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# Photonuclear reaction cross-section evaluation of $^{181}$Ta and $^{209}$Bi considering experimental double differential cross-section data

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**Abstract.** Experimental data of photoneutron double differential cross-sections (DDXs) on $^{181}$Ta and $^{209}$Bi for photon energies of 13 MeV and 17 MeV were incorporated into the photonuclear data evaluation using the CCONE code system and reaction cross-section data from the EXFOR database. By increasing the preequilibrium photoneutron emissions through a reduction in single-particle state density of neutron for the target nuclei within the exciton model, the evaluation results, including the reaction cross-sections and DDXs for 13 MeV photons, show good agreement with the corresponding experimental data. However, the evaluation results underestimate the experimental DDXs for 17 MeV photon energy.

## 1 Introduction

Photonuclear data have attracted interest from basic research and application fields, including shielding design for electron accelerators and the study of nuclear physics [1]. The evaluation process to develop a reliable photonuclear data library involves compiling experimental data and selecting suitable parameters for the reaction models (e.g., gamma strength function) that fit the compiled data. To date, the evaluation work has focused primarily on reaction cross-sections, with limited consideration of double differential cross-sections (DDXs) of particle production due to the scarcity of such experimental data.

This study incorporates DDXs of photoneutron production on $^{181}$Ta and $^{209}$Bi for 13 MeV and 17 MeV quasi-monoenergetic, linearly polarized photon beams [2,3] into the evaluation process. The incorporation of experimental DDXs and maintenance of the agreement with the measured reaction cross-sections could help to improve the reliability of nuclear data. In addition, the monoisotopic nuclei, $^{181}$Ta and $^{209}$Bi, were chosen for their roles of collimators and targets in medical electron accelerators, as well as their importance in basic nuclear research.

The CCONE code system [4], the output of which is the JENDL nuclear data library, has been used for the evaluation. The code employs the Hauser-Feshbach (HF) statistical model and preequilibrium two-component exciton model for the emission processes. For photonuclear reactions, the initial configuration for the exciton model is set to 1p-0h state with the initiated particle as a neutron. Additionally, DDX data from the latest JENDL-5 Photonuclear sublibrary will be shown together in this study to assess the differences between with and without incorporating experimental DDXs in the evaluation works.

## 2 Methodology

The evaluation involves the compilation of experimental data on reaction cross-section from the EXFOR database [5] and DDXs of photoneutron production [2,3], and the adjustment of relevant parameters in the theoretical nuclear models within the CCONE code based on the compiled experimental data. For reaction cross-sections, our concerns are the total photoneutron cross-section $(\gamma, \mathrm{sn})$, photoneutron production cross-section $(\gamma, \mathrm{xn})$, and partial photoneutron production cross-sections— $(\gamma, 1\mathrm{nX})$ and $(\gamma, 2\mathrm{nX})$. Since our present interests is $^{181}$Ta and $^{209}$Bi, which are heavy nuclei, the $(\gamma, \mathrm{sn})$ cross-section is approximately regarded as the absorption cross-section. Therefore, the $(\gamma, \mathrm{sn})$ cross-section was first reproduced by adjusting the types and parameters of the gamma strength function (GSF) of nuclei. The standard Lorentzian GSF model was used in this work.

The main point of this study is to incorporate the DDXs of photoneutron production into the evaluation process. Some comparisons [3,6,7] show that the calculation results of the nuclear models, the combination of the HF statistical and exciton models, underestimate the experimental DDX data for 17 MeV photon energy on several target nuclei, especially for the high-energy photoneutron range. Therefore, we aimed

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to increase the preequilibrium photoneutron emission described by the exciton model.

In the exciton model, the emission rate depends on the state density of both the target and residual nuclei [8]. A reduction in the state density of the target nuclei leads to an increase in the emission rate. Based on this concept, we apply a multiplying factor, referred to as the n-factor to the single-particle state density of neutron in order to reduce the state density of the target nuclei. Figure 1 shows the influence of different n-factor values on the DDXs of $^{181}Ta$ for 17 MeV incident photons. The value of the n-factor was determined to reach the experimental DDX data in the high-energy photoneutron range for both 13 MeV and 17 MeV photon energies as much as possible. The change of DDX curves in Figure 1 indicates that the n-factor value less than 1.0 (default one) results in increased photoneutron emission during the preequilibrium process, which is aligned with our concept. The increment of preequilibrium photoneutrons also leads to a corresponding reduction in the compound process. Besides, the application of the n-factor should not largely affect the reproducibility of the $(\gamma, xn)$ cross-section.

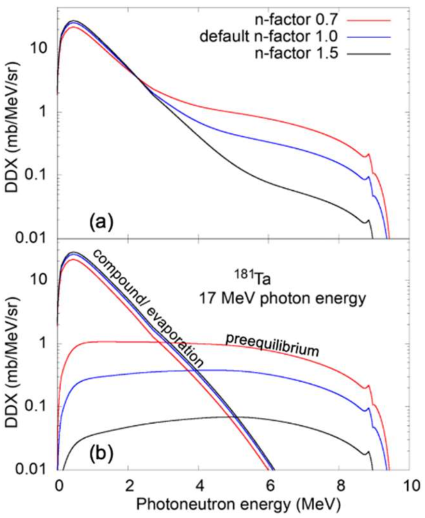


**Figure 1.** The influence of the n-factor values on the DDXs of photoneutron production on $^{181}Ta$ for 17 MeV photon energy: (a) total and (b) two components of DDXs.

The DDX data for photoneutron production were measured using quasi-monoenergetic, linearly polarized photon beams at the NewSUBARU facility, meaning the emitted neutrons are influenced by photon polarization. For comparison with the CCONE calculation results, we selected data where the emitted neutrons are perpendicular to both the direction of the incident photons and their polarization, as illustrated in Figure 2. The mentioned neutron detector position is least influenced by the polarization of photons. The details of experimental setup could be found in Ref. [2,6].

