Comparison of double-differential cross-section between nuclear data library and experimental data for photoneutron production

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Abstract. In this study, we compared double differential cross-sections (DDXs) between the experimental data obtained by 16.6 MeV of polarized photons and the DDXs from JENDL2004 and JENDL/PD-2016.1 for ^{197}Au, ^{nat}Pb, ^{nat}Cu, and ^{nat}Ti targets. Using Python-based software, we extracted the DDXs from the nuclear data libraries (NDLs), which were subsequently deduced considering the abundances of each target's isotopes, the width of the photon beam, and the energy resolution of the neutron detectors. For the Ti target, the experimental DDX data were consistent with that of the NDLs. For Pb, Au, and Cu targets, the experimental DDX data at neutron energies higher than 4 MeV were larger than the DDX values obtained from the NDLs. The inconsistency between the DDXs of the experimental data and those of the NDLs indicates the need to improve the physical models to generate the spectrum of photoneutrons.

1 Introduction

High-energy photons can interact with or excite nuclei and induce nucleon emission via photonuclear reactions. Neutron products from this reaction are of serious concern because they are very penetrating, challenging to shield, and can activate other materials. Experimental data of double differential cross-sections (DDXs) of photoneutron (γ,xn) reaction are an effective resource for the development of reaction models used in applications for nuclear physics studies, radiation shielding design, radiation transport analysis, and evaluation of dosimetry. For many years, photonuclear data have been obtained via experiments using various photon sources [1–4].

In recent years, laser Compton scattering technology has been proven to be a promising solution for producing mono-energetic and polarized photon beams [5,6], which are essential for better understanding the (γ,xn) reactions. In our previous studies [7,8], we performed experiments to measure the (γ,xn) reaction for ^{197}Au, $^{nat.}$Pb, $^{nat.}$Sn, $^{nat.}$Cu, $^{nat.}$Fe, and $^{nat.}$Ti targets with a linearly polarized and mono-energetic 16.6 MeV incident photon beam produced at NewSUBARU BL-01, Hyogo, Japan. We observed two components in the neutron spectra: a lower energy component following Maxwellian distribution below 4.2 MeV and a high energy component.

Comparisons of the experimental DDXs among PHITS, MCNP, and FLUKA were studied and reported in a previous study [9]. However, the consistency between DDXs obtained from experimental data and nuclear data libraries (NDLs) for the (γ,xn) reaction has not yet been studied. This report compares the results obtained in our previous study [8] with the values from JENDL-2004 and JENDL/PD-2016.1 NDLs for medium-heavy targets.

2 Double differential cross-section of photoneutron production from NDLs

The DDX data for all isotopes of interest in this study were extracted from JENDL-2004 [10] and JENDL/PD-2016.1 [11]. These DDXs were then normalized to the natural isotope abundance and summed to calculate the DDXs of the corresponding natural target. Moreover, we smeared these DDXs spectra by considering the resolutions of the incident photon spectrum and neutron detectors before comparing them with the experimental results [8]. In this section, we explain the details of this analysis by considering the $^{nat.}$Pb target as an example.

The DDXs of (γ,xn) from ^{208}Pb in JENDL-2004 and JENDL/PD-2016.1 are shown as black and red lines, respectively, in Figure 1. These DDXs were calculated using a photon energy of 16.6 MeV. In JENDL/PD-

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2016.1, the discrete levels in the residual nuclei after neutron emission were considered during the production of the neutron spectrum, whereas they were not considered in JENDL-2004. Figure 2 shows a schematic diagram of neutron emission with the transition from ^{208}Pb to ^{207}Pb, both of which have discrete and continuous nuclear energy levels. These discrete energy levels correspond to different transition probabilities and induce fluctuations in the JENDL/PD-2016.1 calculation for neutron energies higher than 6 MeV, as shown in Figure 1.

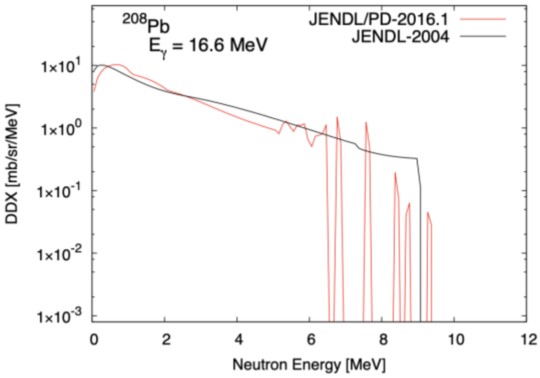

Fig. 1. DDX results extracted from JENDL for ^{208}Pb.

