Validation of ENDF/B-VIII.0-Based Photonuclear Cross-Section Library through Photoneutron Yield Benchmarks

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1. Introduction

The interest in photonuclear data is growing due to the demand for application in various research fields such as radiation shielding, absorbed dose calculation during radiotherapy, activation analysis, safeguards and inspection technologies, nuclear waste transmutation, fission and fusion reactor technologies, astrophysical nucleosynthesis, etc.

International Atomic Energy Agency (IAEA) has produced photonuclear data by organizing two international collaborations under the Coordinated Research Project (CRP). Through the first CRP in 1999 [1], photonuclear data of 164 nuclides were newly evaluated, and among them, data of 163 nuclides were adopted for ENDF/B-VII.0 [2]. In the second CRP in 2019 [3], photonuclear data of 219 nuclides were produced. Nuclear Data Center (NDC) of Korea Atomic Energy Research Institute (KAERI) contributed photonuclear data of 124 nuclides for the first IAEA library in 1999, and contributed data of 30 nuclides for the second IAEA library in 2019.

In this study, the photonuclear data of the latest ENDF/B-VIII.0 was processed with NJOY2016 code [4] to generate an ACE-format library for MCNP code and the library was validated through the photoneutron yield benchmarks.

2. Photonuclear Cross-Section Library for MCNP

Currently available photonuclear data libraries in the MCNP6.2 code package [5] are LA150U and ENDF7U. LA150U contains data for only 13 important nuclides, and ENDF7U contains data for 157 nuclides processed from ENDF/B-VII.

Photonuclear data of ENDF/B-VIII.0 [6] was essentially a bug-fix of ENDF/B-VII photonuclear data. Therefore, ENDF/B-VIII.0 photonuclear library is expected to show similar calculation results to ENDF7U. Nevertheless, in this study, KNE80U, an ACE-format photonuclear cross-section library based on ENDF/B-VIII.0, was generated through NJOY2016 code processing, which contains data of all 163 nuclides of ENDF/B-VIII.0.

3. Photoneutron Yield Benchmarks

The literatures on validation of photonuclear data is very rare. In the 1950s, Barber and George conducted the measurements of neutrons produced per electron incident on several materials at Stanford Linear Accelerator Center (SLAC). [7] They measured the photoneutron yields in target materials such as C, Al, Cu, Ta, Pb, and U with various thicknesses in units of radiation length for different incident electron energies. In the 1970s, Swanson obtained neutron yields from electrons incident on semi-infinite slab geometry of Al, Fe, Cu, Ta, W, and Pb based on differential photon fluxes calculated from analytical shower theory and measured photoneutron cross-sections. [8] White established the photoneutron yield benchmarks based on the research works of Barber and George and Swanson to validate the preliminary version of the LA150U. [9]

In this study, validation calculations were performed for the Photoneutron Yield Benchmark Suite of White with LA150U, ENDF7U, and KNE80U photonuclear data libraries. MCNP6.2 was used for the coupled neutron-photon-electron transport calculations with neutron libraries of LA150N (ENDF60 for Ta), ENDF70, and KNE80, respectively.

3.1 Swanson's Theoretical Benchmarks

Except for the large difference at 15 MeV for the Al target, the calculation results for the Al, Cu, Ta, and Pb targets generally agree well within the benchmark uncertainties.

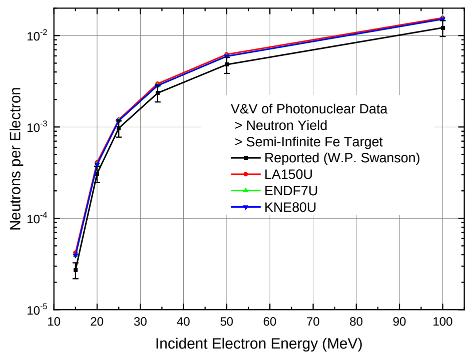

Fig. 1. Neutron yield per incident electron on a semi-infinite Fe target.

As shown in Fig. 1, the validation calculation results for the Fe target overestimate the benchmark results over the entire energy range. On the other hand, the calculation results for the W target in Fig. 2

underestimate the benchmark results as a whole. For consistent comparison with the validation results using LA150U, calculations using ENDF7U and KNE80U were performed using only Fe-56 and W-184 nuclides available in LA150U. Therefore, it is necessary to check the additional calculation results considering the natural isotopic abundance of Fe and W.

