Reliability assessment of partial photoneutron cross sections for 142-146, 148, and 150Nd

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Abstract

Systematic discrepancies primarily exist in part of the available partial photoneutron cross-section $\sigma(\gamma$, inX) (i=1,2) data measured at Saclay Laboratory in France and Livermore Laboratory in the United States, which were obtained using quasi-monoenergetic annihilation photons and a neutron-multiplicity sorting method. In this study, we adopt an experimental-theoretical approach that satisfies data reliability criteria proposed on the basis of theoretical models to assess the reliability of the $\sigma(\gamma$, inX) data for $^{142\text{-}146,148,150}$Nd isotopes measured at Saclay. The data reliability criteria are applied to evaluate the Saclay data for $^{142\text{-}146,148,150}$Nd isotopes. The evaluation results are then compared with major nuclear data libraries, and discrepancies with existing experimental data are analyzed. It is found that the ^{142}Nd data obtained at Saclay are overestimated, whereas the ^{146}Nd data are underestimated. It is also found that the Saclay $\sigma(\gamma$, 1nX) data are overestimated while the $\sigma(\gamma$, 2nX) data are underestimated, which is consistent with the conclusions of Varlamov; in contrast, for the ^{142,143}Nd cases, $\sigma(\gamma$, 1nX) is underestimated and $\sigma(\gamma$, 2nX) is overestimated. Possible reasons for the above inconsistencies in neodymium isotopes are further analyzed. Notably, after subtracting the contribution from isotopic impurities in the target material, the discrepancies in the ^{143}Nd case are significantly reduced. However, this method is no longer applicable to the ^{142}Nd case, and other factors such as detector efficiency and random coincidence events must be fully taken into account to resolve such discrepancies.

Full Text

Preamble

Reliability evaluation on partial photoneutron cross sections for 142−146,148,150Nd

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Systematic disagreements exist mainly in the available partial photoneutron cross sections $\sigma(\gamma$, inX)(i=1, 2), which were measured using quasimonoenergetic annihilation photons at the Saclay (France) and Livermore (USA) laboratories based on neutron multiplicity sorting methods. In this study, the reliability of the $\sigma(\gamma$, inX) for 142−146,148,150Nd isotopes obtained at Saclay was evaluated using an experimental-theoretical method that satisfies the data reliability criteria proposed based on the theoretical model in TALYS. Our evaluations were then compared with the major Evaluated Nuclear Data Libraries, and the differences from the available experimental data were analyzed. It was found that the $\sigma(\gamma$, 1nX) data of Saclay were overestimated and the $\sigma(\gamma$, 2nX) data were underestimated in the 144−146,148,150Nd cases, which is consistent with the conclusion of Varlamov; on the contrary, the $\sigma(\gamma$, 1nX) were underestimated and the $\sigma(\gamma$, 2nX) were overestimated in the 142,143Nd cases. Possible reasons for the above inconsistency in the Nd isotopes were further analyzed.

Notably, subtracting the contribution of isotopic target impurities significantly reduced the discrepancy in the 143Nd case. However, this is no longer applicable to the 142Nd case, and other factors, including the detector efficiency and accidental-coincidence events, should be fully considered to resolve such discrepancies.

Keywords: Partial photoneutron cross sections, 142−146,148,150Nd, TALYS, Experimental-theoretical method, Evaluated nuclear data libraries

INTRODUCTION

The giant dipole resonance (GDR) [1] is a fundamental collective excitation mode in the nucleus. Measurements of the cross sections of partial photoneutron reactions within the GDR energy range, primarily (γ, 1nX) and (γ, 2nX), play an important role in obtaining experimental nuclear reaction data. These data are essential for studies on GDR excitation and the competition among its decay channels. In addition, they can be widely used in various applications, including beam luminosity monitoring in ultra-relativistic heavy-ion colliders, non-destructive assay of special nuclear materials, and the development of new production routes for medical radioisotopes [2–5]. Recently, experimental measurements of the photoneutron cross sections for some nuclides of interest, including 197Au, 159Tb, and 63Cu, have been performed and researched at the Shanghai Laser Electron Gamma Source (SLEGS) [6–10].

