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Cross Sections of Partial Photoneutron Reactions for the ^{115}In Nucleus and the Neutron Multiplicity Sorting

V. V. Varlamov[a], V. N. Orlin[a], N. N. Peskov[a], and M. E. Stepanov[a, b]

[a]Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia
[b]Physics Department, Moscow State University, Moscow, 119991 Russia
e-mail: Varlamov@depni.sinp.msu.ru

Abstract—A joint analysis of the experimental data on cross sections of total and partial photoneutron reactions is performed for the ^{115}In isotope. The data are obtained by using the quasimonoenergetic photons generated upon the annihilation of relativistic positrons. Well-known systematic discrepancies between the results of various experiments are analyzed using objective absolute criteria of data reliability and authenticity. Methods for taking these discrepancies into account are considered. New reliable and authentic evaluations for cross sections of the σ(γ, n), σ(γ2n), and σ(γ, 3n) reactions are obtained using the data on the cross section of the reaction of photoneutron total yields σ(γ,*x*n) in the context of a new experimental-theoretical approach to evaluating the cross sections of partial reactions. These data are free from the shortcomings of experimental methods for the photoneuron multiplicity sorting.

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INTRODUCTION

It is well known that reliable and authentic data on the cross sections of total and partial photoneutron reactions are extensively used in fundamental and applied investigations to solve a number of problems. They have long been used in investigating the relationships between direct and statistic processes upon the formation and decay of highly excited nuclear states, for determining the role of different components in the isospin splitting of the giant dipole resonance (GDR), the competition between the different types of transitions that form the components of configurational GDR splitting, and many other fundamental problems of electromagnetic interactions.

A fairly large number of data have now been published (and included in the appropriate atlases (e.g., [1, 2]) and databases (e.g., [3])). These often deal with the cross sections of the reaction of total neutron yield

$$\sigma(\gamma, xn) \approx \sigma(\gamma, n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + ..., \quad (1)$$

total photoneutron reaction

$$\sigma(\gamma, sn) \approx \sigma(\gamma, n) + \sigma(\gamma, 2n) + \sigma(\gamma, 3n) + ... \quad (2)$$

and components of their partial reactions (γ, n), (γ, 2n), and (γ, 3n).

In recent years, such data have found application in monitoring the luminescence of ultrarelativistic nuclei beams in modern crossed beam colliders. For the problems of such monitoring to be solved, correlated pairs of the neutrons formed upon the mutual electromagnetic dissociation of each colliding nucleus, which takes place under the action of Lorentz-compressed Coulomb nuclear fields, are recorded. The key mechanisms of mutual electromagnetic dissociation are the excitation of GDR states and their subsequent decay in each colliding nucleus through a single-neutron channel. The reliability of collider beam monitoring is thus directly related to the reliability of the data on cross sections of partial photoneutron reactions (particularly the (γ, n) single-neutron reaction) for specially chosen nuclei of Au, Pb [4], and In [5]. A detailed analysis of the relationship between different GDR decay channels for the first of these nuclei was performed in [5].

This work is devoted to analyzing the reliability of the experimental data on cross sections of partial photoneutron reactions on the ^{115}In nucleus, and their reliable evaluation within a new experimental-theoretical approach.

SYSTEMATIC DISCREPANCIES IN THE RESULS FROM DIFFERENT EXPERIMENTS, CONSIDERED THROUGH THEIR MUTUAL CONSISTENT ADJUSTMENT

Most of the data on cross sections of partial photoneutron reactions has been obtained by using quasimonoenergetic photons at the Lawrence Livermore National Laboratory (Livermore, CA, USA) and the Centre d'Etudes Nucleaires de Saclay (Saclay, France). Investigations devoted to comparative analysis of the results from different experiments [6–9] showed that there were substantial discrepancies between them that were clearly systematic. There was fairly good agreement between cross sections of the reaction of the total neutron yield (1), which do not depend on the problems of neutron multiplicity sorting, but the discrepancy between cross sections of the partial reactions σ(γ, n), σ(γ, 2n), and σ(γ, 3n) were as great as ~100%. Such discrepancies in the data on the cross sections of partial reactions obtained at Livermore and Saclay were often conflicted with one another: as a rule, cross sections for the reaction of single neutron formation σ(γ, n) obtained at Saclay were substantially higher than those, obtained in Livermore, while an inverse relationship was observed for cross sections of the reaction of two-neutron formation.

The authors of [7] performed a detailed comparison of the data on photosplitting of the ^{181}Ta nucleus, obtained using one of the neutron multiplicity sorting methods and an alternative method of induced activity that did not require such sorting. It was shown that the discrepancy in the data on the cross section of the ^{181}Ta (γ, n)^{180}Ta partial reaction obtained at Livermore and Saclay can be ascribed to the shortcomings of the neutron multiplicity sorting method used at Saclay. While the number of neutrons with multiplicity 2 was determined correctly enough at Livermore, the cross sections obtained at Saclay were underestimated. Since there are only two partial reactions that are possible in the analyzed energy range, unjustified overestimation of the number of neutrons with multiplicity 1 was merely a natural consequence. Such interpretation of the reasons for the discrepancy allowed a relatively simple method [7] to be used to bring the data from these experiments into agreement: "returning" the excess part of the cross section of the σ(γ, n) reaction estimated at Saclay to the corresponding cross section of the σ(γ, 2n) reaction.

