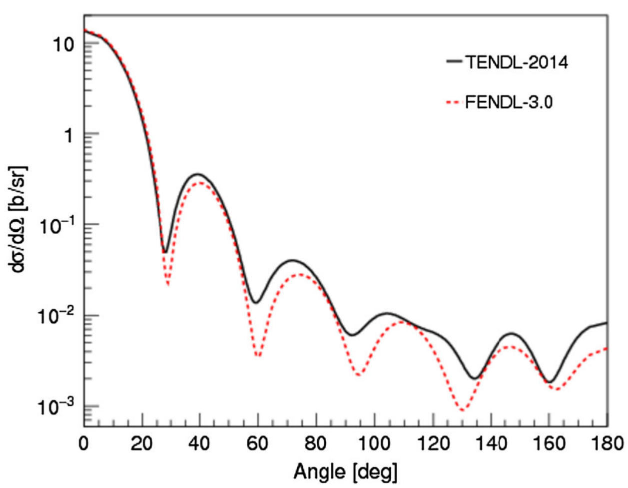

Fig. 5 (Color online) Angular distributions of the neutron elastic scattering for tungsten at the incident neutron energy of 14.5 MeV in TENDL-2014 and FENDL-3.0

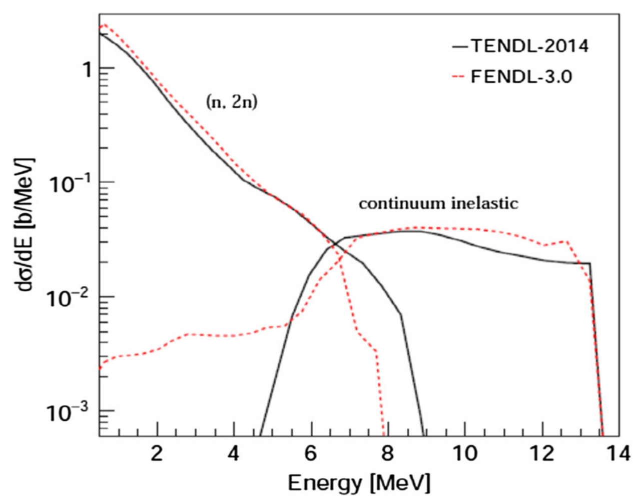

Fig. 6 (Color online) Contributions to the total energy spectra from the continuum inelastic and (n, 2n) for tungsten at the incident neutron energy of 14.5 MeV in TENDL-2014 and FENDL-3.0

two angles. The neutron data of JEFF-3.2 for tungsten are highly recommended for the design of engineering applications in this energy range. The calculated spectra with FENDL-3.0 are well in agreement with the experimental ones except the elastic scattering peak. These discrepancies may be caused by the improper evaluation of the cross-sectional and angular distribution of the elastic scattering channels in FENDL-3.0 libraries. There are some disagreements between the calculated results with TENDL-2014 library and measured ones in the energy range from 5 to 13.5 MeV. It is pointed out that the further work should be done for the improvement in the prediction ability of TENDL-2014 library.

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