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NUCLEI
Theory

Modern Status of Photonuclear Data

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Abstract—The reliability of experimental cross sections obtained for $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial photoneutron reactions using beams of quasimonoenergetic annihilation photons and bremsstrahlung is analyzed by employing data for a large number of medium-heavy and heavy nuclei, including those of ^{63,65}Cu, ^{80}Se, ^{90,91,94}Zr, ^{115}In, $^{112-124}$Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, ^{181}Ta, $^{186-192}$Os, ^{197}Au, ^{208}Pb, and ^{209}Bi. The ratios of the cross sections of definite partial reactions to the cross section of the neutron-yield reaction, $F_i = \sigma(\gamma, in)/\sigma(\gamma, xn)$, are used as criteria of experimental-data reliability. By definition, positive values of these ratios should not exceed the upper limits of 1.00, 0.50, 0.33, …for $i = 1$, 2, 3, …, respectively. For many nuclei, unreliable values of the above ratios were found to correlate clearly in various photon-energy regions F_i with physically forbidden negative values of cross sections of partial reactions. On this basis, one can conclude that correspondent experimental data are unreliable. Significant systematic uncertainties of the methods used to determine photoneutron multiplicity are shown to be the main reason for this. New partial-reaction cross sections that satisfy the above data-reliability criteria were evaluated within an experimental–theoretical method $[\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}}(\gamma, in) \times \sigma^{\text{expt}}(\gamma, xn)]$ by employing the ratios $F_i^{\text{theor}}(\gamma, in)$ calculated on the basis of a combined photonuclear-reaction model. It was obtained that cross sections evaluated in this way deviate substantially from the results of many experiments performed via neutron-multiplicity sorting, but, at the same time, agree with the results of alternative activation experiments. Prospects of employing methods that would provide, without recourse to photoneutron-multiplicity sorting, reliable data on cross sections of partial photoneutron reactions are discussed.

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1. INTRODUCTION

Photonuclear reactions play an important role both in basic and applied nuclear-physics studies. The parameters of giant dipole resonances (GDR) observed in cross sections of various photon-induced reactions are of great interest from the point of view of studying nuclear structure and dynamics and nuclear-reaction mechanisms. One employs them in a wide variety of fields, including nuclear physics; nuclear power engineering; astrophysics; radiation sections of chemistry, geology, and medicine; materials science; ecology; and various applied problems, such as monitoring of colliding beams and noninvasive control methods. With the aim of meeting needs for data on various photonuclear reactions, the IAEA Nuclear Reaction Data Centers Network [1], including the SINP (Skobeltsyn Institute of Nuclear Physics) Center for photonuclear experiments data of Lomonosov Moscow State University, created and maintains the EXFOR international database of nuclear reactions [2], which is well known to a wide range of users. Along with data on nuclear reactions induced by neutrons, charged particles, and heavy ions, this database contains a vast amount photonuclear data obtained in various experiments [3].

After a nucleus absorbs a photon of energy up to about 50 MeV, the removal of the introduced excitation proceeds via the emission of individual nucleons and their combinations. The nucleus emits one nucleon with the highest probability, two nucleons with a lower probability, and a greater number of nucleons with a still lower probability; this determines the main channels of GDR decay. The sum of all reactions involving the emission of various numbers of nucleons (partial reactions) and the photofission reaction for relatively heavy nuclei determines photoabsorption reaction; that is,

$$\begin{aligned}(\gamma, abs) = (\gamma, 2n) + (\gamma, 1n1p) + (\gamma, 2n) \quad (1)\\ + (\gamma, 3n) + \ldots + (\gamma, 1p) + (\gamma, 2p) + \ldots + (\gamma, f).\end{aligned}$$

In the energy region around the GDR maximum, the (γ, abs) cross section is basically exhausted for the majority of nuclei by the $(\gamma, 1n)$ cross section [in the region of light and medium-heavy nuclei, by the

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sum of the $(\gamma, 1n)$ and $(\gamma, 1p)$ cross sections]. As the energy of incident photons increases, reactions involving a greater number of emitted nucleons (with their higher multiplicities) begin to make a sizable contribution to the photoabsorption cross section.

The ratio of cross sections of reactions involving the emission of different numbers of neutrons is an important feature characterizing the photodisintegration of a nucleus and depending on mechanisms of its excitation. For example, a discrepancy between the energy dependence of the $(\gamma, 1n)$ cross section and respective statistical-model predictions may indicate that processes involving direct neutron knockout from the target nucleus by photons come into play, whereas the ratio of the $(\gamma, 1n)$ and $(\gamma, 2n)$ cross sections determines the relative probabilities for direct and statistical processes in the excitation and decay of nuclei, the properties of isospin splitting, and many other special features of electromagnetic interactions of nuclei.

Obviously, the validity and efficiency of employing experimental data on the cross sections of partial photonuclear, especially photoneutron, reactions to solve various basic and applied problems depends, first of all, on the degree to which the determination of the cross section of a partial reaction is reliable in that energy region where the beam energy is sufficient for the occurrence of some other partial reaction. Since the energy thresholds $B1n$, $B2n$, $B3n$, ... for $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, ... partial reactions are relatively close to one another, several of the aforementioned reactions may proceed simultaneously in many regions of incident-photon energies peculiar to giant dipole resonances. Unfortunately, data for such reactions from different experiments show a rather broad spread. In view of this, a reliable sorting of reactions producing different numbers of emitted neutrons (in other words, the separation of GDR decay channels characterized by different multiplicities) is an important task.