Neodymium (Nd) isotopes (142−146,148,150Nd) are key nuclei for probing the nuclear structure of the giant dipole resonance (GDR) and are important fission products in activation analysis and reactor physics. In 1971, Carlos et al. [11] employed quasimonoenergetic annihilation photon beams [12, 13] based on positron annihilation and a large Gd liquid scintillation detector to measure the photoneutron cross sections for Nd isotopes at the Center d' Etudes Nucleaires of Saclay laboratory (France) [14–16]. The experimental data were included in the experimental nuclear reaction database (EXFOR) [17]. The cross sections for the partial reactions (γ, 1nX) and (γ, 2nX) of 142−146,148,150Nd were measured only once using the neutron multiplicity sorting method with a quasimonoenergetic γ-ray source. However, according to Varlamov' s research, there may be systematic disagreements in the experimental data based on the Center d' Etudes Nucleaires of Saclay laboratory. An empirical conclusion was proposed and validated for 52 nuclei, excluding Nd. For the experimental data from the Saclay laboratory, the $\sigma(\gamma$, 1nX) data were overestimated, and the $\sigma(\gamma$, 2nX) data were underestimated [18–20].

Subsequently, Xu et al. [21] performed preliminary calculations and data evaluations for Nd isotopes using the MEND-G codes [22] in combination with experimental data, and the results were incorporated into CENDL-3.2. However, significant discrepancies exist between the experimental data and the major nuclear data libraries CENDL-Beta [23], IAEA-2019 [24], TENDL-2023 [25], and JENDL-5 [26]. Since experimental measurements serve as a crucial foundation for the photonuclear database, it is worthwhile to evaluate and analyze the reliability of photonuclear data for 142−146,148,150Nd, thereby supporting systematic evaluations and the development of comprehensive nuclear data libraries.

For data evaluation, γ strength function [27, 28] is important for photoneutron reactions, as it provides the energy-dependent transition strength of γ-rays and is directly related to the spectrum of absorbed γ-rays. In this study, we evaluated the reliability of the experimental data, analyzed the potential uncertainty in previous experiments, and obtained new evaluated data for Nd isotopes. Including the influence of γ strength function, the optimal model was selected based on its consistency with the experimental cross sections. For the evaluation of 144−146,148,150Nd, we found σexp(γ, 1nX) was overestimated and σexp(γ, 2nX) was underestimated, consistent with the conclusion of Varlamov. However, the results of 142,143Nd are inconsistent with the conclusion of Varlamov.

In the present study, the influence of target uncertainty was considered, and the data of 143Nd were corrected. These results examine the conclusions reported in the study by Varlamov and provide guidance for future high-precision measurements of photoneutron cross sections in the Nd isotopic chain using new γ-ray sources.

The theoretical-experimental method for evaluating is introduced in Sect. II. The experimental data and new evaluation obtained are analyzed in Sect. III.

The uncertainty between them is discussed in Sect. IV. Finally, the conclusions and perspectives are given in Sect. V.

II. METHOD

A. The experimental-theoretical method

An experimental-theoretical method independent of neutron multiplicity sorting was proposed in Ref. [29, 30] to obtain partial photoneutron cross sections free of systematic uncertainties. The method is based on using neutron yield reaction cross section $\sigma(\gamma$, xn) data as the initial experimental information,

$$\sigma_{xn} = \sigma(\gamma, xn) = \sigma(\gamma, 1n) + \sigma(\gamma, np) + \sigma(\gamma, n\alpha) + \cdots + 2\sigma(\gamma, 2n) + 2\sigma(\gamma, 2np) + 2\sigma(\gamma, 2n\alpha) + \cdots = \sum_i i\sigma_{inX},$$

and for the total photoneutron reaction cross section $\sigma(\gamma$, sn),

$$\sigma_{sn} = \sigma(\gamma, sn) = \sigma(\gamma, 1n) + \sigma(\gamma, np) + \sigma(\gamma, n\alpha) + \cdots + \sigma(\gamma, 2n) + \sigma(\gamma, 2np) + \sigma(\gamma, 2n\alpha) + \cdots = \sum_i \sigma_{inX}.$$