Using the coefficient R,

$$R = \sigma_S^{xn} / \sigma_L^{xn} = \left(\sigma_S^{n} + 2\sigma_S^{2n}\right) / \left(\sigma_L^{n} + 2\sigma_L^{2n}\right), \qquad (3)$$

which normalizes the cross sections of the reaction of the total photoneutron yield (1) in the energy range to the threshold B2n in the (γ, 2n) reaction, we calculate the part of the cross section of the σ(γ, n) reaction estimated at Saclay that was ascribed to it by mistake and which can be "returned" (after appropriate recalculation) to the cross section of the σ(γ, 2n) reaction. After an elementary modification of Eq. (3), the cross section of the reaction of the total photoneutron yield obtained at Saclay can be written as

$$R = \sigma_S^{xn} / \sigma_L^{xn} = \left(\sigma_S^{n} + 2\sigma_S^{2n}\right) / \left(\sigma_L^{n} + 2\sigma_L^{2n}\right), \qquad (4)$$

$$\sigma_S^{xn} = \left(\sigma_S^{n} + 2\sigma_S^{2n}\right) = R\sigma_L^{xn} = R\left(\sigma_L^{n} + 2\sigma_L^{2n}\right), \qquad (5)$$

and

$$R\sigma_L^{2n} = \sigma_S^{2n*} = \sigma_S^{2n} + 1/2\left(\sigma_S^{n} - R\sigma_L^{n}\right). \qquad (6)$$

In this case, the corrected cross section of the (γ, n) reaction (6) takes the form

$$R\sigma_L^{n} = \sigma_S^{n*} = \sigma_S^{n} - \left(\sigma_S^{n} - R\sigma_L^{n}\right), \qquad (7)$$

where the difference ($\sigma_S^{n} - R\sigma_L^{n}$), is calculated for the range of energies higher than B(2n).

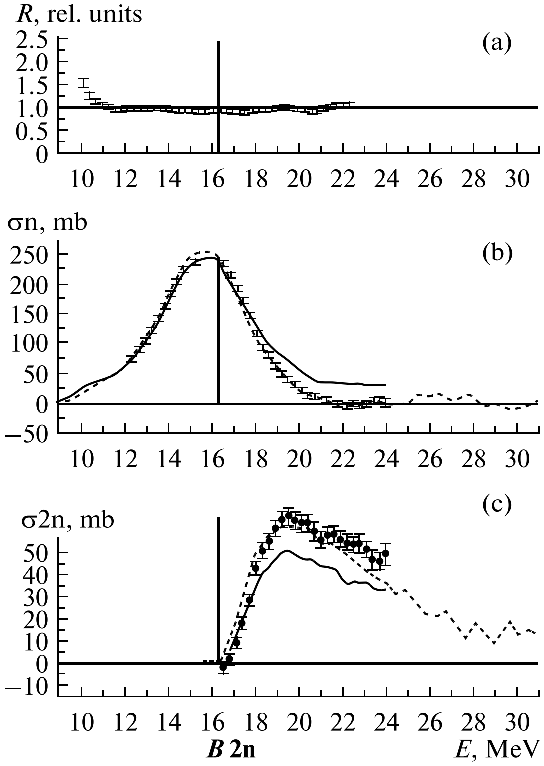

Fig. 1. Results from the mutual correction of cross sections for total and partial phoroneutron reactions on the ^{115}In nucleus, obtained at Livermore [10] and Saclay [11]. (a) $R(E)$ correlations for the cross sections of the (γ, xn) reaction. (b) Data on the cross sections of the (γ, n) reaction; the solid line shows the Saclay data on σ_S^{n}, the dots with errors show estimated Saclay data (7) on σ_S^{n*}, the dashed line shows the estimated Livermore data on $R\sigma_L^{n}$, (c) Data on the cross sections of (γ, 2n) reactions. The curve designations are the same as those in Fig. 1b.

For the 12 nuclei studied in Livermore and Saclay [7–9] and then supplemented [9] by the data for 7 other nuclei, it was shown that in the result from the joint correction of cross sections of the σ(γ, xn), σ(γ, n) and σ(γ, 2n) reactions, the cross sections of partial σ(γ, 2n) estimated using the Livermore ($\sigma_L^{2n*} = R\sigma_L^{2n}$) and Saclay ($\sigma_S^{2n*}$ (6)) data substantially converge (along with the cross sections of the σ(γ, n) reaction corresponding to them). This means that in the result from mutual correction, the "bad" Saclay data approach the "good" Livermore data normalized using the coefficient R (Eq. (4)), and they may be considered reliable and authentic estimates.

The results obtained within such an approach [9] for the ^{115}In isotope are shown in Fig. 1. We can clearly see in Table 1 the above systematic discrepancies in the data before correction (1.09, 0.55, and 0.94) and their elimination after the mutual correction described above (1.00, 1.02, 1.00). This situation is characteristic

Table 1. Data [7, 9] on the relationships between cross sections of the (γ n), (γ, 2n), and (γ, *xn*) reactions obtained at Livermore [10] and Saclay [11] before and after their mutual correction

	$R(\mathrm{n}) = \sigma_S^{\mathrm{int}}(\gamma, \mathrm{n})/\sigma_L^{\mathrm{int}}(\gamma, \mathrm{n})$	$R(2\mathrm{n}) = \sigma_S^{\mathrm{int}}(\gamma, 2\mathrm{n})/\sigma_L^{\mathrm{int}}(\gamma, 2\mathrm{n})$	$R(x\mathrm{n}) = \sigma_S^{\mathrm{int}}(\gamma, x\mathrm{n})/\sigma_L^{\mathrm{int}}(\gamma, x\mathrm{n})$
Before	1.09 (1470/1354)	0.55 (278/508)	0.94
After	1.00 (1298.0/1298.2)	1.02 (364.6/358.3)	1.00

for all of the 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, and ^{238}U) considered in [9].

