Benchmarking of Uranium-238 Evaluations against Spherical Transmission and (n,xn)-Reaction Experimental Data

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Abstract. The double differential cross sections for the U(n,xn) reaction at 14 MeV and neutron leakage spectra from the uranium sphere of 24 cm outer and 8 cm inner diameters with the central T-D and ^{252}Cf neutron sources measured at the Institute of Physics and Power Engineering were used for benchmarking the evaluated cross sections from ENDF-B6, JEFF-3.0, and "Maslov" libraries and preliminary versions of JEFF-3.1 and ENDF-B7 evaluations for ^{238}U.

INTRODUCTION

Uranium is one of the main elements in the fission reactor cores and is potential material for neutron multiplication in the accelerator-driven and fusion facilities. The evaluated cross-section data applied for neutronics characterization of such systems need experimental validation. This paper presents measured double differential cross sections (DDX) for the U(n,xn) reaction at 14 MeV and neutron leakage spectra from a uranium shell with T(d,n) and ^{252}Cf neutron sources performed in IPPE [1-5]. These data are used for validation of the ENDF-B6, JEFF-3.0, and "Maslov" [6] evaluations and preliminary versions of ENDF-B7 [7] and JEFF-3.1 [8] for ^{238}U.

EXPERIMENTAL DATA

Three experiments have been carried out on the fast-neutron spectrometer of IPPE by time-of-flight technique (TOF). The pulsed neutron generator KG-0.3 was employed to produce 14-MeV neutrons via the T(d,n) reaction for the measurement of the neutron emission cross sections from the U(n,xn) reaction and neutron leakage spectra from the U sphere, whereas a ^{252}Cf fission chamber has been used for the neutron transmission study with the same U shell.

The U(n,xn) neutron emission cross sections were measured in the set-up shown in Fig. 1. The uranium sample was located 15 cm from the neutron source. It had a shape of a hollow cylinder (external/internal diameters 4.52/3.98 cm, height 4.87 cm) and was made of depleted U (^{235}U content 0.2%). The TOF-monitor and a BF_3 counter in paraffin moderator checked the neutron source pulse mode and intensity.

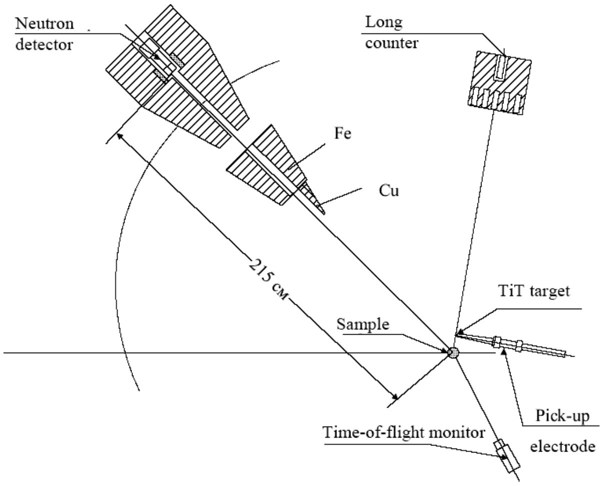

FIGURE 1. The set-up for the measurement of neutron emission cross sections from the U(n,xn) reaction at 14 MeV.

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The neutron detector (NE-218 liquid scintillator and XP-2041 photomultiplier) was located at a 2.2-m flight path from the sample in a lead/paraffin shield, rotating around the sample to measure neutron spectra between 30° and 150°. The neutron background was measured with removed sample. The efficiency of detector was determined up to 10 MeV by measuring neutron spectra from the spontaneous fission of ^{252}Cf [9] and at 14 MeV by the associated α-particle method. A correction for multiple scattering and neutron attenuation in the sample was calculated by the MCNP code [10] using ENDF-B6 neutron cross-section data. To get the spectrum of inelastically scattered neutrons the “elastic” peak was subtracted at every scattering angle. Its shape was determined by measurement of the bare T(d,n) neutron spectrum.

The spherical benchmarks with T(d,n) and ^{252}Cf neutron sources have been performed with a depleted uranium (0.4% of ^{235}U) sphere having outer and inner radii of 12.0 and 4.0 cm and a Ø8.0-cm hole for the neutron source accommodation.