T. Kawano et al. [24] pointed out that when the emission of charged particles is negligible in experimental photonuclear reaction, the measured one-neutron emission cross section is identical to that for the production of the (Z, A − 1) nucleus. In this case, the measured one-neutron emission cross section $\sigma(\gamma$, 1nX) is given by

$$\sigma_{1nX} = \sigma(\gamma, 1nX) = \sigma(\gamma, 1n) + \sigma(\gamma, np) + \sigma(\gamma, n\alpha) + \ldots,$$

where X stands for anything except i-neutrons.

Figure 1 [Figure 1: see original paper] shows a comparison of the experimental cross sections for 144Nd measured at the Saclay laboratory with TALYS calculations using default parameters. The experimental data were obtained using quasimonoenergetic annihilation photons and a Gd liquid scintillation detector at the Saclay laboratory, while the theoretical data were calculated using the modern Hauser-Feshbach nuclear reaction code TALYS (version 1.96) [31]. The discrepancy between the theoretical and experimental data may originate from substantial systematic uncertainties associated with the neutron multiplicity sorting method employed at Saclay.

Due to these systematic uncertainties, Varlamov et al. [30] introduced the transition multiplicity function F_i, defined as a reliability criterion for partial photoneutron cross sections in the form of a ratio,

$$F_i = \frac{\sigma(\gamma, inX)}{\sigma(\gamma, xn)},$$

to facilitate the evaluation of the experimental partial photoneutron cross sections. According to Eq. (4), values such as $F_1 > 1.0$ or $F_2 > 0.50$ cannot be considered reliable. F_i values larger than the mentioned top limits indicate that the experimental sorting of neutrons between partial reactions has been carried out with large systematic uncertainties; therefore, the obtained reaction cross sections are not reliable. It should also be emphasized that, because F_i is defined purely as a ratio of cross sections, its values must always be positive.

The evaluated partial photoneutron cross sections $\sigma_{\text{eval}}(\gamma, inX)$ are obtained by multiplying the experimental photoneutron yield cross section $\sigma_{\text{exp}}(\gamma, xn)$ given in Eq. (1) by the theoretical functions F_i^{th} computed with the theoretical code,

$$\sigma_{\text{eval}}(\gamma, inX) = F_i^{\text{th}}\sigma_{\text{exp}}(\gamma, xn) = \frac{\sigma_{\text{th}}(\gamma, inX)}{\sigma_{\text{th}}(\gamma, xn)}\sigma_{\text{exp}}(\gamma, xn),$$

where the $\sigma_{\text{th}}(\gamma, xn)$ is the theoretical photoneutron yield cross section and the $\sigma_{\text{th}}(\gamma, inX)$ is the theoretical partial photoneutron reaction cross section.

The differences between the experimental and the evaluated cross sections were determined separately for reactions (γ, 1nX) and (γ, 2nX),

$$\Delta\sigma_1 = \Delta(\gamma, 1nX) = \sigma_{\text{exp}}(\gamma, 1nX) - \sigma_{\text{eval}}(\gamma, 1nX),$$

$$\Delta\sigma_2 = \Delta(\gamma, 2nX) = \sigma_{\text{exp}}(\gamma, 2nX) - \sigma_{\text{eval}}(\gamma, 2nX).$$

In Refs. [32-37], the experimental partial photoneutron cross sections obtained by quasimonoenergetic annihilation photons of many atomic nuclei (90,91,92,94Zr, 115In, 112−124Sn, 159Tb, 186,188,189,190,192Os, 208Pb, etc.) were analyzed using an experimental-theoretical method, and obtained new evaluation data.