2. SYSTEMATIC DISCREPANCIES BETWEEN THE RESULTS OF DIFFERENT EXPERIMENTS

The majority of cross sections of partial photoneutron reactions were obtained in experiments based of the use of quasimonoenergetic annihilation photons and performed at the Lawrence Livermore National Laboratory (USA) and at the CEA Saclay Nuclear Research Centre (France). These data, included in the EXFOR international database [3], can be found in numerous review articles (see, for example, [4, 5]) and atlases (for example, [6, 7]). The data in question were obtained by directly detecting emitted neutrons—specifically, a single neutron from a $(\gamma, 1n)$ reaction was detected once, both neutrons from a $(\gamma, 2n)$ were detected twice, and each of the three neutrons from a $(\gamma, 3n)$ reaction was detected three times. In order to identify a definite reaction involving the production of a detected neutron, it is necessary to know its multiplicity. Herein lies the well-known problem of photoneutron-multiplicity sorting.

In the aforementioned Livermore and Saclay experiments, the multiplicity of a detected neutron was determined on the basis of its measured energy. This method was based on the assumption that the energy spectra of neutrons from $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, ... reactions differ substantially from one another. Since the excitation energy of the nucleus on which the $(\gamma, 2n)$ reaction proceeds is shared between the two neutrons, either has an energy smaller than the energy of the single neutron from the respective $(\gamma, 1n)$ reaction; therefore, the neutrons of higher kinetic energy should have a multiplicity of 1, whereas the neutrons of lower kinetic energy should have a multiplicity of 2. At the same time, the methods used to measure the kinetic energies of the neutrons were different. For this reason, the results obtained at the two laboratories for the same nucleus showed intricate discrepancies of manifestly systematic character and significant magnitude. For example, it was found in [8, 9] that, as a rule, the Saclay results were greater in magnitude for the $(\gamma, 1n)$ cross sections and were smaller for the $(\gamma, 2n)$ cross sections, the scale of the discrepancies reaching 100%. On the contrary, the cross sections of the multiplicity-independent neutron-yield reaction

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

proved to be close (on the basis of an analysis of more than 500 cross sections of neutron-yield reactions on nuclei of ^{3}H to ^{238}U, it was found that, according to data obtained at various laboratories worldwide in beams of not only quasimonoenergetic annihilation photons but also bremsstrahlung, the average spread of the integrated cross sections of the reactions in (2) is about 10%). The discrepancies under discussion were the subject of many studies (see, for example, [8–14]). Unfortunately, those studies did not employ systematic approaches, relying on various assumptions on the reasons of the discrepancies between data for definite nuclei and leading, rather frequently, to opposite recommendations, which reduced the discrepancy between the data in some cases but enlarged them in other ones.

In [13, 14], the above discrepancies between the cross sections of partial photoneutron reactions were considered most comprehensively and most systematically. As a result, it turned out that the ratios of

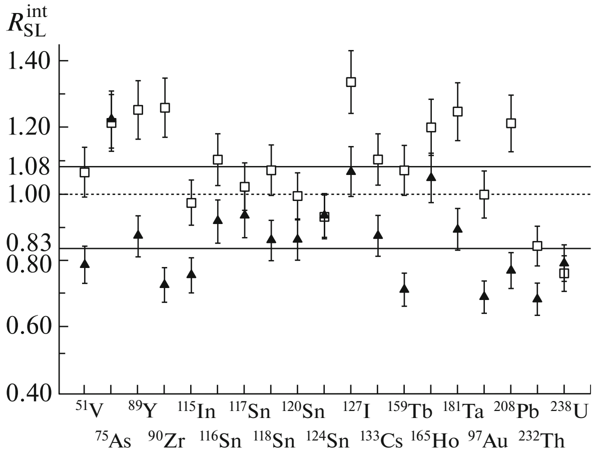

Fig. 1. Systematics of the ratios (open boxes) $R_{\rm SL}^{\rm int}(n) = \sigma_{\rm S}^{\rm int}(\gamma, n)/\sigma_{\rm L}^{\rm int}(\gamma, n)$ and (closed triangles) $R_{\rm SL}^{\rm инт}(2n) = \sigma_{\rm S}^{\rm int}(\gamma, 2n)/\sigma_{\rm L}^{\rm int}(\gamma, 2n)$ according to data obtained in Saclay and Livermore experiments. The straight lines correspond to the following characteristic values of $R_{\rm SL}^{\rm int}$: $\langle R^{\rm int}(1n)\rangle = 1.08$, and $\langle R^{\rm int}(2n)\rangle = 0.83$.

the integrated cross sections obtained in Saclay and Livermore for partial reactions,

$$R_{\rm SL}^{\rm int} = \sigma_{\rm S}^{\rm int}/\sigma_{\rm L}^{\rm int}, \qquad (3)$$

on 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) have a spread ranging between about 0.65 and about 1.35. Their average values are $\langle R^{\rm int}(1n)\rangle \sim 1.08$ for reactions producing one neutron (see Fig. 1) and $\langle R^{\rm int}(2n)\rangle \sim 0.83$ for reactions producing two neutrons. Obviously, these oppositely directed discrepancies such large in magnitude that they exceed greatly the declared statistical accuracies suggest the presence of substantial systematic uncertainties in the data and, hence, question their reliability.

