Photoneutron reaction cross sections for ^{75}As and ^{181}Ta: Sytematic uncertainties and data reliability

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Abstract. There is well–known problem of significant systematic disagreements between data for reactions $(\gamma, 1n)$, $(\gamma, 2n)$, obtained at Livermore (USA) and Saclay (France) using the method of photoneutron multiplicity sorting. The averaged ratios $R^{int}_{S/L}$ of integrated cross sections obtained at Saclay and Livermore for 19 nuclei from ^{51}V to ^{239}U are equal to 0.84 for $(\gamma, 2n)$ and 1.07 for $(\gamma, 1n)$ reactions. For ^{75}As $R^{int}_{S/L}$ ratios for both partial reactions are very close (1.22 and 1.21) but for ^{181}Ta – are quite different (0.89 and 1.25). Using the objective physical data reliability criteria it was found that there are serious doubts in reliability of Saclay and Livermore data. The newly evaluated reliable cross sections disagree with experimental data. In addition to unreliable sorting of many neutrons between both partial reactions many neutrons were lost – on the case of ^{181}Ta in 1n channel, in the case of ^{75}As in both 1n and 2n channels.

1 Introduction

The majority of data for the partial $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, and total $(\gamma, tot) = (\gamma, 1n)+(\gamma, 2n)+(\gamma, 3n)$ and $(\gamma, Sn) = (\gamma, 1n)+2(\gamma, 2n)+3(\gamma, 3n)$ reactions were obtained at Livermore (USA) and Saclay (France) using the quasi-monoenergetic annihilation photon beams and the photoneutron multiplicity sorting method [1, 2]. In figure 1 the ratios $R^{int}_{S/L} = \sigma^{int}_S/\sigma^{int}_L$ of integrated cross sections obtained at Saclay and Livermore for $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions for 19 nuclei (^{51}V, ^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, ^{116,117,118,120,124}Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, ^{238}U) [3–5] are presented. As a rule $\sigma(\gamma, 1n)$ have larger values at Saclay but $\sigma(\gamma, 2n)$ at Livermore. $R^{int}_{S/L}$ changing from 0.69 to 1.34 have averaged values $< R^{int}_{S/L} > = 0.84$ for $\sigma(\gamma, 2n)$ and 1.07 for $\sigma(\gamma, 1n)$. At the same time the averaged disagreement between neutron yield cross sections

$$(\gamma, Sn) = (\gamma, 1n) + 2(\gamma, 2n) + 3(\gamma, 3n), \quad (1)$$

obtained in various laboratories is about 10%.
Using the objective physical criteria for data reliability [6] and the experimental-theoretical method for evaluation of partial reaction cross sections it was shown that for many nuclei the main reason for definite systematic uncertainties is unreliable neutron sorting between 1n, 2n, and 3n channels [6–15].
In figure 1 one can see two very interesting cases: ^{75}As, for which $R^{int}_{S/L}$ ratios for both partial reactions are very close (1.22 and 1.21) and ^{181}Ta, for which $R^{int}_{S/L}$ ratios are significantly different (0.89 and 1.25).
This article is devoted to the comparative investigation in detail experimental data for partial photoneutron reaction cross sections for ^{75}As and ^{181}Ta.

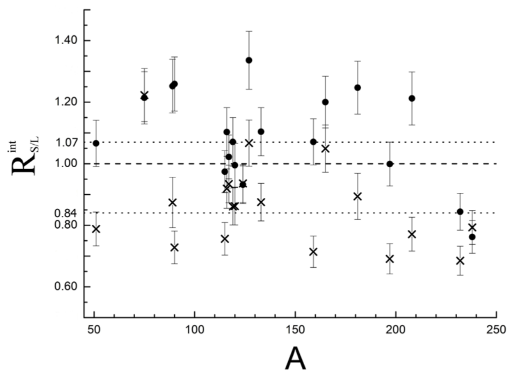

Figure 1. Systematics of $R^{int}_{S/L}$, (circles - 1n, crosses - 2n).