The data on the integral cross sections of the σ(γ, n) and σ(γ, 2n) reactions for the ^{115}In isotope obtained at Livermore [10] and Saclay [11] as a result of their joint analysis [7–9] are presented in Table 1.

NEED FOR AN OBJECTIVE CRITERION OF DATA RELIABILITY

It can be seen in Fig. 1b that the behavior of the "good" cross section of the ^{115}In(γ, n)^{114}In reaction obtained at Livermore for the energy range of ~21–25 MeV is somewhat strange. It falls rapidly, moves to a region of physically unreliable negative values, returns to the region of positive values, and then returns to the region of negative values. The physically uncertain negative values that appear in the "good" Livermore cross section makes the interpretation of the correctness of the neutron multiplicity sorting in this experiment doubtful. The above method for mutual data correction [7–9] is one way of determining the excess contributions to the cross sections of reactions with multiplicity 1, their return to the cross sections of reactions with multiplicity 2, and bringing the results from the different experiments in agreement. Unfortunately, it does not eliminate the source of the above discrepancies, i.e., the mistakes made in the process of photoneutron multiplicity sorting. We must therefore put the development of an approach that would be free of the shortcomings in the experimental methods for neutron multiplicity determination on the agenda.

An approach based on using special multiplicity transition functions was proposed in [12, 13] for objectively analyzing the validity and reliability of data on the multiplicity sorting of neutrons:

$$F_i = \sigma(\gamma, i\mathrm{n})/\sigma(\gamma, x\mathrm{n}) = \sigma(\gamma, i\mathrm{n})/\sigma[(\gamma, \mathrm{n}) + 2\sigma(\gamma, 2\mathrm{n}) + 3\sigma(\gamma, 3\mathrm{n}) + \ldots], \quad (8)$$

By definition, these functions cannot exceed the values of 1.00, 0.50, and 0.33, respectively. Any excess in the above limiting values points to a physically unreliable relationship between the cross sections of (γ, n), (γ, 2n), and (γ, 3n) reactions that would manifest itself most clearly in the appearance of physically unreliable negative values in the underestimated cross sections (particularly for the (γ, n) reaction).

The functions F_1 and F_3 are of no interest due to the triviality of the first and the dearth of data on the second (unfortunately, the (γ, 3n) reaction remains poorly studied). However, the function F_2 is a very efficient tool for studying the relationship between the cross sections of all three partial reactions, i.e., (γ, n), (γ, 2n), and (γ, 3n).

Since the function F_2 is formed by dividing the cross section of the σ(γ, 2n) by its own doubled value (with additions from the cross sections of the σ(γ, n) and σ(γ, 3n) reactions), it cannot assume values greater than 0.50 at any photon energy. Because the cross section of σ(γ, 2n) is positioned in the region of the descending tail of the σ(γ, n) cross section, any deviation from the value of 0.50 in the low energy range is determined by the value of σ(γ, n); the function F_2 should tend to a value of 0.50 upon an increase in the photon energy (but not reaching it). Deviations of the function F_2 from 0.50 in the range of energies higher than B3n are determined by the magnitude of 3σ(γ, 3n).

Figure 2 shows a comparison of the $F_{1,2,3}^{\mathrm{exp}}(E)$, functions obtained for the ^{115}In nucleus based on the experimental data of [10, 11] with the results from calculations for $F_{1,2,3}^{\mathrm{theor}}(E)$ performed within the modern photonuclear reaction model (see below) [14, 15].

It should be noted that the behavior of the $F_{1,2,3}^{\mathrm{theor}}(E)$ functions is physically valid and has been substantiated, and it fully corresponds to Eq. (8).

Up to the threshold B2n = 16.3 MeV of the (γ, 2n) reaction, $F_1^{\mathrm{theor}} = 1$; after the 2n channel is opened, F_1^{theor} diminishes depending on the competition between a reduction in the cross section of the σ(γ, n) reaction and an increase in the cross section of the σ(γ, 2n) reaction (which smoothly approaches 0). The slight increase in the energy range around ~22 MeV was ascribed to the contribution from the cross section of the σ(γ, np) reaction, which is substantial up to quite high energies. Up to the threshold B2n = 16.3 MeV of the (γ, 2n) reaction, $F_2^{\mathrm{theor}} = 0$; after the opening of the 2n channel, F_2^{theor} increases depending on the competition between an increase in the cross section of the σ(γ, 2n) reaction and a reduction in the cross section of the σ(γ, n) reaction; it approaches 0.50 from below (but does not reach it) and diminishes when the 3n channel is opened, since the contribution of 3σ(γ, 3n) appears in the denominator of relationship (8). The slight drop in the energy range around ~22 MeV is also ascribed to the contribution from the cross section of the σ(γ, np) reaction. Up to the threshold $B3n = 25.8$ MeV of the (γ, 3n) reaction, $F_3^{\text{theor}} = 0$, and at higher energies it increases depending on the competition between an increase in the cross section of the σ(γ, 3n) reaction and a reduction in the cross section of the σ(γ, 2n) reaction.

Figure 2 gives a clear picture of how the photoneutron multiplicity sorting in both experiments was performed in a physically ungrounded and unreliable manner: the behavior of the $F_{1,2,3}^{\text{exp}}(E)$ function differs substantially from the physically groundless behavior of the $F_{1,2,3}^{\text{theor}}(E)$ functions analyzed above.