B. γ strength function models

The key to obtaining the theoretical F_i values is to determine the photoneutron yield cross sections of 142−146,148,150Nd. These cross sections were calculated with common classical γ strength function models in TALYS, and the results were compared by means of χ^2 analysis,

$$\chi^2 = \sum_{i=1}^{N} \frac{(\sigma_{\text{th}} - \sigma_{\text{exp}})^2}{\sigma_{\text{err}}^2},$$

where N is the total number of experimental points, σ_{th}, σ_{exp} and σ_{err} are the theoretical value of the neutron yield cross sections, the experimental measurement value of the neutron yield cross sections, and the uncertainty of the experimental measurement value, respectively.

The theoretical photoneutron yield cross sections $\sigma(\gamma, xn)$ of 144Nd, calculated using Eq. (1), are shown in Fig. 2 [Figure 2: see original paper], along with the experimental data. γ-ray strength functions play a crucial role in describing transitions involving γ rays in nuclear reactions [38, 39]. Figure 2 demonstrates that the choice of γ-ray strength function has a considerable impact on the calculated photoneutron yield cross sections.

As shown in Fig. 3 [Figure 3: see original paper], for $A \geq 145$, the Brink-Axel Lorentzian (BAL) model is very close to Goriely' s T-dependent HF model and Goriely' s hybrid model, while for $A \leq 143$, the BAL and the SMLO models describe the data equally well. The BAL model generally results in the lowest χ^2 values over all isotopes, with only a minor deviation at $A = 150$, where Goriely's hybrid model performs marginally better. The average χ^2 value obtained using the BAL model is 11.41. To ensure consistent and systematic treatment across the entire isotopic chain, the BAL model was adopted in the present analysis. A quantitative comparison shows that the average relative deviations in neutron multiplicity functions (F_1, F_2) between other γSF models and BAL are 10.60%, 12.53%, 10.69%, 9.21%, 8.79%, 13.59%, 7.37%, 6.86% and 10.15% for models 1 through 10 (excluding 2), indicating that moderate differences exist among the models and warrant consideration in model-based evaluations.

The Brink-Axel Lorentzian model is based on the Brink-Axel hypothesis [40], which states that the photon absorption cross section is independent of the excitation energy of a nuclear system and is an assumption used in nuclear structure studies and calculations. This model offers a solid theoretical basis for our analysis, balancing the reliability and precision of neutron interaction modeling.

Table 1 lists the photoneutron yield model parameters for 142−146,148,150Nd in TALYS with Brink-Axel Lorentzian model. The parameters of γ-strength function models for each nuclide are listed in Table 1, where E, Γ and σ are the energy center value, width, and strength of the formant, respectively.

Using the Brink-Axel Lorentzian model in TALYS, the theoretical neutron multiplicity functions F_i^{th} were obtained using Eq. (4) and are shown in Fig. 4 [Figure 4: see original paper]. These results were compared with the experimental neutron multiplicity functions F_i^{exp} derived from the 144Nd data measured at the Saclay laboratory. Up to the (γ, 2nX) reaction threshold of $S_{2n} = 13.94$ MeV, F_1^{th} remains equal to 1. Once the (γ, 2nX) channel opens, F_1^{th} diminishes in correspondence with the competition from the growing $\sigma(\gamma, 2nX)$ and shrinking $\sigma(\gamma, 1nX)$ cross sections, eventually approaching zero. There is a clear discrepancy between the experimental and calculated values of F_1 and F_2. The F_1^{exp} value is consistent with F_i^{th} value only when the γ energies are below the two-neutron separation energy S_{2n}. For γ energies above S_{2n}, the F_1^{exp} shows an underestimated trend. This suggests that in the Saclay (γ, xn) measurements of Nd isotopes, (γ, 2nX) events may have been erroneously classified as (γ, 1nX) events. F_2^{exp} shows an overestimated trend.