In the case of the T(d,n) source the neutron intensity was determined by the registration of the associated α particles with a calibrated silicon detector installed in a deuteron drift tube at 175° (Fig. 2). The neutron detector (6.3×5 cm stilben crystal, FEU-30 photomultiplier) registered leaking neutrons at 8°, 30°, and 60° with respect to the deuteron beam. The background neutron spectra were measured with a 1.3-m-long iron/polyethylene shadow bar. Corrections for the TOF measuring technique were applied.

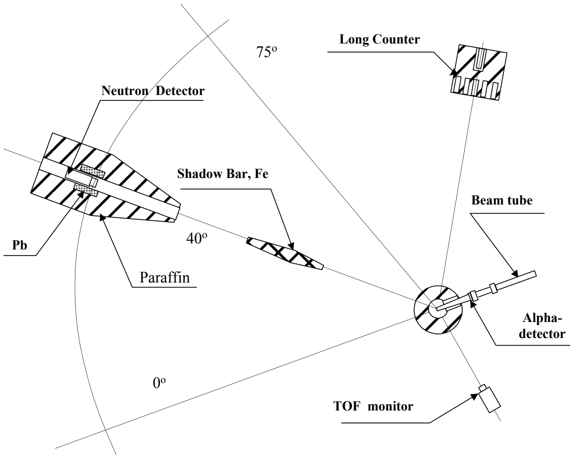

FIGURE 2. The experimental set up for the neutron leakage spectra measurement from U sphere with T(d,n) source.

The neutron leakage with a ^{252}Cf neutron source has been measured using a fast ionization chamber (Fig. 3), having 34 mm diameter and 120 mm length and filled with Ar-CO$_2$ gas. The one disc electrode had a ^{252}Cf layer with an intensity of 4×10^5 n/s. The output of the chamber, with discrimination against pulses from α particles, supplied the stop pulses for the TOF measurement as well as the total number of disintegrations during the experiment.

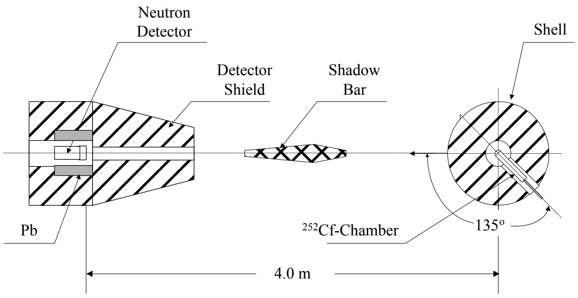

FIGURE 3. Experimental set-up for the neutron leakage spectra measurement from the U sphere with the ^{252}Cf source.

The scintillator detector was located at 4.0 m flight path from the sphere center. The angle between the axis of the hole in the sphere and the direction to the detector was 135° to reduce the influence of the streaming of source neutrons through the hole. For background measurements an iron shadow bar was installed between detector and sphere. The efficiency of the detector was measured employing the same ^{252}Cf neutron source by removing the uranium sphere. This results in elimination of part of the experimental uncertainties.

EVALUATED DATA VALIDATION

The neutron emission cross sections and transport calculations have been made by the MCNP code [10] using ENDF-B6, JEFF-3.0, Maslov [6], and preliminary versions of ENDF-B7 [7] and JEFF-3.1 [8] evaluations for ^{238}U (^{235}U data were taken from ENDF-B6). These calculations involve detailed modeling of the experiment: the energy-angular distribution of the source neutrons, the sizes and position of the samples and neutron detector, and response function of the TOF neutron spectrometer.

The measured angular integrated cross section for the U(n,xn) reaction are compared with recent measurements of Baba et al. [11] in Fig. 4. It is noted that the two sets of experimental data reasonably agree except around 14 MeV, where large differences result from the subtraction of elastically scattered neutrons in our data. To exclude this reason of uncertainty we consider data only up to 10 MeV. Figure 5 shows the angular distributions of neutrons from the U(n,xn) reaction integrated over the indicated energy bins. The present results agree with other measurements [11,12], generally within experimental uncertainties.