The cross section of the σ(γ, n) reaction obtained at Saclay is obviously overestimated (Fig. 2a), while that of the σ(γ, 2n) reaction is underestimated (Fig. 2b), in comparison to the calculated cross sections. At Livermore, the cross section of the σ(γ, n) reaction in the energy range of 21–25 MeV assumes (Fig. 2a) physically groundless negative values, and the cross section of the σ(γ, 2n) reaction is the same ($F_2^{\text{exp}} > 0.50$) (though positive) (Fig. 2b). According to the Livermore data, the cross section of the σ(γ, 3n) reaction in the energy range of 26–30 MeV assumes physically groundless negative values (Fig. 2c).

The data of Fig. 2 illustrate that dividing photoneutrons between 1n, 2n, and 3n channels at almost all of the investigated energies does not meet objective, physically grounded criteria; i.e., the data for the cross sections of these channels are unreliable and without grounds. We must therefore develop an approach that is free of the shortcomings in the experimental neutron multiplicity sorting methods.

EXPERIMENTAL–THEORETICAL APPROACH TO EVALUATING DATA ON REACTION CROSS SECTIONS

The new experimental–theoretical approach in [12–15] to evaluating the cross sections of partial photoneutron reactions employs experimental data on the cross sections of the total neutron yield reaction $\sigma^{\text{exp}}(\gamma, xn)$ that are not related to the problem of neutron multiplicity sorting. The contributions to this total cross section of the (γ, n) and (γ, 2n) partial reactions are estimated using relationships calculated within the theoretical pre-equilibrium model of photonuclear reactions [14, 15]. The possibility of such an approach stems from the apparent progress that has

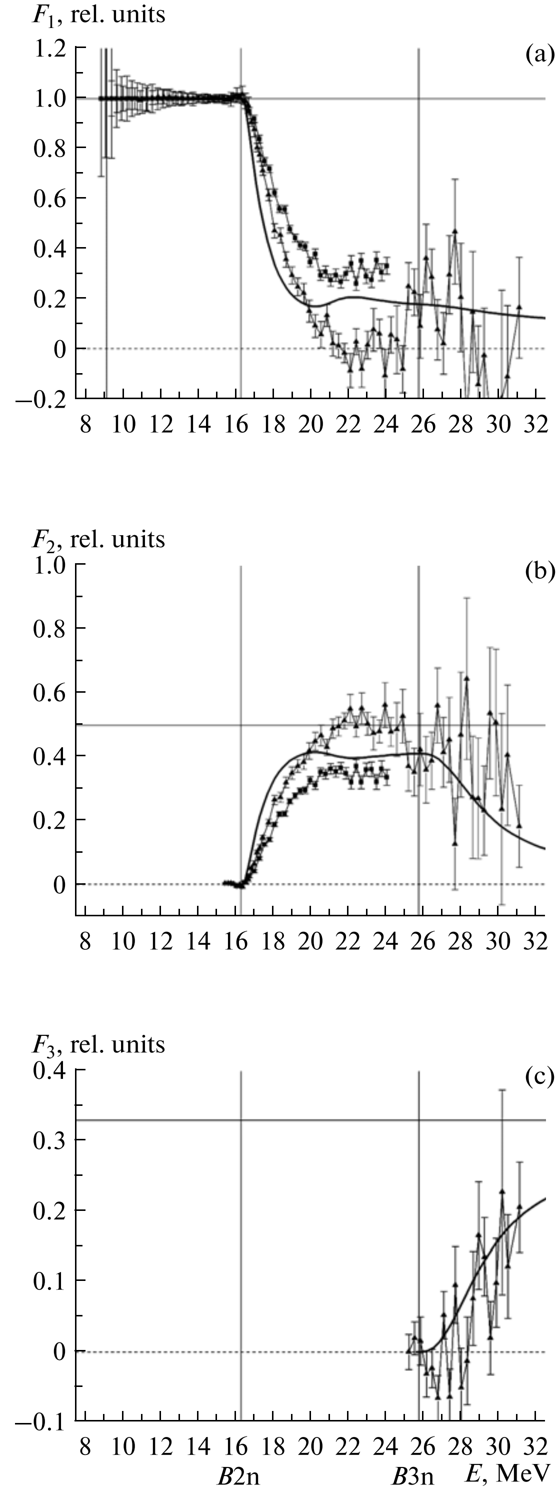

Fig. 2. Comparison of the multiplicity functions $F_{1,2,3}^{\text{exp}}(E)$ obtained from the experimental data using the theoretical dependence $F_{1,2,3}^{\text{theor}}(E)$. Triangles denote the data obtained via quasimonoenergetic photons at Livermore [10]; squares, the data obtained at Saclay [11]. The solid line shows the results from calculations [14, 15].