III. RESULTS

After F_i is determined, the evaluated value of the photoneutron reaction cross section can be calculated using Eq. (5). $\sigma_{\text{eval}}(\gamma, inX)$ for Nd isotopes are displayed in the following paragraph. The results can be classified based on the comparison between $\sigma_{\text{exp}}(\gamma, inX)$ and $\sigma_{\text{eval}}(\gamma, inX)$ at energies above the two-neutron threshold S_{2n}. (A) In most energy regions (approximately 90%), case of $\Delta\sigma_2 \leq 0$ is satisfied, as observed for 144—146,148,150Nd; (B) In most energy regions (approximately 90%), case of $\Delta\sigma_2 \geq 0$ is satisfied, as observed for 143Nd; (C) For some energies, case (A) is satisfied, while for some energies, case (B) is satisfied, as observed for 142Nd. While case (A) is consistent with Varlamov' s conclusion, cases (B) and (C) diverge from his expectations.

A. Evaluation of isotopes 144—146,148,150Nd

The isotope comparison between $\sigma_{\text{eval}}(\gamma, inX)$, $\sigma_{\text{exp}}(\gamma, inX)$ and the existing evaluation data for 144Nd is shown in Fig. 5 [Figure 5: see original paper]. Figures 5(a) and 5(b) indicate the comparison of 144Nd (γ, 1nX) reaction and 144Nd (γ, 2nX) reaction, respectively. Figure 5(c) shows the values of $\sigma_{\text{exp}}(\gamma, inX) - \sigma_{\text{eval}}(\gamma, inX)$. The integrated cross section σ_{int} containing the energy ranges of only 1n and 1n + 2n are obtained and presented in Table 2 .

The average relative deviations (ARD) between the experimental/evaluated results and the cross sections from nuclear data libraries are defined as

$$\text{ARD}_1 = \sum \frac{|\sigma_{\text{lib}} - \sigma_{\text{exp}}|}{|\sigma_{\text{exp}}|},$$

$$\text{ARD}_2 = \sum \frac{|\sigma_{\text{lib}} - \sigma_{\text{eval}}|}{|\sigma_{\text{eval}}|}.$$

The effectiveness level is defined as the difference between the two ARD values, let effectiveness level = ARD2 - ARD1.

As shown in Figs. 5(a) and (b), for the isotope 144Nd, compared with the Saclay measurements $\sigma_{\text{exp}}(\gamma, inX)$, the evaluated cross sections $\sigma_{\text{eval}}(\gamma, inX)$ show improved consistency with JENDL-5, CENDL-Beta, and TENDL-2023, whereas their agreement with IAEA-2019 is comparatively poorer. These results demonstrate the effectiveness of the proposed evaluation method. For the (γ, 1nX) case, the effectiveness levels for databases of JENDL-5, CENDL-Beta, TENDL-2023 and IAEA-2019 are 3.75%, -5.52%, 14.11%, and -37.21% respectively; For the (γ, 2nX) case, the effectiveness levels are 22.76%, 3.27%, -27.74%, and -67.67%, respectively.

The differences between the evaluated and experimental cross sections were determined separately for the reactions (γ, 1nX) and (γ, 2nX), as shown in Fig. 5(c). At energies below the threshold S_{2n} of reaction (γ, 2nX), where there is little problem in neutron multiplicity sorting, the difference between the experimental and theoretical integrated cross section $\sigma(\gamma, 1nX)$ is only 0.05% (532.70 mb and 532.40 mb, respectively). But at high energies where reactions (γ, 1nX) and (γ, 2nX) compete with each other in the range 13.80 to 20.21 MeV, the data on both differ markedly: $\sigma_{\text{int}}^{\text{eval}}(\gamma, 1nX) = 570.08$ mb, which is 27% smaller than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 1nX)$ (784.88 mb). $\sigma_{\text{int}}^{\text{eval}}(\gamma, 2nX) = 670.62$ mb, which is 19% larger than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 2nX)$ (563.28 mb). Such large and opposite-direction divergences between the cross sections of reactions (γ, 1nX) and (γ, 2nX) convincingly demonstrate the reasons for the substantial systematic uncertainties in the experiments at the Saclay laboratory, which are due to the unreliable transmission of a large number of neutrons from channel 2n to channel 1n.