2 The experimental-theoretical method for reliable cross-section evaluation

The ratios,

$$F_i(\gamma, in) = \sigma(\gamma, in)/\sigma(\gamma, Sn) \quad (2)$$

where (γ, in) is the definite partial reaction and (γ, Sn) is the neutron yield reaction (1), were proposed [6] as the objective physical criteria of partial reaction cross-section reliability. The definitely positive Fi must not have values higher than 1.00, 0.50, 0.33 for i = 1, 2, 3. Larger F_i^{exp}

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values mean that cross sections contains significant systematic uncertainties.
The experimental-theoretical method was developed for evaluating the partial reaction cross sections satisfying reliability criteria [6]. The experimental $\sigma^{exp}(\gamma, Sn)$ rather independent from the experimental neutron multiplicity sorting problems was decomposed into the partial reaction cross sections,

$$\sigma^{eval}(\gamma, in) = F_i^{theor} * \sigma^{exp}(\gamma, Sn) \qquad (3)$$

using the functions F_i^{theor} (2) calculated in the Combined model of photonucleon reactions (CMPNR) [16, 17]. For ^{181}Ta, ^{197}Au and ^{209}Bi it was shown that the newly evaluated partial reaction cross sections agree with the data obtained using the activation method [18, 19] and therefore are reliable. It was found that for many nuclei the experimental partial reaction cross sections do not satisfy the proposed data reliability criteria and are noticeably different from evaluated cross sections [6–15, 20]. It was shown that the main reason of that is unreliable transmission of many neutrons from one partial reaction to another because of shortcomings of procedures used to separate counts into 1n and 2n events.

3 Photoneutron reaction cross sections for ^{181}Ta – strange features

Experimental [21, 22] and evaluated [10] cross sections for ^{181}Ta are compared in Figure 2. In the (γ, Sn) obtained at Livermore [21] one see the neutrons at photon energies only up to ~ 17.5 MeV though at Saclay [22] - up to ~ 25 MeV.
Table 1 gives the respective ratios $\sigma_S^{int}(\gamma, 1n)/\sigma_L^{int}(\gamma, 1n)$ of integrated cross sections obtained up to energy E^{int} = 25 MeV. Evaluated data are enough close to Saclay [22] but not for Livermore data [21] the larger the fraction of the $\sigma(\gamma, 1n)$ reaction in the cross-section: for the total reactions, the higher the degree to which the latter is underestimated (1.24 → 1.30→ 1.46). For $\sigma(\gamma, 2n)$, in which the fraction of the $\sigma(\gamma, 1n)$ is equal to zero, the $\sigma_{eval}^{int}/\sigma_L^{int}$ = 1.05. Those data and correspondingly the differences $\Delta\sigma = \sigma^{eval} - \sigma^{exp}$ presented in figure 3 confirm that experimental cross section $\sigma(\gamma, 2n)$ [22] in general is reliable, but $\sigma(\gamma, 1n)$ is absolutely unreliable because many neutrons were lost. Incorrect behavior of the $\sigma(\gamma, 1n)$ is due to a very large (46%) underestimation of the number of multiplicity 1 neutrons in the $\sigma(\gamma, Sn)$ cross-section rather than to unjustifiably associating extra neutrons of multiplicity 2 with the $(\gamma, 2n)$ reaction.

4 The systematic uncertainties of ^{75}As experimental partial photoneutron cross sections

Averaged disagreement between $\sigma(\gamma, Sn)$ in general is about 10% [5]. But for ^{75}As [23, 24] the disagreement between Livermore and Saclay data is much more: 1.22 [6–9]. The experimental $\sigma(\gamma, 1n)$ and $\sigma(\gamma, 2n)$ obtained