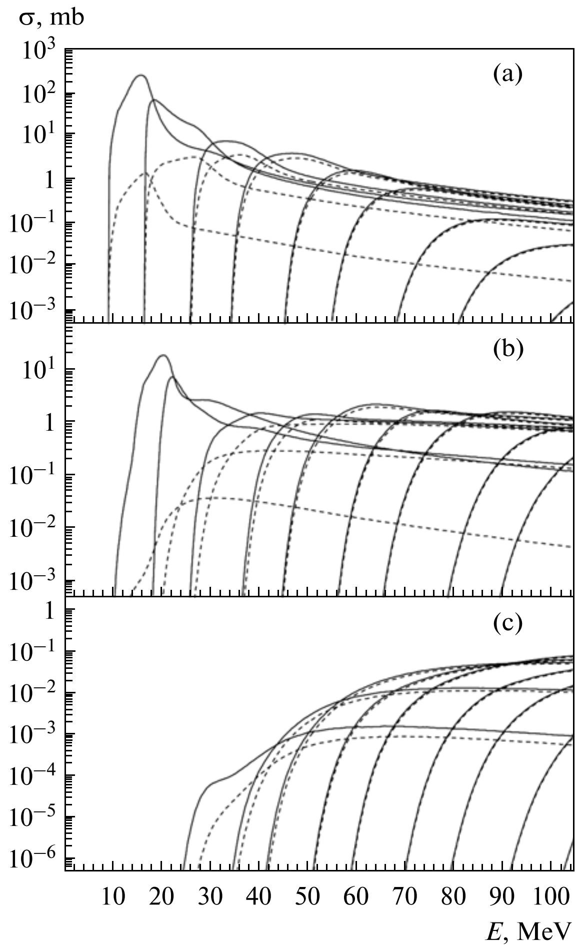

Fig. 3. Calculated [14, 15] cross sections of the reactions (a) (γ, 0p*k*n), (b) (γ, 1p*k*n), and (c) (γ, 2p*k*n) for the ^{115}In isotope. The solid lines show total cross section; the dashed lines, the contribution from the quasideuteron component.

been made lately [14–16] in theoretically describing individual channels of GDR formation and decay and their competition for a large number of nuclei, the ^{115}In nucleus included. Within the modern theoretical pre-equilibrium exciton model based on the densities of nuclear levels calculated in the Fermi gas model [14, 15], it is possible to trace in detail the influence of the effects caused by nucleus deformation and configurative and isospin GDR splitting on the processes of GDR formation and decay. Such a model allows us to reliably separate the contributions from different partial reactions and to study their competition in different photon energy ranges. Figure 3 shows reaction cross sections calculated [14, 15] for purely neutron (γ, 0p*k*n) channels of GDR decay, and for decay channels with one proton (γ, 1p*k*n), which are the strongest of all. The competition between different GDR channels of ^{115}In decay can be clearly seen.

Within the experimental–theoretical approach (which does not depend on the shortcomings of experimental neutron multiplicity sorting methods), the competing (γ, n), (γ, 2n), and (γ, 3n) reactions are sorted as follows.

The theoretically calculated [14, 15] cross sections of the σ^{theor}(γ, n), σ^{theor}(γ, 2n), and σ^{theor}(γ, 3n) reactions are combined into cross sections of the total photoneutron yield reaction (Eq. (1)) σ^{theor}(γ, *x*n); transition functions (8) $F_i^{theor}(E)$, that describe the contributions from the cross sections of reactions with the formation of *i* neutrons to the cross section of the total neutron yield reaction σ(γ, *x*n) are constructed for each photon energy value *E*. The cross sections of σ^{eval}(γ, *i*n) are estimated from the energy dependences of the transition functions $F_i^{theor}(E)$ and the experimental data on the total cross section of the photoneutron yield reaction σ^{exp}(γ, *x*n):

$$\sigma^{eval}(\gamma, i\mathrm{n}) = F_i^{theor}\sigma^{exp}(\gamma, x\mathrm{n}). \quad (9)$$

In agreement with the above, the relationships between the contributions from the evaluated cross sections for σ^{est}(γ, *i*n) reactions with the formation of *i* neutrons ($\sigma^{оцен}$(γ, n) for $i = 1$, σ^{est}(γ, 2n) for $i = 2$, σ^{est}(γ, 3n) for $i = 3$, ...) to the cross section of the total neutron yield reaction σ^{exp}(γ, *x*n) correspond to the concepts on the probabilities of GDR decay channels in the current model of photonuclear reactions [14, 15].

The pros and cons of studying ^{181}Ta nucleus photodisintegration by means of photoneutron multiplicity sorting and the alternative method of induced activity, which is free of the problems of neutron multiplicity sorting since the reaction is identified on the basis of a finite nucleus, were discussed in detail in [17, 18]. It was shown that the cross sections of partial photoneutron reactions evaluated using the described experimental–theoretical approach differ from the data obtained by means of photoneutron multiplicity sorting, but are in agreement with the results from studies based on induced activity method.

NEW EVALUATED DATA ON THE CROSS SECTIONS OF PARTIAL PHOTONEUTRON REACTIONS ON THE ^{115}In NUCLEUS

The cross sections of the abovementioned (γ, n), (γ, 2n), and (γ, 3n) partial reactions that were also used to obtain the evaluated cross section for total (γ, *s*n) reaction (2) were evaluated (Fig. 4) using the approach described above.

There was good agreement between cross sections of the ^{115}In(γ, *x*n) reaction of the total neutron yields obtained at Livermore [10] and Saclay [11] (Fig. 4a). However, since the Livermore cross section was determined in a broader energy range (up to 32 MeV) that covered the energy range above the *B*3n threshold of the (γ, 3n) reaction, it was used as our source value for the above evaluation procedure (9).

Figure 4 shows both the initial experimental data and the evaluated data for cross sections of all the above total and partial reactions on the ^{115}In nucleus. The integral characteristics of the analyzed cross sections for the complete (up to $E^{\mathrm{int}} = 31.1$ MeV) and common (up to $E^{\mathrm{int}} = 24.0$ MeV) energy ranges are given in Table 2. The data in Fig. 4 and Table 2 give a clear understanding of how the experimental data [10, 11] on the relationships between the partial reaction cross sections diverge from the concepts of the current model of photonuclear reactions [14, 15].