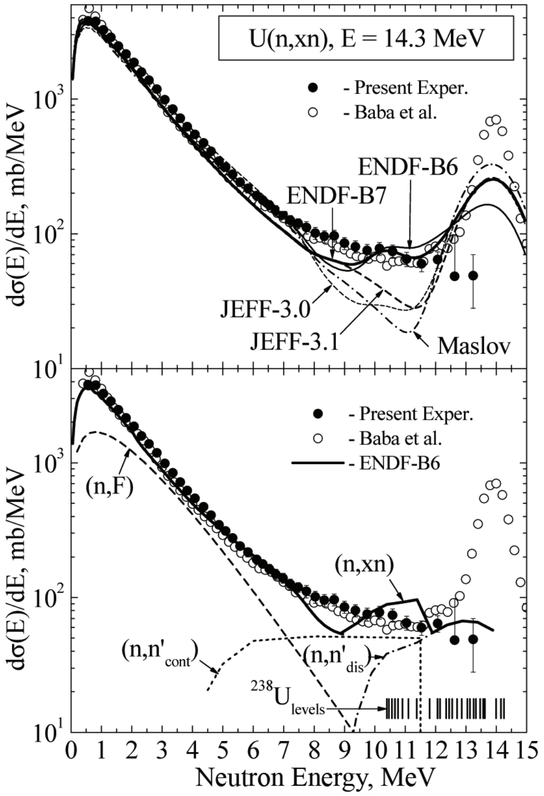

FIGURE 4. Angular integrated neutron emission cross sections for the U(n,xn) reaction at 14 MeV. Experiment: ● – present, ○ - Baba et al. [11]. Evaluated data from libraries (top) and neutron spectra presented in ENDF-B6 (bottom).

The evaluated data libraries agree with measured energy spectra within 10-20% in the energy interval 0.4–6 MeV (Fig. 4, top). Above this energy all libraries, except ENDF-B6 and ENDF-B7, underpredict measured the secondary neutron spectrum by a factor up to 5, which points out the underestimation of the continuum and discrete inelastic neutron scattering (Fig. 4, bottom). As for the secondary neutron angular distributions (Fig. 5), all libraries, except Maslov evaluation, reasonably predict the angular anisotropy for the secondary neutrons with energy below 7 MeV but underestimate forward angle (0-60°) emission of the neutrons with energies above 7 MeV.

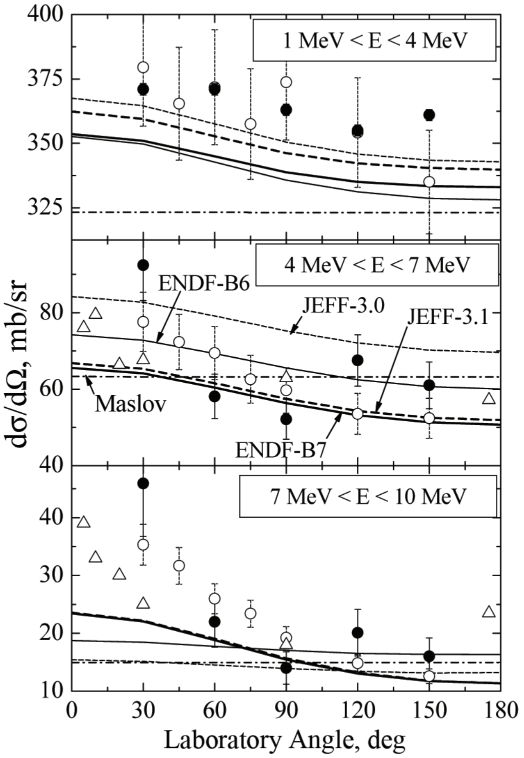

FIGURE 5. Angular differential cross sections for the U(n,xn) reaction at 14 MeV: ● – present experiment, ○ – Baba et al. [11], Δ - Degtyarev et al. [12].

The experimental and calculated energy distributions of neutrons (and their ratios for indicated energy intervals) leaking from a uranium sphere with T(d,n) and ^{252}Cf neutron sources are shown in Table 1 and Figs. 6 and 7. It is seen that all libraries rather accurately reproduce the attenuation of 14-MeV neutrons and the total (in the measured energy range) neutron multiplication in the sphere. As for the energy differential results one can notice the overprediction by ENDF-B6 and JEFF-3.0 in the medium-energy bins 2.5 to 6.5 MeV for both T(d,n) and ^{252}Cf sources and underestimation by JEFF and Maslov for high-energy bins 6.5-10.5 MeV, which reflects similar underestimation observed for DDX at 14 MeV.