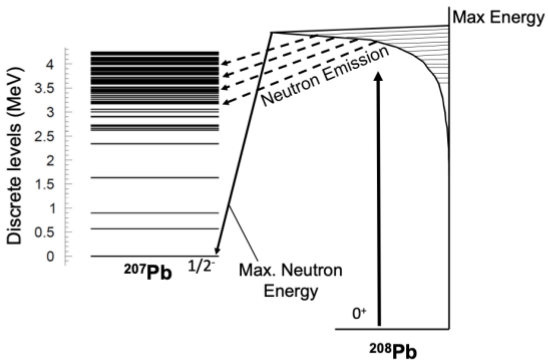

Fig. 2. Schematic diagram of the (γ,n) reaction on ^{208}Pb excited by incident photons.

The DDX for each target was obtained as the sum of the weighted DDXs from their corresponding isotopes, where the weight factors are the natural isotope abundances. The DDX from the $^{nat.}$Pb target calculated with JENDL/PD-2016.1 is plotted with a red line in Figure 3, along with the DDXs of ^{206}Pb, ^{207}Pb, and ^{208}Pb, which are the three isotopes used in the calculation.

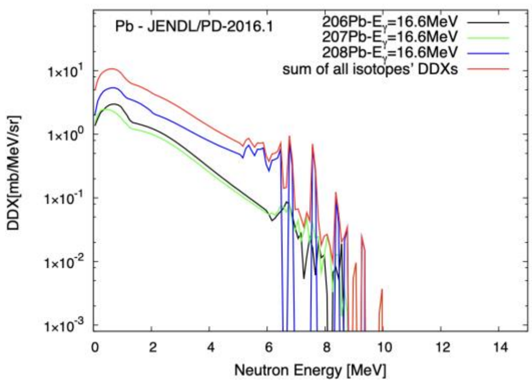

Fig. 3. JENDL/PD-2016.1 DDX data normalized with the abundance of isotopes in a Pb target using 16.6 MeV photons.

The DDX from $^{nat.}$Pb was then processed with the first smearing step by considering the photon energy width. In our previous experiment [8], the photon energy ranged from 14.7 to 17 MeV, with different intensities provided by the energy distribution of the incident photons. The DDXs at different photon energies were calculated with NDLs, normalized with these photon energy intensities, and summed. Figure 4 presents the DDXs at different photon energies after normalization, and the highest intensity occurs for the DDX at 16.6 MeV after the smearing step.

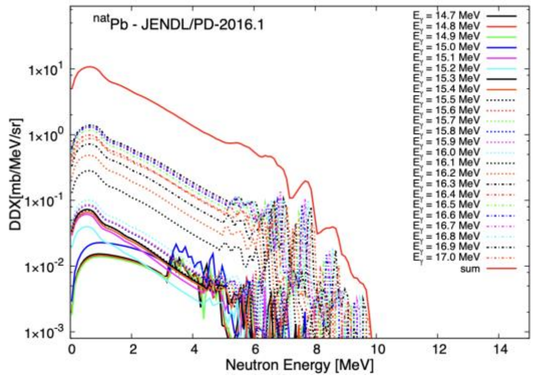

Fig. 4. JENDL/PD-2016.1 DDX data of Pb normalized with the photon energy width.

The final smearing step was performed using the energy-resolution function of the neutron detector used in the experiment. The function was obtained by fitting the resolution values obtained from the calibration in our previous study [8]. This function calculates the resolution in each energy bin, and the intensity in each energy bin is smeared by its resolution value. Figure 5 shows the DDX spectrum of $^{nat.}$Pb obtained after smearing. We can observe that the peak structure is smeared out at approximately 6–8 MeV, and the maximum energy observed is extended from 10 to 12 MeV.

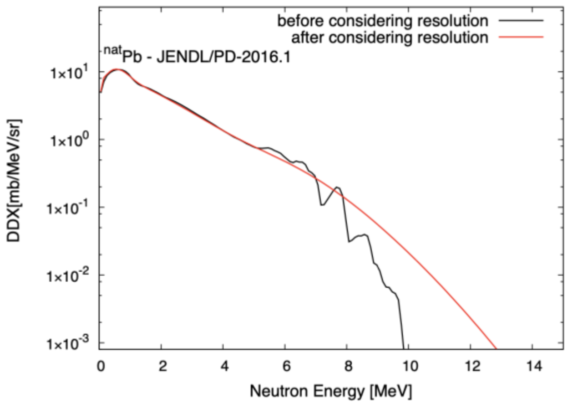

Fig. 5. JENDL/PD-2016.1 DDX data of Pb normalized with the neutron energy width.