For example, the "bad" cross section of the (γ, n) reaction is overestimated (Figs. 2a and 4c) by 115.3 (1466.7–1311.4) MeV mb (11%), while the "bad" cross section of the (γ, 2n) reaction is underestimated (Figs. 2b and 4d) by 102.6 (376.2–273.6) MeV mb (27%), in full agreement with the results from the earlier Saclay experiments [7–9]. Figures 2a and 2b clearly show that a substantial number of neutrons was needlessly transferred from the 2n channel to the 1n channel. Though both of the above experimental cross sections lie in the range of values that are physically admissible from the standpoint of the behavior of the $F_{1,2}^{\mathrm{exp}}$ functions (Fig. 2), their distortion is substantial.

The situation with the correlation between the cross sections of the (γ, n) and (γ, 2n) reactions obtained at Livermore (which were earlier interpreted as "good") turns out to be even more complex. Figure 5 compares the differences between the cross sections: $\left[\sigma_{\mathrm{L}}^{\mathrm{exp}}(\gamma, \mathrm{n}) - \sigma^{\mathrm{est}}(\gamma, \mathrm{n})\right]$ and $\sigma^{\mathrm{est}}(\gamma, 2\mathrm{n}) - \sigma_{\mathrm{L}}^{\mathrm{exp}}(\gamma, 2\mathrm{n})]$. This demonstrates that the experimental data on the cross section of the (γ, n) reaction are overestimated in the energy range below $E \sim 20$ MeV with respect to the evaluated values by the same magnitude to which the cross section of the (γ, 2n) reaction is underestimated. In the energy range of $E \sim 20$–26 MeV, however, the correlation between the cross sections of the (γ, n) and (γ, 2n) reactions is the opposite: the cross section of the (γ, n) reaction is overestimated and that of the (γ, 2n) reaction is underestimated. In this case, the overestimation of the cross section of the (γ, 2n) reaction in the energy range $E \sim 22$–26 MeV turns out to be so great that the correlation of the cross sections is physically unreliable ($F_2^{\mathrm{exp}} > 0.50$) rather than simply distorted.

In the energy range above the threshold B3n of the (γ, 3n) reaction, the number of neutrons with multiplicity 2 (F_2 in Figs. 2b and 5a) obtained at Livermore substantially exceeds the theoretical value and, as a result, the number of neutrons with multiplicity 3 turns out to be underestimated. This underestima-

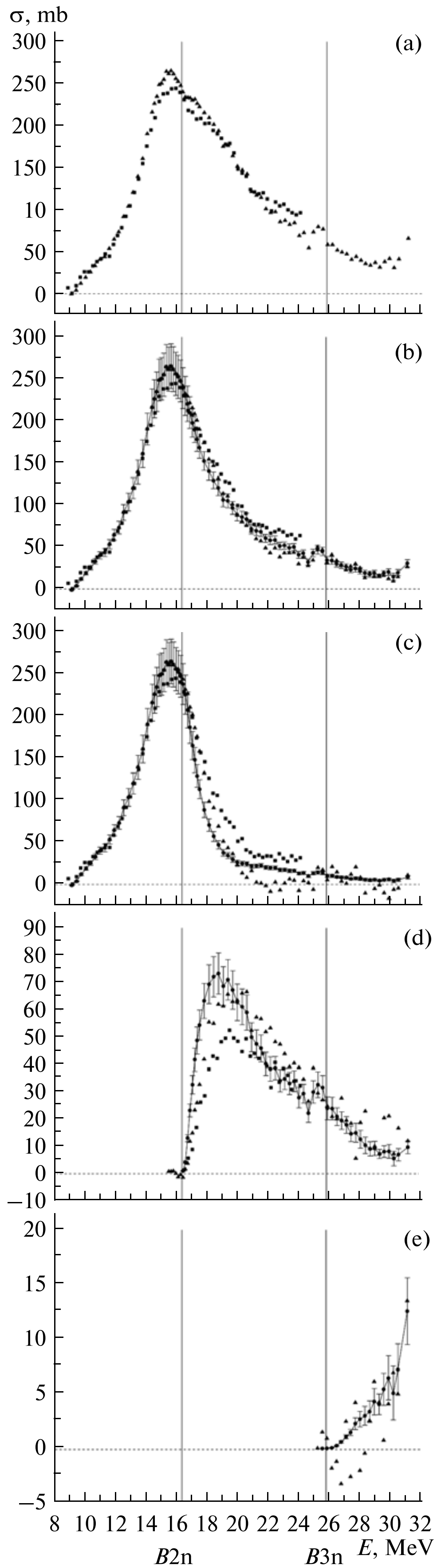

Fig. 4. Comparison of the evaluated (dots with errors) and experimental (triangles) cross sections of total and partial photoneutron reactions of the ^{115}In nucleus for Livermore [10] and Saclay (squares) [11]: (a) σ(γ, *x*n); (b) σ(γ, *s*n); (c) σ(γ, n); (d) σ(γ, 2n); (e) σ(γ, 3n).