3. ANALYSIS OF RELIABILITY OF RESULTS FROM VARIOUS EXPERIMENTS

3.1. Putting into Consistency “Unreliable” Saclay Results with “Reliable” Livermore Results

In order to resolve the problem of the reliability of data obtained in different experiments, the results on ^{181}Ta photo- and electrodisintegration, additionally resorting to the results of measurements performed by an alternative, activation, method were compared in [11]. It was found found that $\sigma(e, 2n)$ agrees with the cross section obtained by rescaling the Livermore data on $\sigma(\gamma, 2n)$ and that, accordingly, $\sigma(e, 1n)$ agrees with the cross section obtained by rescaling $\sigma(\gamma, 1n)$. The respective conclusion was that the results of Livermore experiments were reliable. On the other hand, the cross section $\sigma(e, 2n)$ did not agree with respective Saclay data, which proved to be underestimated for $(\gamma, 2n)$ cross sections but overestimated for $(\gamma, 1n)$ cross sections. In view of substantial uncertainties in the procedure for determining multiplicities in photoneutron reactions, the Saclay data were therefore declared to be unreliable. A method for correcting the Saclay data that was based on specially rescaling them with the aim of transmitting part of the $(\gamma, 1n)$ cross section in the $(\gamma, 2n)$ cross section was proposed in order to remove the effect of such errors and to render the Saclay data closer to the Livermore data. Correspondingly, the Livermore data were also slightly corrected, since the method was based on the requirement of best agreement between the Livermore and Saclay data in the energy region that lay below the $(\gamma, 2n)$ threshold $B2n$ and in which the results should have in principle been identical. The partial-reaction cross sections corrected (evaluated) and putted into consistency in this way [13, 14] were included in the EXFOR international database [3] as the most reliable ones and were used in creating the IAEA electronic library of evaluated photonuclear data [15].

3.2. Substantial Systematic Uncertainties in Livermore Data on Cross Sections of Partial Photoneutron Reactions

Even at the stage of creating the electron library in question, there arose, however, serious doubts as to whether the Livermore data may be viewed as reliable results. First of all, physically forbidden negative values of the $(\gamma, 1n)$ cross sections obtained in Livermore for many nuclei appeared over broad energy ranges. Figure 2 gives typical examples of this: for ^{65}Cu [16] (Fig. 2*a*), ^{94}Zr [17] (Fig. 2*b*), and ^{116}Sn [18] (Fig. 2*c*) nuclei, negative values of the $(\gamma, 1n)$ cross sections appeared in the energy regions of $E \sim 22$–28, ∼20–29, and ∼22–26 MeV, respectively. The fact that the experimentally measured $(\gamma, 1n)$ cross sections take negative values at energies as low as about 22, 20, and 22 MeV questions the reliability of the data under discussion, since it suggests the presence in this cross sections of substantial systematic uncertainties associated with special features of the method for photoneutron-multiplicity sorting.

There are even more causes for concern in the case of the ^{181}Ta nucleus [19], even though the authors of [11] earlier concluded on the basis of data on the $(\gamma, 2n)$ reaction for precisely this nucleus that the data in question are reliable. The point is that, in Fig. 2*d*, one can clearly see that the $(\gamma, 1n)$ cross section becomes zero even at an energy of about 17.5 MeV. Moreover, the experiment did not detect neutrons of higher energy from this reaction.

3.3. Objective Physical Criteria of Reliability of Data on Cross Sections of Partial Photoneutron Reactions

Thus, serious doubts about the validity of the Livermore data are added to the doubts expressed earlier in [11–15] as to whether the Saclay data are reliable. Because of general doubts that both the Saclay and the Livermore data are reliable, it is of importance to perform such objective physical criteria of reliability of experimental data that would not depend on the method for obtaining these data and to develop methods that would permit evaluating data on cross sections of partial photoneutron reactions and which would satisfy these criteria. In [20, 21] it was proposed employing transition multiplicity functions in the form of the ratios

$$\begin{aligned} F_i &= \sigma(\gamma, in)/\sigma(\gamma, xn) \qquad (4) \\ &= \sigma(\gamma, in)/[\sigma(\gamma, 1n) + 2\sigma(\gamma, 2n) \\ &\quad + 3\sigma(\gamma, 3n) + \ldots]. \end{aligned}$$

as criteria of the reliability of experimental data on cross sections of partial photoneutron reactions. By the physical meaning of their definition, these ratios make it possible to demonstrate readily the presence of systematic uncertainties in experimental data and to evaluate these uncertainties. According to (4), the function F_1 cannot exceed the value of 1.00, the function F_2 cannot exceed the value of 0.50, the function F_3 cannot exceed the value of 0.33, and so on. Values of the functions F_i in excess of the respective upper limits would imply that the distribution of photoneutrons between channels that have different multiplicities (multiplicity sorting) was incorrect in the experiment being considered, so that partial-reaction cross sections obtained by means of this sorting are physically unreliable. Since all terms in the ratios given by (4) are reaction cross sections, which have dimensions of area, the functions F_i should be positive. Their negative values, which correspond to negative reaction cross sections, are also indicative of the unreliability of data.

In Fig. 3, the ratios F_i^{expt} obtained for the results of (triangles) Livermore [16–19] and (squares) Saclay [22, 23] experiments are compared with the ratios F_i^{theor} calculated (solid curves) on the basis of the combined model of photonuclear reactions that was proposed in [24, 25]. The preequilibrium exciton model is based on employing nuclear level densities calculated within the Fermi gas model and on taking into account the impact of nuclear-deformation-induced effects and effects of isospin GDR splitting on GDR formation and decay. The model in question was successfully tested in describing experimental data on the neutron-yield cross sections of a large number of medium-heavy and heavy nuclei. It enables one to calculate cross section of partial reactions without considering problems of neutron-multiplicity sorting.