TABLE 1. Calculation–to-experiment ratios for the neutrons leaking from a U sphere in the indicated energy bins.

Energy, MeV	T(d,n) Source					^{252}Cf Source				
	ENDF-B6	**ENDF-B7**	**JEFF-3.0**	**JEFF-3.1**	**Maslov**	**ENDF-B6**	**ENDF-B7**	**JEFF-3.0**	**JEFF-3.1**	**Maslov**
0.2 – 0.4						0.99 ± .08	1.04 ± .08	1.00 ± .08	1.06 ± .08	1.02 ± .08
0.4 – 0.8	0.86 ± .09	0.84 ±.09	0.83 ±.08	0.89 ±.09	0.85 ± .09	1.03 ± .07	0.96 ± .07	1.00 ± .07	1.03 ± .07	1.01 ± .07
0.8 – 1.4	1.04 ± .08	0.93 ± .07	0.90 ± .07	0.92 ± .07	0.93 ± .07	1.15 ± .08	1.00 ± .07	1.00 ± .07	0.99 ± .07	1.04 ± .07
1.4 – 2.5	1.04 ± .07	0.91 ± .06	0.94 ± .06	0.89 ± .06	0.87 ± .06	1.10 ± .08	0.93 ± .07	0.97 ± .07	0.91 ± .06	0.94 ± .07
2.5 – 4.0	1.14 ± .08	1.02 ± .07	1.15 ± .08	0.97 ± .07	0.96 ± .07	1.17 ± .08	1.06 ± .08	1.09 ± .08	1.02 ± .07	1.00 ± .07
4.0 – 6.5	1.11 ± .08	1.03 ± .07	1.28 ± .09	0.96 ± .07	1.00 ± .07	1.15 ± .08	1.17 ± .08	1.22 ± .09	1.11 ± .08	1.09 ± .08
6.5 – 10.5	0.86 ± .08	0.85 ± .08	0.77 ± .07	0.77 ± .07	0.75 ± .07	0.96 ± .10	1.02 ± .10	0.98 ± .10	0.95 ± .10	0.94 ± .09
10.5 – 14.	1.03 ± .10	1.02 ± .10	1.01 ± .10	1.00 ± .10	1.03 ± .10					
Total	0.97 ± .09	0.91 ± .09	0.92 ± .09	0.92 ± .09	0.91 ± .09	1.06 ± .07	1.00 ± .07	1.01 ± .07	1.02 ± .07	1.01 ± .07

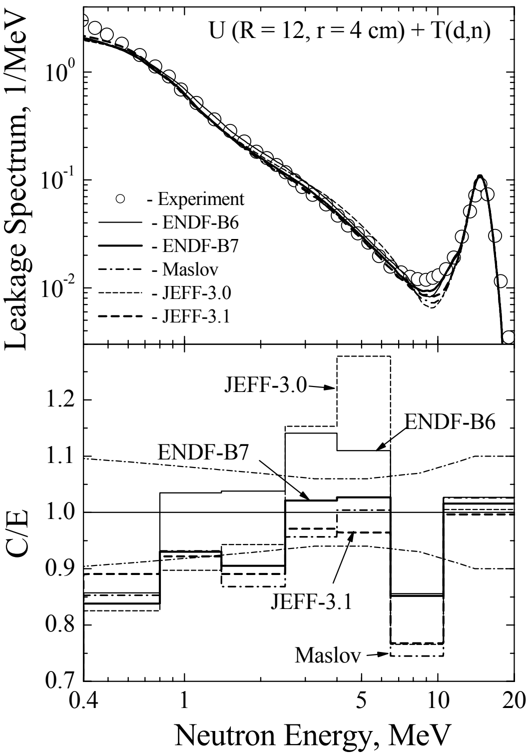

FIGURE 6. Neutron leakage spectra and C/E ratio for the U sphere with the T(d,n) neutron source. Dashed curves indicate the uncertainty corridor.