Table 2. Main characteristics (center of gravity E^{cg} and integral cross section σ^{int}) of the evaluated cross section of total and partial photoneutron reactions, compared to the experimental data from Livermore and Saclay

Reaction	E^{cg}, MeV	σ^{int}, MeV mb	E^{cg}, MeV	σ^{int}, MeV mb	E^{cg}, MeV	σ^{int}, MeV mb
	evaluated data		livermore data [10]		saclay data [11]	
E^{int} = 24.0 MeV						
(γ, *x*n)	17.2(0.04)*	2063.1(7.9)*	17.2(0.04)	2063.8(7.9)	17.3 (0.04)	2013.0 (5.1)
(γ, *s*n)	16.6(0.05)	1687.0(22.7)	16.5(0.04)	1694.2(6.8)	16.8 (0.04)	1739.4 (4.6)
(γ, n)	15.6(0.04)	1311.4 (21.0)	15.4(0.05)	1328.0(9.1)	16.1(0.05)	1466.7 (4.6)
(γ, 2n)	20.0(0.07)	376.2(8.4)	20.5(0.07)	369.6(4.1)	20.5 (0.06)	273.6 (2.2)
(γ, 3n)	29.9(0.2)	23.6(2.5)**	30.4(0.5)	17.6(3.3)**		
E^{int} = 31.1 MeV						
(γ, *x*n)	18.7*	2430.3*	18.7	2430.3		
(γ, *s*n)	17.7	1889.0	17.5	1883.6		
(γ, n)	16.1	1371.3	15.6	1356.9		
(γ, 2n)	21.6	494.2	22.3	511.5		
(γ, 3n)	29.9	23.6	30.4	17.6		

Notes: * Experimental cross section (Livermore [10] used as a source for evaluation.
** Data up to energy E^{int} = 31.0 MeV.

tion is so great that the function F_3 (Fig. 2c) and the cross section of the (γ, 3n) reaction (Fig. 4e) are in the range of physically inauthentic negative values. Figure 5c, which presents the corresponding differences that almost coincide, $\left[\sigma_L^{exp}(\gamma, 2n) - \sigma^{est}(\gamma, 2n)\right.$ and $[\sigma^{est}(\gamma, 3n) - \sigma_L^{exp}(\gamma, 3n)]$, clearly show the reason for this: the needless transfer of a substantial number of neutrons from the 3n channel to the 2n channel.

POSSIBLE PHYSICAL REASONS FOR DISTORTION OF THE DATA ON CROSS SECTIONS OF PHOTONEUTRON REACTIONS DETERMINED BY MEANS OF NEUTRON MULTIPLICITY SORTING

Let us note the physical reasons for such strong distortions in neutron multiplicity sorting in the experiments performed at both laboratories. Since the errors in multiplicity determination at Saclay and Livermore were systematic [6–9, 12, 13], they were evidently related to some imperfections of the systems for recording neutrons and identifying their multiplicity from the neutron kinetic energy which were used in the experiments. The observed dependence of discrepancies for a specific nucleus seems to indicate that the discrepancies in the results in both types of experiments are associated not only with how and to what degree of error the energy of the identified neutron is determined, but also with the group to which a neutron with a specific kinetic energy belongs (1n, 2n, or 3n).

It is obvious from the above that the relationship between the neutron kinetic energy and its multiplicity is neither simple nor direct; and this produces various distortions. Without going into the fine points of either technique, we should note that though they differ from one another, they have a common feature that yields the observed distortion in the experimentally evaluated multiplicity of neutrons: the assumption that the energy of the sole neutron from the (γ, n) reaction is higher than that of the two neutrons from the (γ, 2n) reaction.

In line with this assumption, neutrons were recorded and their multiplicities were identified at Saclay using a large-volume liquid scintillator that was specially calibrated for neutron sources and can examine large numbers of PEMs simultaneously. The amplitude of the PEM signals from neutrons with high kinetic energies (hypothetically from the (γ, n)) reaction should be high, while those of low energy neutrons (hypothetically from the (γ, 2n) reaction) should be low. However, since the two neutrons in the (γ, 2n) reaction are formed for a characteristically short nuclear time, it is quite possible that with inadequate time resolution by the system, the signals from weak signals overlapped, yielding overestimates of the contribution from the n channel with respect to the 2n channel.

The Livermore researchers used the “ring-ratio” method: detectors in the decelerator were positioned around the target in concentric rings with different diameters. It was assumed that low energy neutrons (from the (γ, 2n) reaction) would have time to moderate to the thermal energy of trapping with the BF3 counter on the path toward the inner ring, while neutrons with higher energies (from the (γ, n) reaction would get through this ring and became moderated only on their way to the outer ring. However, since the path of the fast neutron in the decelerator is not necessarily rectilinear along the radius of the detector ring, it is quite possible that the fast neutron would return to the inner ring after covering its curvilinear path. This would obviously result in overestimates of the 2n contribution.

In addition, experimental and theoretical studies of the spectral of neutrons from (γ, n), (γ, 2n), and (γ, 3n) reactions demonstrate that the relationship between the spectra of the first, second, and third neutron emitted in the reactions do not correspond to the main assumption that underlies both neutron multiplicity sorting techniques: It was assumed that the energy of the sole neutron from the γ, n) reaction was higher than that of each neutron from the (γ, 2n) reaction. However, the relationship between the kinetic energy of the neutron and its multiplicity is not so simple and direct. It was shown in [18] that the mean energy of the first neutron from the (γ, n) reaction substantially exceeds the energy of the second (e.g., at a photon energy of 25 MeV, the energy of the first neutron is 4 MeV; that of the second neutron, 1.4 MeV). With a similar relationship between the energies of the first and second neutrons from the (γ, 3n) reaction, the energy of the second neutron turns out to be substantially higher than the energy of the third neutron.

This is all quite clear if we keep in mind that one and the same nucleus is formed after the emission of the sole neutron in the (γ, n) reaction and the first neutron in the (γ, 2n) and (γ, 3n) reactions. In the experiments in [10, 11], proton channels were not considered at all, though it is obvious that when only neutrons are recorded the corresponding cross sections of the reactions with the formation of one neutron should contain proton contributions as well (in fact, the cross section of the σ(γ, n) is the sum of σ(γ, n) + σ(γ, np) + σ(γ, n2p) + ...,and the cross section of σ(γ, 2n) is the sum of σ(γ, 2n) + σ(γ, 2np) + σ(γ, 2n2p) + ...). It should be noted that proton channels were considered in the theoretical cross sections used to calculate the functions $F_{1,2,3}^{\text{theor}}$ (8). Due to the difference between the thresholds of the corresponding reactions and the schemes of low-lying levels in the nuclei that are formed upon emission of the second and the third neutron, the energy of the first neutron will undoubtedly depend on their energies. However, the results from studies of such spectra [18] show that these differences are negligible.