Similar to the conclusions for 144Nd, the evaluated cross section data for the (γ, 1nX) and (γ, 2nX) reactions of 145,146,148,150Nd were compared with the corresponding experimental results and the values from the evaluated nuclear data libraries, as shown in Fig. 6 [Figure 6: see original paper]. The relative differences between integrated $\sigma_{\text{exp}}(\gamma, 1nX)$ and $\sigma_{\text{eval}}(\gamma, 1nX)$ are 36%, 48%, 26%, 108%, respectively. For (γ, 2nX), they are 14%, 17%, 5%, 21%, respectively. The relative average differences between the evaluated cross sections and those from various nuclear data libraries (JENDL-5, TENDL-2023, IAEA-2019, and CENDL-Beta) also exhibited significant variation for 145,146,148,150Nd. As shown in Table 3 , consistent with the conclusions for the 144Nd isotope, for the isotopes 145,146,148,150Nd, the values of $\sigma_{\text{eval}}(\gamma, inX)$ are closer to those of JENDL-5, CENDL-Beta, and TENDL-2023, whereas the experimental data $\sigma_{\text{exp}}(\gamma, inX)$ are more consistent with IAEA-2019.

B. Evaluation of isotope 143Nd

The isotope comparison between $\sigma_{\text{eval}}(\gamma, inX)$, $\sigma_{\text{exp}}(\gamma, inX)$ and the existing evaluation data for 143Nd is shown in Fig. 7 [Figure 7: see original paper]. Figures 7(a) and 7(b) indicate the comparison of 143Nd (γ, 1nX) reaction and 143Nd (γ, 2nX) reaction, respectively. Figure 7(c) shows the values of $\sigma_{\text{exp}}(\gamma, inX) - \sigma_{\text{eval}}(\gamma, inX)$. The integrated cross section σ_{int} for the energy ranges of only 1n and 1n + 2n are obtained and presented in Table 4 . Because the experimental (γ, 2nX) cross section still exists at energies below the S_{2n} threshold, the $\sigma_{\text{int}}^{\text{exp}}$ of the (γ, xn) reaction is larger than that of the (γ, 1nX) reaction when $E_{\text{int}} = 9.31$–15.71 MeV.

As shown in Figs. 7(a) and (b), a similar trend is observed for 143Nd, where $\sigma_{\text{eval}}(\gamma, inX)$ shows closer agreement with JENDL-5, CENDL-Beta, and TENDL-2023 than with IAEA-2019 when compared to the experimental data $\sigma_{\text{exp}}(\gamma, inX)$. This further confirms the effectiveness of the evaluation method used in this study. For the (γ, 1nX) case, the effectiveness levels for databases of JENDL-5, CENDL-Beta, TENDL-2023 and IAEA-2019 are 3.43%, 2.72%, 2.93%, and -1.55% respectively; For the (γ, 2nX) case, the effectiveness levels are 35.15%, 23.86%, 29.61%, and -67.91%, respectively.

The differences $\Delta\sigma$ between the experimental and evaluated cross sections [Fig. 7(c)] obtained for partial reactions seem to be 'mirrored' . Almost all values of (γ, 1nX) are negative, whereas those of (γ, 2nX) are positive. In the energy range 14.08 to 19.80 MeV, $\sigma_{\text{exp}} - \sigma_{\text{eval}}$ is opposite: $\sigma_{\text{int}}^{\text{eval}}(\gamma, 1nX) = 611.71$ mb, which is 16% greater than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 1nX)$ (524.94 mb). $\sigma_{\text{int}}^{\text{eval}}(\gamma, 2nX) = 140.96$ mb, which is 20% smaller than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 2nX)$ (178.35 mb). For the isotope 143Nd, it is interesting to find that $\Delta\sigma_1$ is greater than zero and $\Delta\sigma_2$ is less than zero at these energies. However, the results at 18.71 MeV and 19.80 MeV exhibit opposite behaviors in $\Delta\sigma_1$ and $\Delta\sigma_2$.