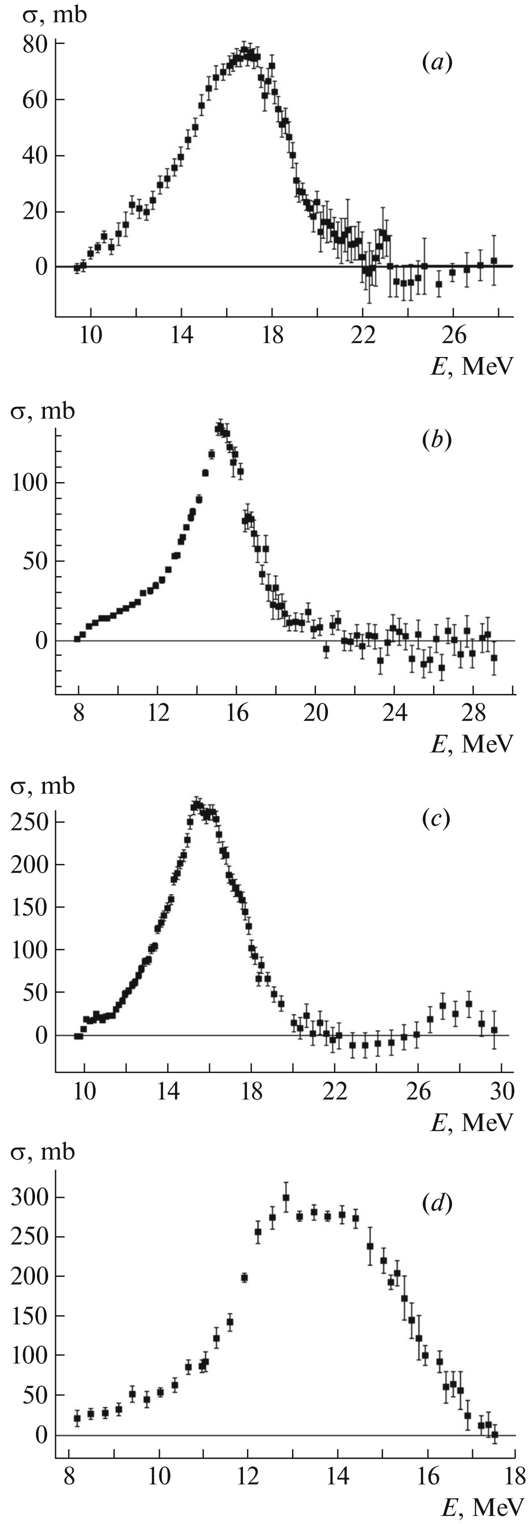

Fig. 2. Energy regions containing physically forbidden negative values of the $(\gamma, 1n)$ cross sections obtained in Livermore for (*a*) ^{65}Cu [16], (*b*) ^{94}Zr [17], (*c*) ^{116}Sn [18], and (*d*) ^{181}Ta [19].

One can see that, over broad regions of photon

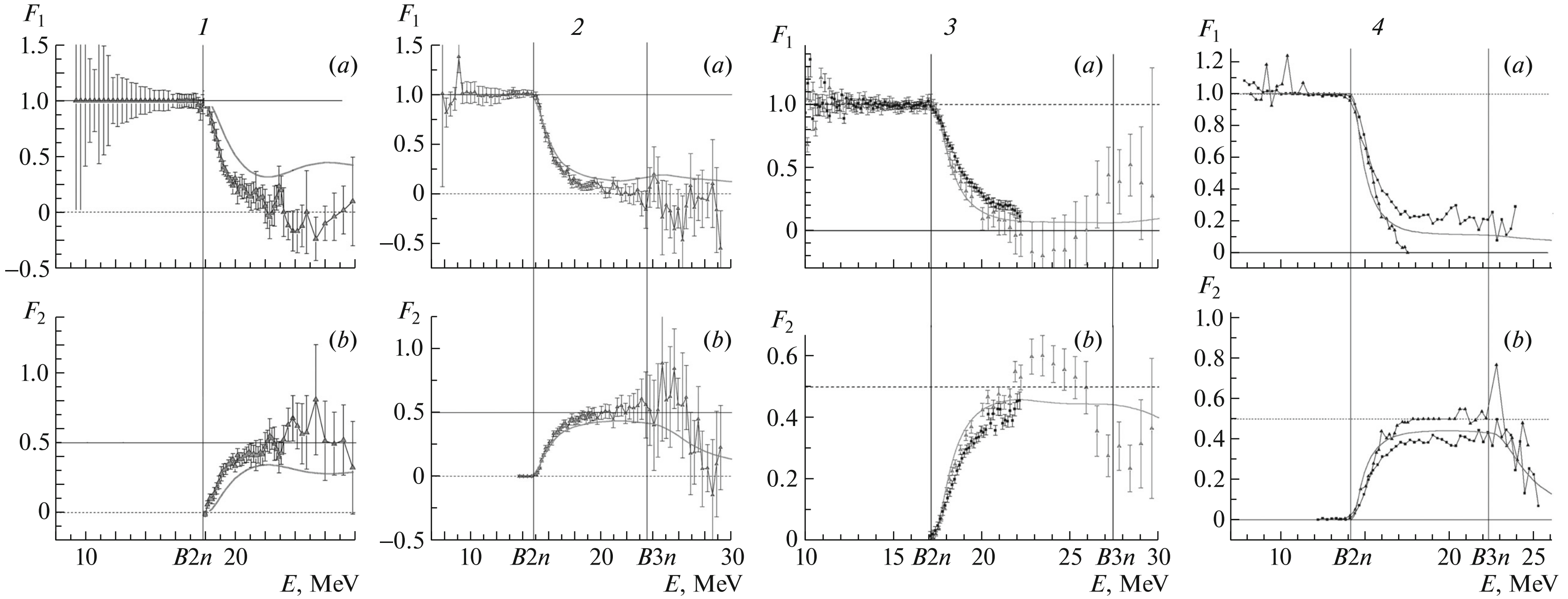

Fig. 3. Comparison of the ratios F_i^{exp} (F_1 in *a* and F_2 in *b*) obtained for the results of the (closed triangles) Livermore [16–19] and (closed boxes) Saclay [22, 23] experiments with the ratios F_i^{theor} (solid curves) calculated on the basis of the combined model [24, 25] for (panel *1*) ^{65}Cu [16], (panel *2*) ^{94}Zr [17], (panel *3*) ^{116}Sn [18, 22], and (panel *4*) ^{181}Ta [19, 23].