The corrections using isotope abundance and smearing using resolutions of photon energy and neutron detectors were performed for both JENDL/PD-2016.1 and JENDL-2004 on all other targets, i.e., ^{197}Au, $^{nat.}$Cu, and $^{nat.}$Ti. As there were no data for ^{48}Ti in JENDL-2004, we did not perform a comparison with the DDXs of Ti from JENDL-2004.

3 Results and Discussion

Figure 6 shows DDXs as a function of neutron energy for medium targets (Cu, Ti) and heavy targets (Pb, Au). The experimental DDXs are indicated by red and black circles, corresponding to the highest DDXs obtained at 90° horizontal (H90) and the lowest DDXs at 90° vertical (V90), respectively. Both experimental DDXs were obtained using monoenergetic polarized photons with a polarization angle of 0°.

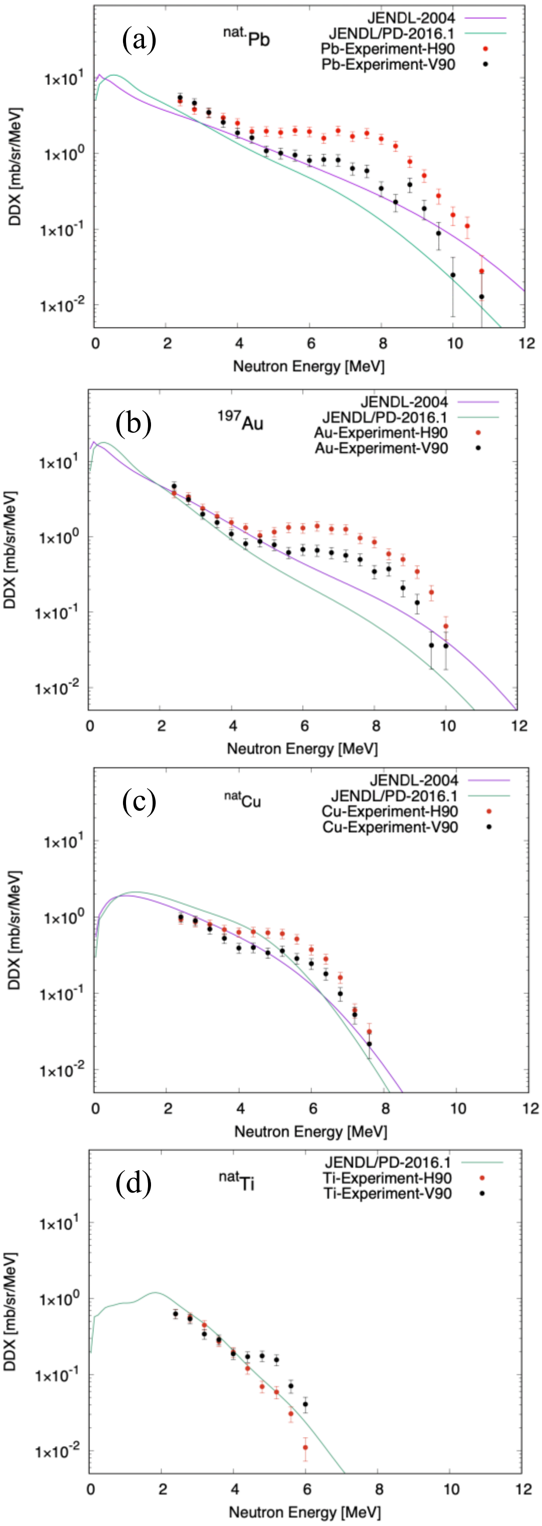

Fig. 6. DDXs from the experiment and nuclear data libraries corrected for Pb (a), Au (b), Cu (c), and Ti (d).

The experimental spectra were not consistent with that extracted from the JENDL libraries. The calculation results for heavy targets (Pb, Au) indicated that the photoneutrons in energy regions of more than 4 MeV were underestimated.

For the Cu target, all three DDXs from the experimental data and the two NDLs were consistent for energies below 4 MeV. The experimental DDX was slightly higher than the other two for energy regions higher than 4 MeV. Overall, the experimental DDX values could be sufficiently explained by the DDX data obtained from JENDL/PD-2016.1 within 2.4–5 MeV.

4 Conclusion

We report a comparison of (γ,xn) DDXs on Pb, Au, Cu, and Ti between the nuclear data libraries (JENDL-2004 and JENDL/PD-2016.1) and experimental data measured using a mono-energetic polarized photon beam [8]. For all targets, the experimental DDX at neutron energies higher than 4 MeV was greater than the DDXs in JENDLs. The inconsistency shown in this report indicates the need to improve the theoretical models for producing neutrons from (γ,xn) reactions.

Acknowledgements

This work was supported by JSPS KAKENHI, Japan (Grant Number JP20K1248).

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