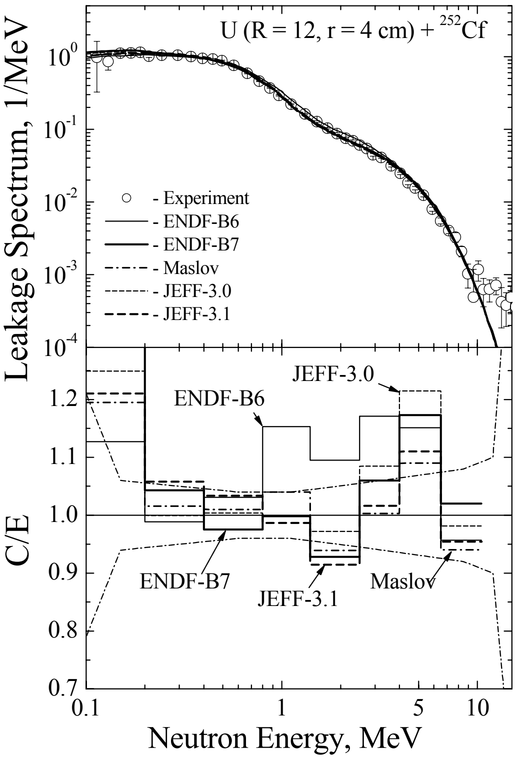

FIGURE 7. Neutron leakage spectra and C/E ratio for the U sphere with the ^{252}Cf neutron source. Dashed curves indicate the uncertainty corridor.

CONCLUSION

The validation of the evaluated neutron cross sections has been performed against U(n,xn) double differential cross sections at 14 MeV and neutron leakage spectra from a U sphere with T(d,n) and the ^{252}Cf neutron source. It was found that the latest ^{238}U evaluations such as a preliminary ENDF-B7 and JEFF-3.1 versions better agree with experimental results (typically within 10% or comparable with experimental uncertainties). Further improvement can be reached by better representation of the energy and angular distributions of high-energy neutrons from the U(n,xn) reaction at 14 MeV.

REFERENCES

1. Devkin B.V., Kobozev M.G., Lychagin A.A., Simakov S.P, Talalaev V.A., Differential cross-sections for the U(n,xn) reaction at a neutron energy of 14.3 MeV, Report INDC(CCP)-426, IAEA, Vienna 2001, pp. 17-26.
2. Androsenko A.A., Androsenko P.A., Devkin B.V. et al. Kernenergie **31**(10), 422 (1988).
3. Simakov S.P., Androsenko A.A. et al., “Neutron leakage spectra from U and Th spheres with Cf neutron source,” Report ZFK-646, Dresden, 1988, p. 111.
4. Simakov S.P., Devkin B.V., Kobozev M.G. et al., “Neutron leakage spectra from Be, Al, Fe, Ni, Pb, LiPb, Bi, U and Th with T(d,n) and ^{252}Cf neutron sources,” in *Fusion Technology* (Elsevier, 1993, v. 2, p. 1489.
5. Simakov S.P., Devkin B.V., Kobozev M.G. et al., 14 MeV Facility and Research in IPPE, Report INDC(CCP)-351, IAEA, Vienna, 1993.
6. Maslov V. et al., “Neutron Data Evaluation of ^{238}U,” Report INDC(BLR)-016, IAEA, 2003, private communication.
7. “LANL n-238U preliminary Evaluation 02-28-2003,” Los Alamos Laboratory web site, 2003.
8. M.J. Lopez Jimenez et al., “n + ^{238}U Cross-Section Evaluation,” JEF/DOC-938, NEA Data Bank, Dec. 2002.
9. Mahnhart W., “Evaluation of the Cf-252 fission neutron spectrum between 0 and 20 MeV,” in Report IAEA-TECDOC-410, IAEA, Vienna, 1987, p. 158.
10. Briesmeister J.F., “MCNP – A General Monte Carlo N-Particle Transport Code, Version 4b,” Los Alamos National Laboratory Report LA-12625-M (1997).
11. Baba M. et al., “Measurements of prompt fission neutron spectra and double-differential neutron inelastic scattering cross sections for 238-U and 232-Th, Report INDC(JPN)-129, IAEA, Vienna, 1989.
12. Degtyarev A.P. et al., Sov. Jour. Yadernaya Fizika **34**(2), 299 (1981).