Table 1. Examples of energy regions where the $(\gamma, 1n)$ cross sections take negative values correlated with values of $F_2^{\text{exp}} > 0.50$

Nucleus	Energy region, MeV	Maximum value of the ratio F_2^{exp}	References
^{65}Cu	∼22.0–26.0	∼0.80	[16]
^{91}Zr	∼23.0–30.0	∼0.80	[17]
^{94}Zr	∼21.5–27.0	∼0.70	[17]
^{115}In	∼20.5–31.0	∼0.60	[17]
^{116}Sn	∼21.5–26.0	∼0.62	[18]
^{159}Tb	∼18.5–22.0	∼0.60	[32]
	∼22.5–24.0	∼2.00	
^{181}Ta	∼20.0–23.0	∼0.80	[19]

energies, physically forbidden negative values of the $(\gamma, 1n)$ cross sections obtained in Livermore and, accordingly, of the ratios F_1^{exp} correlate with physically unreliable values of the ratios F_2^{exp}. The reason is that, because of an unjustified inclusion of some neutrons from the $(\gamma, 1n)$ channel in the $(\gamma, 2n)$ channel, the cross section $\sigma(\gamma, 1n)$ decreases to physically unreliable negative values, while the cross section $\sigma(\gamma, 2n)$ increases accordingly to values at which $F_2^{\text{expt}} > 0.50$. Thus, the Livermore data do not meet the proposed reliability criteria and are therefore unreliable.

One can see that we cannot blame the same fault on the Saclay data, since they formally satisfy the proposed criteria. At the same time, the aforementioned unreliability of the Saclay data stems from serious discrepancies between the values of F_i^{exp} and F_i^{theor}.

Similar correlation between the functions F_1^{exp} and F_2^{exp} [and the functions F_3^{exp} in the cases where there are data on the $(\gamma, 3n)$ cross sections] were found in [20, 21, 26–31] for ^{63,65}Cu, ^{80}Se, ^{91,94}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, ^{181}Ta, ^{186}W,^{186,188,189,190,192}Os, ^{197}Au, ^{208}Pb, and ^{209}Bi nuclei, which were studied at Saclay and Livermore. For some nuclei, Table 1 gives the respective maximum values characteristic of F_2^{exp} over rather broad ranges of incident-photon energies.

Additionally, scanty data on cross sections obtained for partial photoneutron reactions in beams of bremsstrahlung photons were analyzed in [33]. Such experiments made it possible to obtain directly cross sections of the neutron-yield reaction in (2); introducing respective corrections calculated on the basis of statistical theory, one thereupon extracted information about the cross section of the total photoneutron reaction

$$(\gamma, sn) = (\gamma, 1n) + (\gamma, 2n) + (\gamma, 3n) + \ldots. \quad (5)$$

In order to obtain cross sections of partial reactions, use was made of respective difference procedures. For example, the procedure based on the following difference relation was applied in the photon-energy region extending up to the $(\gamma, 3n)$ threshold $B3n$:

$$\sigma(\gamma, 2n) = \sigma(\gamma, xn) - \sigma(\gamma, sn). \quad (6)$$

Table 2. Integrated cross sections (in MeV mb units) calculated for partial photoneutron reactions on ^{65}Cu nuclei up to the energy of $E^{\text{int}} = 28$ MeV

Reaction	Experiment [16]	Evaluation [36]	Deviation, %
$(\gamma, 1n)$	432.5 ± 13.0	581.0 ± 13.4	34
$(\gamma, 2n)$	200.0 ± 9.5	121.9 ± 4.9	−64

It turned out that there are ample grounds to question the reliability of data obtained in this way, since, in various broad ranges of photon energies, the ratios F_i^{exp} take either negative values or values exceeding upper limits mentioned above. Characteristic examples for the tin isotopes ^{112,114,119}Sn [34, 35] are given in Fig. 4. One can clearly see correlations, discussed in the present article, between unreliable values of the ratios F_1^{exp} and F_2^{exp}. The unreliability of data on the partial-reaction cross sections obtained by this method is due to obvious flaws in the purely statistical description of special features of giant dipole resonances. It is precisely with the aim of removing these flaws that the combined model [24, 25] used in the present study takes into account nonstatistical effects such as nuclear deformations and isospin GDR splitting.