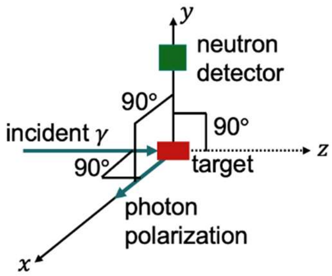


**Figure 2.** Direction of photoneutron emission for the selected experimental data for comparison.

## 3 Results and discussions

### 3.1 Double differential cross-sections of photoneutron production

Figure 3 presents the DDXs of photoneutron production at 13 and 17 MeV photon energies evaluated using the CCONE code (T.Nguyen-2024, colored in black), alongside data from JENDL-5 (red) and experimental DDXs (green). The black and red lines were broadened by considering the neutron energy resolution from the measurements. In our results, the n-factor values applied to the calculations of $^{181}Ta$ and $^{209}Bi$ are 0.7 and 0.55, respectively.

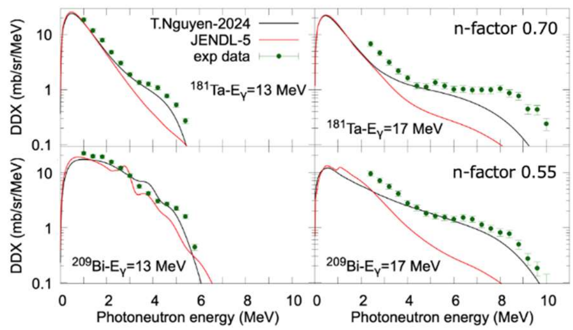


**Figure 3.** Our evaluation results for DDXs of photoneutron production for $^{181}Ta$ and $^{209}Bi$ at 13 and 17 MeV photon energies, together with JENDL-5 and experimental data.

For 13 MeV photon energy, we obtained relatively acceptable evaluation results compared to the experimental data on both target nuclei. However, for 17 MeV photon energy, although our results are better than the results by JENDL-5, they still underestimate the experimental DDXs. Further improvements to our results could be made by adjusting parameters within the exciton model for the preequilibrium process or incorporating an additional emission component for the high-energy photoneutron range.

### 3.2 Reaction cross-sections

In addition to improving the evaluation results for DDXs, maintaining agreement with the experimental reaction cross-sections is crucial in the evaluation process. The $(\gamma, sn)$, $(\gamma, xn)$, $(\gamma, 1nX)$, and $(\gamma, 2nX)$ cross-sections for $^{181}$Ta and $^{209}$Bi are shown in Figures 4 and 5. Our results (T.Nguyen-2024) and JENDL-5 are represented by black and red lines, respectively, along with several experimental datasets downloaded from the EXFOR database.

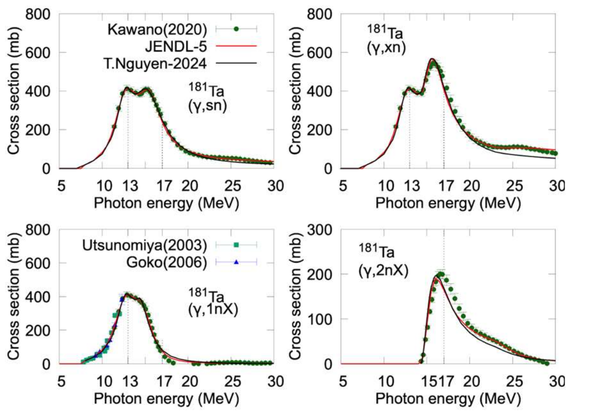


**Figure 4.** Present evaluation results (T.Nguyen-2024) for the reaction cross-section together with JENDL-5 and experimental data [9-11] for $^{181}$Ta.

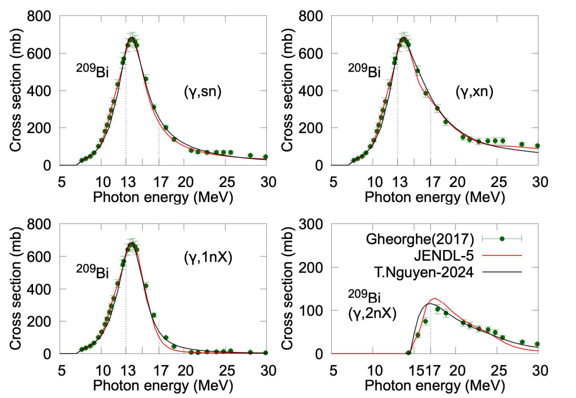


**Figure 5.** Same as Figure 4, but for $^{209}$Bi. The experimental data are taken from Ref. [12].

The differences between our results and JENDL-5 are relatively minor. These are in good agreement with the experimental data on the reaction cross-section. The application of the multiplying factor (n-factor) to the preequilibrium photoneutron emission could help to reach the experimental DDX data while ensuring good agreement for the reaction cross-sections.

## 4 Summary

The evaluation work incorporating the experimental data on DDXs of photoneutron production and reaction cross-sections is done for $^{181}$Ta and $^{209}$Bi. Applying the multiplying factor smaller than unity to the single-particle state density of neutron for the targets gives a reduction in the state density within the exciton model and leads to an increase in the preequilibrium photoneutron emission. This adjustment effectively improves the evaluation results for the DDXs of photoneutron production at 13 MeV photon energy while maintaining agreement with the reaction cross-sections for both target nuclei. Although the evaluation results for DDXs for 17 MeV incident photons are better than JENDL-5, they cannot explain the experimental data yet.

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