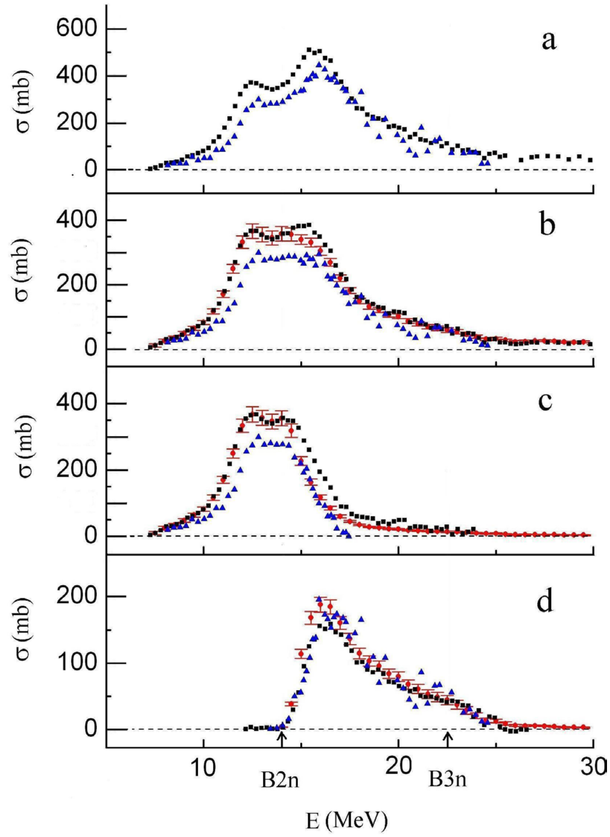

Figure 2. Evaluated ([10], circles) and experimental (Livermore [21], triangles and Saclay [22], squares) cross sections for ^{181}Ta: (a) $\sigma(\gamma, Sn)$, (b) $\sigma(\gamma, tot)$, (c) $\sigma(\gamma, 1n)$, (d) $\sigma(\gamma, 2n)$.

Table 1. Ratios of integrated cross sections $\sigma_{eval}^{int}/\sigma_{exp}^{int}$ for ^{181}Ta obtained up to energy E^{int} = 25 MeV.

Reaction	$\sigma_{eval}^{int}/\sigma_S^{int}$	$\sigma_{eva}^{int}/\sigma_L^{int}$
(γ, Sn)	1.00	1.24
(γ, tot)	0.96	1.30
$(\gamma, 1n)$	0.88	1.46
$(\gamma, 2n)$	1.15	1.05

in both laboratories do not satisfy data reliability criteria: many Saclay and all Livermore $F_{1,2}^{exp}$ values noticeably differ from $F_{1,2}^{theor}$ [15].
The $\sigma^{theor}(\gamma, Sn)$ are much more close to the Saclay $\sigma^{theor}(\gamma, Sn)$ [24], so this last was used in the evaluation procedure. The evaluated (3) and experimental $\sigma(\gamma, 1n)$ and $\sigma(\gamma, 2n)$ are presented in figure 4. The correspondent integrated cross-section values are presented in Table 2. The differences $\Delta\sigma = \sigma^{eval} - \sigma^{exp}$ between the evaluated and the experimental cross sections obtained separately for both partial reactions are presented in Fig. 5a.

In figures 4 and 5 one can see that there is noticeable difference between $\sigma(\gamma, 1n)$ obtained at Livermore and Saclay already at energies below the threshold B2n of $\sigma(\gamma, 2n)$. It means that not only uncertainties of neutron multiplicity sorting exist. The differences $\Delta\sigma$ between the evaluated and experimental cross sections (Fig. 5a) look

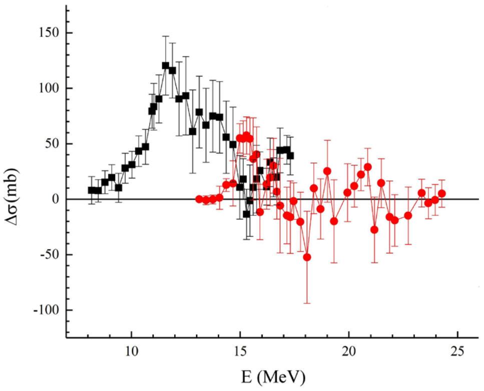

Figure 3. Differences $\Delta\sigma = \sigma^{eval} - \sigma^{exp}$ between the evaluated [10] and the experimental cross sections for ^{181}Ta [21]: squares for reaction $(\gamma, 1n)$, circles – $(\gamma, 2n)$.

Table 2. Integrated cross sections σ^{int} (in MeV mb) obtained up to energy E^{int} = 26.2 MeV cross sections.