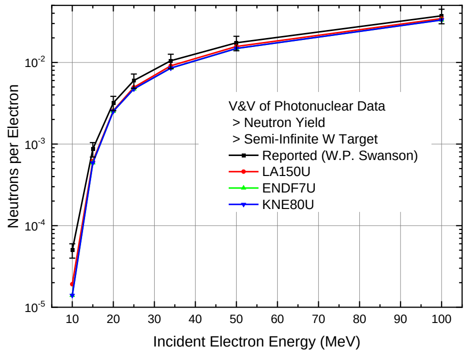

Fig. 2. Neutron yield per incident electron on a semi-infinite W target.

Table I shows the average relative error of the calculation results for each target material using different photonuclear data libraries against Swanson's theoretical benchmark results. As expected in the previous section, the calculation results using the ENDF7U and KNE80U are almost identical. Furthermore, the results using the ENDF7U and KNE80U are slightly improved compared to those using the LA150U, except for the W target.

Table I: Average Relative Error (%) of Calculation Results against Swanson's Theoretical Benchmarks

Target	Average Relative Error (%)		
	LA150U	ENDF7U	KNE80U
Al	49.2	38.3	38.4
Fe	32.6	26.6	26.7
Cu	5.8	3.6	3.6
Ta	13.8	11.5	11.8
W	22.7	27.2	27.4
Pb	15.2	11.8	11.8

3.2 Barber and George's Measurement Benchmarks

The calculation results of the Al target with 1 radiation-length and the Pb target with increasing thicknesses up to 6 radiation-lengths underestimate the measured photoneutron yields beyond the benchmark uncertainties over the entire energy range.

In the case of the Cu target calculated with increasing thicknesses, the calculation results agree well with the measurements at 16.1 and 21.2 MeV, and at higher energies, the differences become larger, but within the benchmark uncertainties. As the thickness of the Cu target increases, the difference between the calculated value and the measured value tends to decrease. Figure 3 shows the validation result for Cu target with 1 radiation-length thickness.

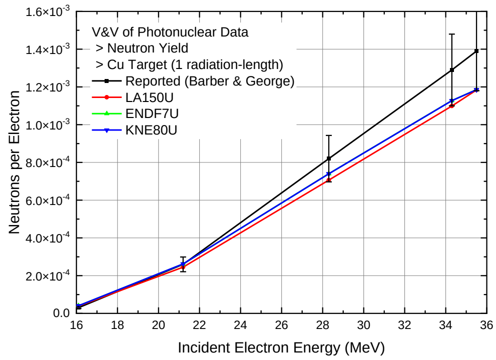

Fig. 3. Neutron yield per incident electron on a Cu target with 1 radiation-length thickness.

As shown in Fig. 4, the validation results for the Ta target generally reproduce the measurements well over the entire energy range.

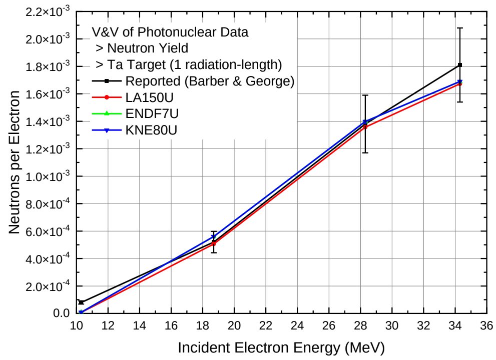

Fig. 4. Neutron yield per incident electron on a Ta target with 1 radiation-length thickness.

Table II: Average Relative Error (%) of Calculation Results against Barber and George's Measurement Benchmarks

Target	Average Relative Error (%)		
	LA150U	ENDF7U	KNE80U
Al-I	24.7	27.0	27.0
Cu-I	15.6	14.5	14.4
Cu-II	13.6	13.8	13.8
Cu-III	9.2	10.4	10.4
Cu-IV	8.5	7.0	6.9
Ta-I	25.8	26.4	26.4
Pb-I	24.7	21.1	21.1
Pb-II	23.7	19.7	19.7
Pb-III	23.3	19.5	19.5
Pb-IV	22.9	19.4	19.4
Pb-VI	23.4	20.3	20.3

Table II shows the average relative error of the calculation results for each target material using different photonuclear data libraries against Barber and George's measurement benchmark results. Calculation results for Al and Ta targets using ENDF7U and KNE80U are slightly worse than those using LA150U. On the other hand, for the Pb targets, the results using ENDF7U and KNE80U are better than those using LA150U.

4. Summary

An ACE-format library for MCNP code based on ENDF/B-VIII.0 photonuclear data was generated and validated through theoretical and measured photoneutron yield benchmarks. Validation results using the library were generally improved compared to those using LA150U. These benchmarks will be used to validate the 'IAEA Photonuclear Data Library 2019' and photonuclear data to be evaluated at NDC/KAERI in the future.

ACKNOWLEDGMENT

The work was supported by the KAERI Institutional Program (Project No. 524410-22).

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