An analysis of experimental data on cross sections of partial photoneutron reactions from various experiments that was performed by employing the above physical reliability criteria indicates that, in many cases, the identification of neutrons that have various multiplicities involved substantial systematic uncertainties, with the result that the respective data were unreliable. Systematic uncertainties inherent in the neutron-multiplicity-sorting method (or in the introduction of corrections calculated on the basis of statistical theory), which was used to obtain the overwhelming majority of data on cross sections of partial photoneutron reactions, can be avoided in experiments performed, for example, by the activation method or by mean of detecting product neutrons in the coincidence mode. Since such experiments, first, present a difficult challenge and, second, are

Table 3. Integrated cross sections $\sigma^{\rm int}$ calculated up to $E^{\rm int} = 35.0$ MeV on the basis of the evaluated cross sections of the total and partial photoneutron reactions on ^{181}Ta nuclei along with experimental data obtained at Saclay and Livermore

Reaction	$\sigma^{\rm int}$, MeV mb		
	evaluated data [28]	Saclay data [23]	Livermore data [19]
(γ, xn)	4078.2 ± 9.3	4078.2 ± 9.3	3068.3 ± 63.1
(γ, sn)	3021.9 ± 36.1	3124.3 ± 30.8	2199.7 ± 46.3
$(\gamma, 1n)$	1956.3 ± 31.0	2189.5 ± 21.5	1315.7 ± 20.7
$(\gamma, 2n)$	958.3 ± 17.4	797.4 ± 20.0	887.0 ± 41.7
$(\gamma, 3n)$	107.3 ± 6.3	137.4 ± 10.0	

not always implementable, it is urging to address the problem of developing methods for data evaluation on the basis of those cross sections of partial photoneutron reactions that satisfy the reliability criteria introduced above.

4. EVALUATION OF PARTIAL-PHOTONEUTRON-REACTION CROSS SECTIONS SATISFYING PHYSICAL RELIABILITY CRITERIA WITH THE AID OF THE EXPERIMENTAL-THEORETICAL METHOD

From the foregoing, it is clear that a method for evaluating partial-reaction cross sections should be free both from the shortcomings of experimental methods for neutron-multiplicity sorting and from limitations of statistical theory in describing the competition of channels of the decay of GDR states. Such an experimental—theoretical method (ETM) was proposed in [20, 21] on the basis of simultaneously employing experimental data on the cross section of the neutron-yield reaction in (2) alone, which does not depend on multiplicity-sorting problems, and relations of the combined model of photonuclear reactions [24, 25].

The method consists in sharing the neutron-yield-reaction cross section (2), which does not depend on photoneutron-multiplicity problems under discussion, into the contributions of partial-reaction cross sections by employing the neutron-multiplicity functions $F_i^{\rm theor}$ (4) calculated on the basis of the combined model; that is,

$$\sigma^{\rm eval}(\gamma, in) = F_i^{\rm theor} \times \sigma^{\rm exp}(\gamma, xn). \qquad (7)$$

Thus, the ratios of the evaluated cross sections $\sigma^{\rm eval}(\gamma, in)$ are determined by the equations of the model in question ($F_i^{\rm theor}$), while their respective sum, $\sigma^{\rm eval}(\gamma, xn)$ is seen to coincide with $\sigma^{\rm exp}(\gamma, xn)$.

This method was used to evaluate the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial-reaction cross sections of a large number of nuclei (which were listed in the preceding section). Respective data were obtained either in beams of quasimonoenergetic annihilation photons by employing the method of photoneutron-multiplicity sorting or in beams of bremsstrahlung by employing corrections calculated within statistical theory.

By way of example, the $(\gamma, 1n)$ and $(\gamma, 2n)$ partial-reaction cross sections evaluated by this experimental—theoretical method in [36] for the ^{65}Cu nucleus are presented in Fig. 5. Table 2 gives the correspondent data on integrated reaction cross sections.

Here, the discrepancies have approximately the same character as those observed earlier in [20, 21, 26—31] for a large number of nuclei. In the energy region of $E \gtrsim 22$ MeV, the experimental data on the $(\gamma, 1n)$ cross section are unreliably underestimated (down to the appearance of physically forbidden negative values) because of the removal from them of the contribution of a significant number of neutrons, which were unjustifiably assigned a multiplicity of 2. At the same time, the experimental data on the $(\gamma, 2n)$ cross section are accordingly overestimated because of the equally unjustifiable inclusion of extra neutrons in them. The contribution of these neutrons leads to an increase in the cross section being considered up to values at which the respective function F_2 becomes greater than 0.50.

Figure 6 and Table 3 give analogous data [together with the cross section obtained for the total photoneutron reaction in (5) with the aid of cross sections of partial reactions] for the ^{181}Ta nucleus. One can clearly see that these data are unreliable in the energy region of $E \gtrsim 18$ MeV.

Figures 5 and 6 also give the results of respective experiments performed with the aid of the method of neutron-multiplicity sorting. One can see that the evaluated and experimental reaction cross sections differ substantially. Via a detailed numerical analysis, it was shown in [30] that, for data on the photodisintegration of the ^{159}Tb nucleus, for example, the integrated cross section $\sigma^{\rm int}$ for the evaluated $(\gamma, 1n)$ cross section is approximately 20% smaller than the respective experimental values obtained in Saclay [23] and is approximately 20% larger than the respective Livermore results [32]. At the same time, $\sigma^{\rm int}_{\rm eval}(\gamma, 2n)$ is approximately 15% larger than Saclay data [23] and is approximately 20% smaller than Livermore data [32]. In view of so large a discrepancy between