C. Evaluation of isotope 142Nd

The isotope comparison between $\sigma_{\text{eval}}(\gamma, inX)$, $\sigma_{\text{exp}}(\gamma, inX)$ and the existing evaluation data for 142Nd is shown in Fig. 8 [Figure 8: see original paper]. Figures 8(a) and 8(b) indicate the comparison of 142Nd (γ, 1nX) reaction and 142Nd (γ, 2nX) reaction, respectively. Figure 8(c) shows the values of $\sigma_{\text{exp}}(\gamma, inX) - \sigma_{\text{eval}}(\gamma, inX)$. The integrated cross sections σ_{int} for the energy ranges of only 1n and 1n + 2n are obtained and presented in Table 5 . Similar to 142Nd, since the experimental (γ, 2n) cross sections were still measured below the S_{2n} threshold, the $\sigma_{\text{int}}^{\text{exp}}$ of the (γ, xn) reaction is larger than that of the (γ, 1nX) reaction when E_{int} = 9.85–17.75 MeV.

As shown in Figs. 8(a) and (b), for the isotope 142Nd, the evaluated cross sections $\sigma_{\text{eval}}(\gamma, inX)$ exhibit improved agreement with all four major nuclear data libraries compared with the experimental data $\sigma_{\text{exp}}(\gamma, inX)$. These results provide further evidence of the applicability of the evaluation method. For the (γ, 1nX) case, the effectiveness levels for databases of JENDL-5, CENDL-Beta, TENDL-2023 and IAEA-2019 are 0.64%, -2.21%, 0.95%, and 0.67% respectively; For the (γ, 2nX) case, the effectiveness levels are 43.15%, 13.61%, 38.71%, and 12.90%, respectively.

As shown in Fig. 8(c) and Table 5, the values of $\sigma_{\text{eval}}(\gamma, inX)$ are very close to $\sigma_{\text{exp}}(\gamma, inX)$ when the γ-ray energy is lower than 17.75 MeV. When the energy is between 17.75 and 20.21 MeV, $\sigma_{\text{int}}^{\text{eval}}(\gamma, 1nX) = 205.65$ mb which is 9% smaller than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 1nX)$ (226.08 mb). $\sigma_{\text{int}}^{\text{eval}}(\gamma, 2nX) = 53.36$ mb, which is 14% larger than $\sigma_{\text{int}}^{\text{exp}}(\gamma, 2nX)$ (46.53 mb). Notably, as shown in Fig. 8(c), the values of $\Delta\sigma_1$ are less than zero before 18.57 MeV and become positive above this energy. The situation for $\Delta\sigma_2$ is the opposite.

IV. DISCUSSION

As shown in the above results, the evaluations of 144−146,148,150Nd are consistent with the conclusion of Varlamov, and the difference between σ_{eval} and σ_{exp} is primarily attributed to detector uncertainty [19, 52]. Meanwhile, some results different from Varlamov' s expectations were also discovered, such as the results of 142,143Nd. In these cases, the reason for the difference between σ_{eval} and σ_{exp} may also originate from the isotopic target impurity.

Isotope targets in the oxide form were used for measurements at the Saclay laboratory. The target materials contained isotope impurities, the parameters of which are provided in [11]. First, the impurity thresholds should be checked to determine whether they may influence the measured results. For (γ, 1nX), if the 1n threshold is lower than the γ-ray energy ($S_n(i) < E$, where $i = 1, 2, ...$

denotes the impurities), the effect of the impurity should

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