Reaction	[23]	[24]	Evaluation [15]
(γ, Sn)	1018.1(3.4)	1308.8(6.6)	1290.7(12.0)
(γ, tot)	841.4(4.1)	1091.3(6.6)	1090.4(11.6)
$(\gamma, 1n)$	666.3(3.7)	873.8(5.6)	890.1(11.0)
$(\gamma, 2n)$	175.1(1.7)	217.4(3.5)	200.3(3.7)

Table 3. Ratios of integrated cross sections $\sigma^{int}_{eval}/\sigma^{int}_{exp}$ for ^{75}As obtained up to energy E^{int} = 26.2 MeV.

Reaction	$\sigma^{int}_{eval}/\sigma^{int}_{S}$	$\sigma^{int}_{eva}/\sigma^{int}_{L}$
(γ, Sn)	0.99	1.27
(γ, tot)	1.00	1.30
$(\gamma, 1n)$	1.02	1.34
$(\gamma, 2n)$	0.92	1.15

as "reflected in a mirror". For both reactions $\Delta\sigma$ is about 3 – 5 %. That means that the main reasons for the systematic uncertainties are shortcomings of sorting a certain number of neutrons between 1n and 2n channels.

For Livermore [23] data the situation is completely different. The differences $\Delta\sigma$ are significantly large (Fig. 5b) in comparison with those for Saclay data (Fig. 5a) and both not naturally are positive.

The ratios $\sigma^{int}_{eval}/\sigma^{int}_{exp}$ of integrated cross sections obtained up to energy E^{int} = 26.2 MeV for various reactions are presented in Table 3. In analogy to the case for ^{181}Ta the larger the fraction of the $\sigma(\gamma, 1n)$ in the cross sectiona for the total reactions, the higher the degree to which the latter is underestimated (1.27 → 1.30 →1.34). But for $\sigma(\gamma, 2n)$ $\sigma^{int}_{eval}/\sigma^{int}_{L}$ = 1.15 is noticeably larger than the correspondent value for ^{181}Ta (1.05). It means that in the case of ^{75}As many neutrons were lost in both $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions. Because the ratios between Saclay and Livermore data for ^{75}As are approximately the same

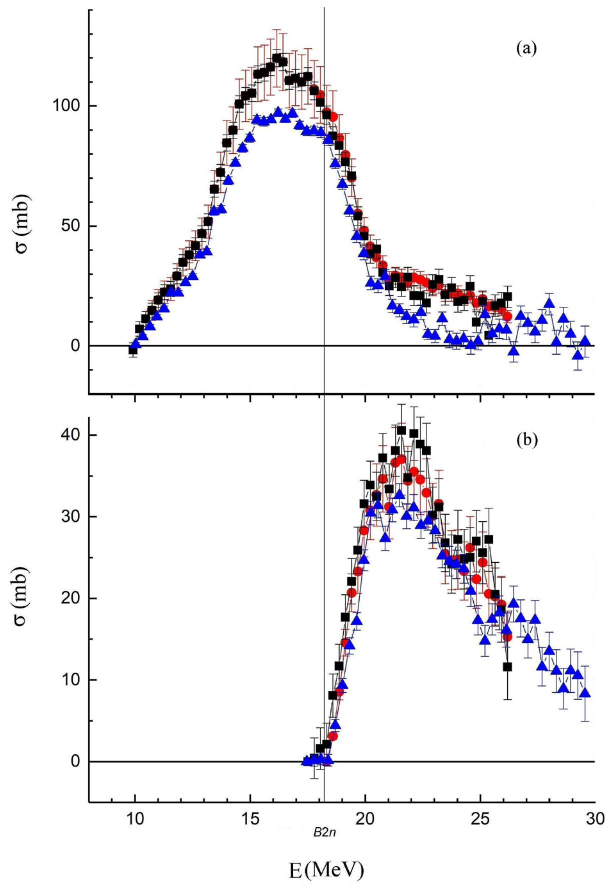

Figure 4. The comparison of the evaluated ([15], circles) and the experimental ([23], triangles and [24], squares) ^{75}As cross sections: (a) $\sigma(\gamma, 1n)$, (b) $\sigma(\gamma, 2n)$