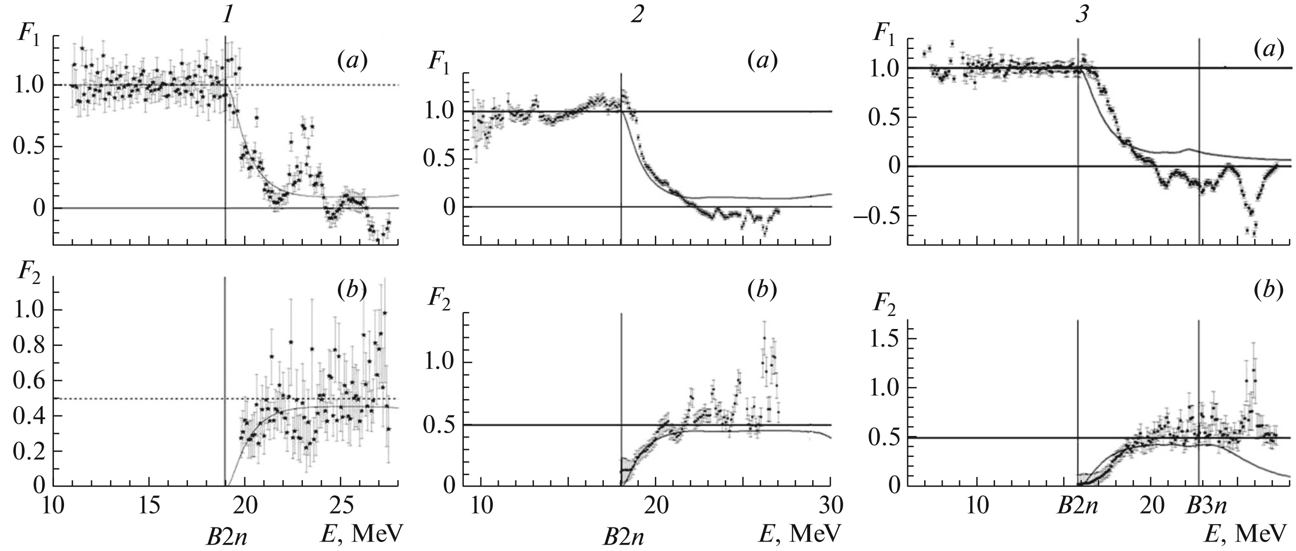

Fig. 4. Ratios F_i^{exp} (F_1 in a and F_2 in b) obtained for the results of the experiments reported in [34, 35] and performed in bremsstrahlung-photon beams for (panel *1*) ^{112}Sn, (panel *2*) ^{114}Sn, and (panel *3*) ^{119}Sn along with the ratios F_i^{theor} calculated on the basis of the combined model [24, 25].

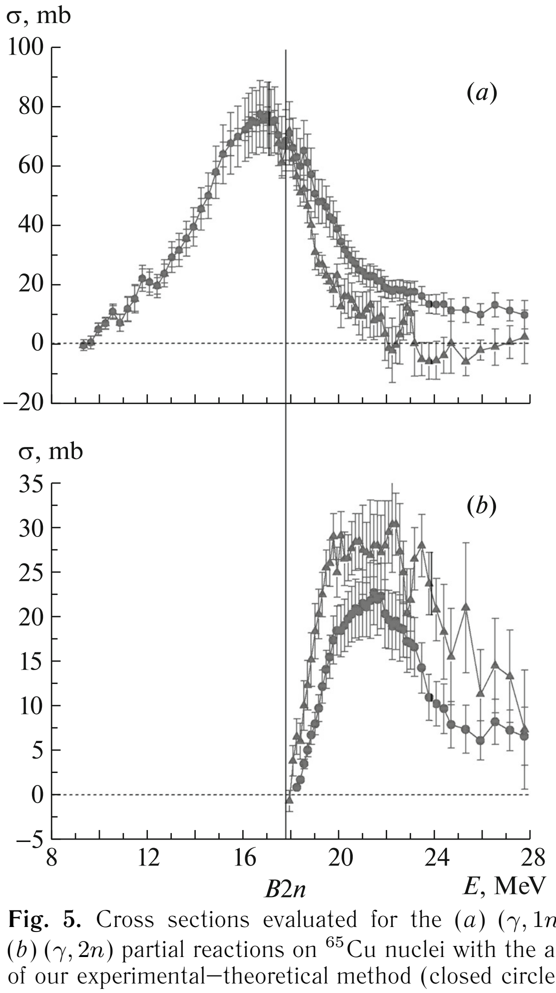

Fig. 5. Cross sections evaluated for the (a) $(\gamma, 1n)$, (b) $(\gamma, 2n)$ partial reactions on ^{65}Cu nuclei with the aid of our experimental–theoretical method (closed circles) along with experimental results from [16] (closed triangles). The lines on display were drawn to guide the eye.

the evaluated partial-reaction cross sections satisfying the proposed reliability criteria and experimental cross sections, which do not satisfy these criteria, it is advisable to revisit estimates of many physical effects that depend on the cross sections of partial reactions and on their ratios. By way of example, we indicate that, for the ^{159}Tb nucleus, the ratio $\sigma^{\text{int}}(\gamma, 2n)/\sigma^{\text{int}}(\gamma, 1n)$ of the evaluated cross-section values, which plays an important role in estimating probabilities for various physical processes—first of all, branching fractions for direct and statistical processes in the decay of highly excited GDR states—differs by 30% from the respective estimates based on various experimental data [23, 37].