The energy of the first neutron from the (γ, 2n) and (γ, np) reactions can thus be very close to the energy of the sole neutron from the (γ, n) reaction, making the sorting of neutrons by partial reactions based on the data on their kinetic energies essentially invalid.

The above studies allow us to draw a number of conclusions.

As distinct from the experimental data in [10, 11], the cross sections of (γ, n), (γ, 2n), and (γ, 3n) partial photoneutron reactions on the ^{115}In nucleus evaluated using the new experimental-theoretical approach are not affected by the problems of neutron multiplicity sorting. The relationships between them correspond to

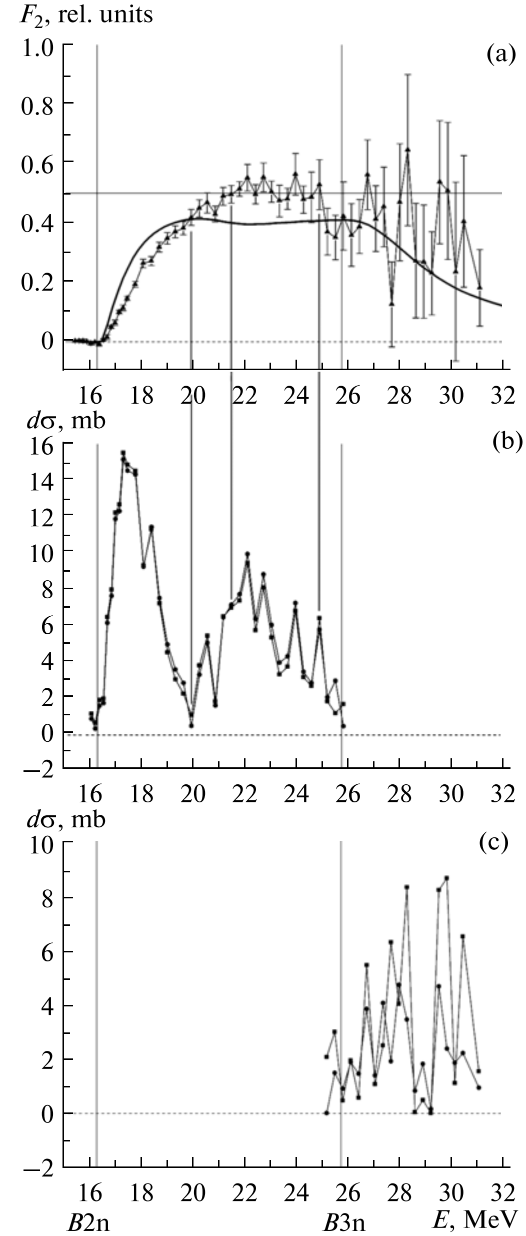

Fig. 5. Validity of removing and adding certain contributions to the partial reaction cross sections: (a) F_{2L}^{exp} function obtained from the Livermore data [10]; (b) the differences between contributions: removed ($\sigma_L^{exp}(\gamma, n) - \sigma^{est}(\gamma, n)$, squares) from the cross section of the (γ], n) and added $\sigma^{est}(\gamma, 2n) - \sigma_L^{exp}(\gamma, 2n)$, circles) to the cross section of the (γ, 2n) reaction; (c) the differences between contributions: removing ($\sigma^{est}(\gamma, 3n) - \sigma_L^{exp}(\gamma, 3n)$, circles) from the cross section of the (γ, 3n) and added $\sigma_L^{exp}(\gamma, 2n) - \sigma^{\text{оцен}}(\gamma, 2n)$, squares) to the cross section of the (γ, 2n) reaction.

the concepts of the current photonuclear reaction model. The results obtained using the new approach for the ^{181}Ta nucleus [17, 18] agree with the results from experiments performed on the basis of induced activity (without multiplicity sorting of photoneutrons).

The cross sections of the partial reactions studied at Saclay were "bad": there was substantial overestimation of the cross section of the ^{115}In(γ, n)^{114}In reaction and a corresponding underestimation of the cross section of the ^{115}In(γ, 2n)^{113}In in reactions. These were ascribed to the needless transfer of some neutrons from the 2n channel to the 1n channel.

At Livermore, the cross sections of all three studied partial reactions were "bad," and the pattern of distortion was even more complex than that the one observed at Saclay.

The cross section of the ^{115}In(γ, n)^{114}In reaction at energies $E \sim 21$–25 MeV falls into the range of physically groundless negative values due to the needless withdrawal of a substantial number of neutrons from the 1n channel and their transfer to the 2n channel. This yielded a physically groundless ($F_2^{\exp} > 0.50$) overestimate of the cross section of the ^{115}In(γ, 2n)^{113}In reaction. In the energy range $E \sim 25$–32 MeV, as a result of overestimating the cross section of the ^{115}In(γ, 2n)^{113}In reaction due to the needless transfer of the substantial number of neutrons from the 3n channel to the 2n channel, the physically groundless ($F_2^{\exp} >$ 0.50) led to a corresponding underestimate of the cross section of the ^{115}In(γ, 3n)^{112}In reaction which, at energies of 26–29 MeV, has physically groundless negative values.

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