(1.21–1.22) for all reactions, it was supposed that the disagreements could be because of errors in normalization. All Livermore [23] cross sections were multiplied by 1.22. The normalized $\sigma^{exp}(\gamma, Sn)$ become very close to that of [24]. But the differences $\Delta\sigma$ are significantly different again (Figure 5). $\Delta\sigma(\gamma, 1n)$ and $\Delta\sigma(\gamma, 2n)$ look absolutely different in comparison with previous once (Fig. 5b). Both looked as "reflected in a mirror", but the values were noticeably large: $\Delta\sigma(\gamma, 1n) \sim 12$ mb, $\Delta\sigma(\gamma, 2n) \sim 7$ mb. In figure 5 lines present the calculated [16, 17] $\sigma(\gamma, 1n1p)$. The sharing of nuclear excitation energy between neutron and proton is similar to that for two neutrons in the reaction $(\gamma, 2n)$ but the multiplicity of outgoing neutron is 1 not 2. So one is forced to conclude that experimental data [23] are really unreliable because of significant systematic uncertainties of three types: i) unreliable sorting of neutrons between $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions, ii) unreliable sorting of neutrons between $(\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions, iii) the lost of many neutrons from both $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions.

5 Summary and conclusions

Using the data reliability criteria and experimental–theoretical method for partial photoneutron reaction cross-section evaluation (3) it was shown that in analogy

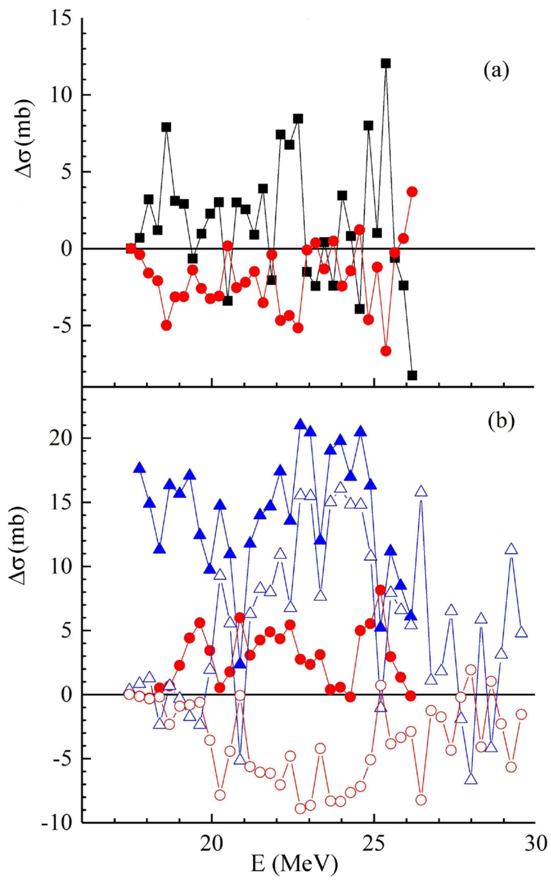

Figure 5. The differences $\Delta\sigma = \sigma^{eval} - \sigma^{exp}$ between the evaluated [15] and the experimental cross sections for ^{75}As: (a) for data [24] (squares – $(\gamma, 1n)$, circles –$(\gamma, 2n)$), (b) for data [23] (full triangles – $(\gamma, 1n)$, full circles – $(\gamma, 2n)$), for corrected (look further) data [23] (open triangles – $(\gamma, 1n)$, open circles – $(\gamma, 2n)$). Lines –calculated [16, 17] $(\gamma, 1n1p)$ reaction cross-section.

to many other nuclei [6–15, 20] the main reason of significant disagreements between data obtained at Saclay and Livermore for ^{75}As and ^{181}Ta is unreliable (erroneous) sorting of photoneutrons from $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions [10, 15]. In addition in the cases of both nuclei there are the uncertainties because of lost of many neutrons. Moreover in the case of ^{75}As addition uncertainties are due to unreliable (erroneous) sorting of photoneutrons from $(\gamma, 2n)$ and $(\gamma, 1n1p)$ reactions.

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