At the same time, it was shown in [38] that partial-reaction cross sections evaluated within the experimental–theoretical method agree with the results of alternative activation experiments, where the final-state nucleus serves as a basis for identifying reactions featuring different numbers of emitted neutrons. For example, it was found that, for the ^{181}Ta nucleus, the ratio $\sigma^{\text{int}}(\gamma, 2n)/\sigma^{\text{int}}(\gamma, 1n)$ of the integrated cross sections was overestimated with respect to the result of the evaluation (0.49) in [32] (0.67) and was underestimated in relation to this scale in [23] (0.36). A similar discrepancy was also observed for the reaction-yield ratio $Y(\gamma, 2n)/Y(\gamma, 1n)$: specifically, the experimental values of 0.42 and 0.24 should be contrasted against the evaluated result of 0.33, which agrees well with the result of the activation experiment (0.34). In [38], it was shown that the cross sections evaluated for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions on the ^{209}Bi nucleus by the experimental–theoretical method with allowance for the above

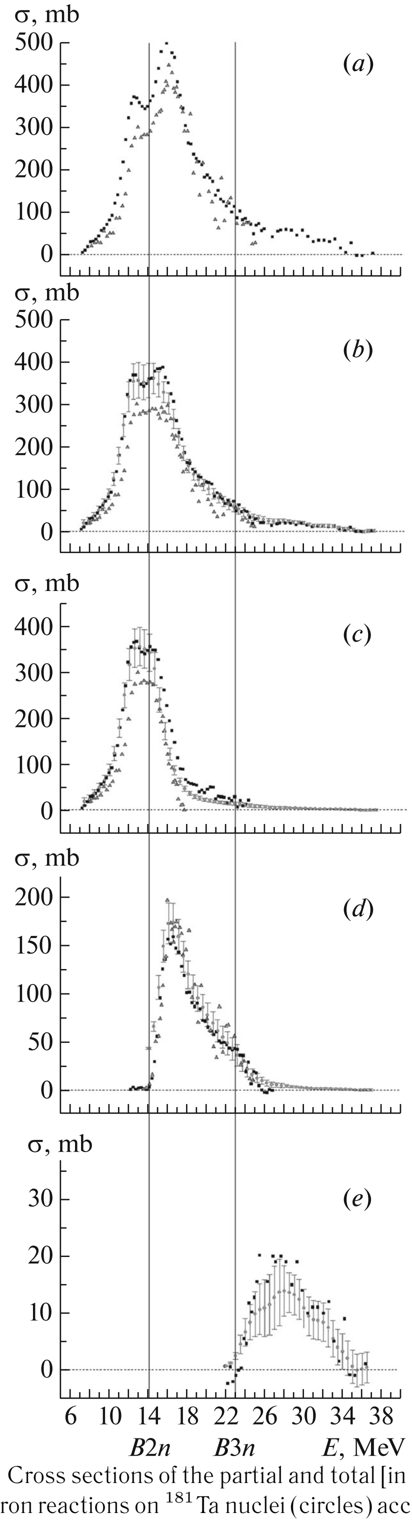

Fig. 6. Cross sections of the partial and total [in (5)] photoneutron reactions on ^{181}Ta nuclei (circles) according to the evaluation in [28] on the basis of the experimental—theoretical method and according to the results of the experiments reported in (triangles) [19] and (squares) [23]: (*a*) (γ, xn), (*b*) (γ, sn), (*c*) $(\gamma, 1n)$, (*d*) $(\gamma, 2n)$, and (*e*) $(\gamma, 3n)$.

objective physical data-reliability criteria are also in agreement with the results obtained by measuring the yields of these reactions in an activation experiment by means of identifying their final-state nuclei of ^{208}Bi and ^{207}Bi, respectively.

In view of this, it is of interest to compare evaluated cross sections of partial reactions with the results of experiments that employ photoneutron detection in the coincidence mode and whose implementation presents serious difficulties because of the smallness of photonuclear-reaction cross sections.

In recent years, investigations of cross sections of partial reactions using photon beams of a new type, such as those that are obtained upon the Compton back scattering of relativistic electrons on a powerful-laser beam, have gained momentum. Such experiments are being performed at Konan University and at the NewSubaru facility in Japan. Similar experiments are planned at the ELI—NP setup under construction in Romania, which is expected to have a monoenergetic photon beam of very high quality. The use in such beams of new-type detectors possessing an efficiency function only slightly dependent on energy [39] gives grounds to hope for a reliable direct measurement of multiplicities of photoneutrons from different partial reactions.

5. CONCLUSIONS

On the the basis of the foregoing, the modern status of photonuclear data can be characterized as follows.

There are serious reasons to question the reliability of cross sections determined for partial photoneutron reactions in experiments for a large number of nuclei with various photon sources (quasimonochromatic annihilation photons and bremsstrahlung gamma radiation from electrons) and by various methods (neutron-multiplicity sorting and introduction of corrections in the cross section of the neutron-yield reaction), since, in broad energy regions, they do not meet objective physical criteria. The reason is that, because of shortcomings in the methods used to determine cross sections of partial reactions, there are substantial systematic errors in their resulting values.

Partial-reaction cross sections evaluated on the basis of experimental—theoretical method, which are free from the aforementioned shortcomings and which satisfy the objective physical reliability criteria, differ substantially from experimental data obtained by means of neutron-multiplicity sorting. A substantial discrepancy between the evaluated and experimental cross sections brings about the question of not only revisiting estimates of many physical effects that depend on partial-reaction cross sections and their ratios but also implementing new modern experiments that would be free from the aforementioned shortcomings of the experiments performed earlier.

It is noteworthy that partial-reaction cross sections evaluated within the experimental—theoretical method agree with results of few alternative activation experiments, which have nothing to do with experimental neutron-multiplicity sorting.

In connection with the above problems of reliability of photonuclear data, of great interest are data that can be obtained in photon beams of new type—first of all, beams formed upon the Compton back scattering of relativistic electrons on a powerful-laser beam. The use in such experiments of neutron detectors belonging to a new type and possessing an efficiency function weakly dependent on energy gives grounds to hope for a reliable direct determination of multiplicities of photoneutrons from different partial reactions.

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