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New Approach to Analyzing and Evaluating Cross Sections for Partial Photoneutron Reactions

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Abstract—The presence of substantial systematic discrepancies between the results of different experiments devoted to determining cross sections for partial photoneutron reactions—first of all, (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions—is a strong motivation for studying the reliability and authenticity of these data and for developing methods for taking into account and removing the discrepancies in question. In order to solve the first problem, we introduce objective absolute criteria involving transitional photoneutron-multiplicity functions F_1, F_2, F_3, $\ldots$; by definition, their values cannot exceed 1.0, 0.5, 0.33, $\ldots$, respectively. With the aim of solving the second problem, we propose a new experimental–theoretical approach. In this approach, reaction cross sections are evaluated by simultaneously employing experimental data on the cross section for the total photoneutron yield, $\sigma^{\rm expt}(\gamma, xn) = \sigma^{\rm expt}(\gamma, n) + 2\sigma^{\rm expt}(\gamma, 2n) + 3\sigma^{\rm expt}(\gamma, 3n) + \ldots$, which are free from drawbacks plaguing experimental methods for sorting neutrons in multiplicity, and the results obtained by calculating the functions $F_1^{\rm theor}$, $F_2^{\rm theor}$, $F_3^{\rm theor}$, $\ldots$ on the basis of the modern model of photonuclear reactions. The reliability and authenticity of data on the cross sections for (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions— $\sigma^{\rm eval}(\gamma, in) = F_i^{\rm theor}\sigma^{\rm expt}(\gamma, xn)$—were evaluated for the ^{90}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, and ^{197}Au nuclei.

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1. INTRODUCTION

Reliable and authentic information about cross sections for total and partial photoneutron reactions is extensively used in fundamental and applied investigations to solve a number of fundamental problems of electromagnetic interactions in the giant-dipole-resonance (GDR) region.

First of all, this information is required for studying relations between direct and statistical processes in the formation and decay of highly excited nuclear states and for determining the role of various components in the formation of the isospin splitting of GDR, the competition between various-type transitions forming the components of the configuration splitting of GDR, and so on. Moreover, data on cross sections for partial photoneutron reactions are widely used in various realms of science and technologies (nuclear physics and nuclear power engineering; radiation chemistry, geology, and medicine; materials science; ecology; and many other fields). In recent years, such data found applications in the latest investigations into the properties of quark–gluon plasma in colliding beams of relativistic nuclei at the facilities largest worldwide (processes of mutual electromagnetic dissociation of colliding nuclei via the excitation of GDRs in them and the subsequent decay of this resonance through the single-neutron channel are used in monitoring luminosities of such accelerators).

The results of a global analysis [1, 2] of cross sections for total and partial photoneutron reactions revealed substantial discrepancies between the results of different experiments. The use of different methods for deducing information about reaction cross sections leads to sizable (12%, on average) systematic discrepancies even in determining cross sections $\sigma(\gamma, xn)$ for the total photoneutron yield [1].

The discrepancies between cross sections for (γ, n), $(\gamma, 2n)$, $(\gamma, 3n)$, $\ldots$ partial reactions are even greater. The majority of experiments aimed at determining them were performed with quasimonoenergetic annihilation photons in Livermore (USA) and Saclay (France) by using various methods of sorting photoneutrons in multiplicity that are based on the assumption that there is a direct relation between this multiplicity and the mean energy of neutrons. There are large (up to 60%) and differently directed discrepancies between the Livermore and Saclay results [2]: in Livermore, the cross sections for $(\gamma, 2n)$ reactions were obviously overestimated, while the cross sections for (γ, n) reactions were underestimated; in Saclay, the situation is reversed (the "Livermore/Saclay" ratio for the $(\gamma, 2n)$ cross

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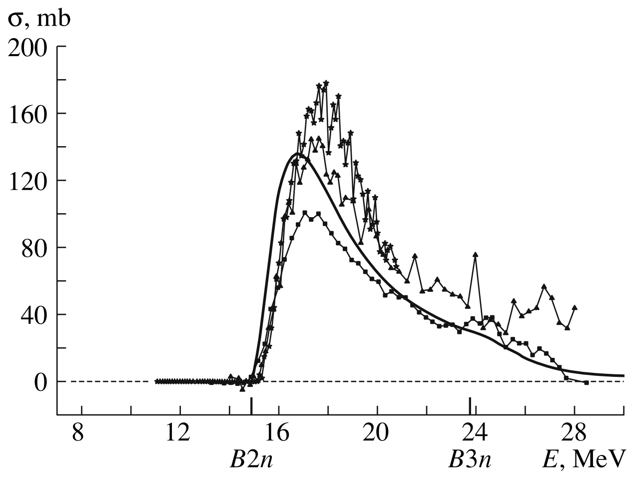

Fig. 1. Data on the cross section for the reaction $^{159}\mathrm{Tb}(\gamma, 2n)$ from various experiments along with the results of calculations: (closed triangles) data from the Livermore experiment with quasimonoenergetic photons [4], (closed boxes) data from the Saclay experiment with quasimonoenergetic photons [5], (stars) data obtained in the present study from the results of the experiment performed in Moscow with bremsstrahlung photons [6] and (curve) results of the theoretical calculations from [7, 8].

section is substantially greater than unity; on the contrary, the respective ratio for the (γ, n) cross section is substantially smaller than unity). In Table 1, we present the results of a detailed analysis [3] of the cross sections for total and partial photoneutron reactions on the ^{159}Tb nucleus. Figure 1 shows a characteristic example of such discrepancies in the form of a comparison of the results from different experiments aimed at determining the cross section for the reaction $^{159}\mathrm{Tb}(\gamma, 2n)$.

The systematic discrepancies in question obviously stem from drawbacks of the methods for sorting photoneutrons in multiplicity that were used in the experiments being discussed: the ratios of the cross sections $\sigma(\gamma, n)$ and $\sigma(\gamma, 2n)$, which depend on special features of the methods used, differ substantially from the cross sections $\sigma(\gamma, xn)$, which are independent of these features.

The reasons for the systematic discrepancies between the cross sections $\sigma(\gamma, n)$ and $\sigma(\gamma, 2n)$ were analyzed only in some individual studies (see, for example, [9, 10]). Table 2 [2, 9] gives a rather comprehensive picture of the scale of the phenomena being discussed. The aforementioned investigations were not systematic, with the result that recommendations concerning the removal of the discrepancies were contradictory: they reduced the mismatch in one group of data but made it more pronounced in another group.

The approach proposed in [2] seems the most consistent. It underlay a systematic analysis of cross sections, both the total one and ones for various partial reactions, that were obtained in Livermore and in Saclay. This analysis was performed for 19 nuclei from ^{51}V to ^{238}U (including 12 nuclei studied in [9]). This led to the conclusion, which is confirmed by the data in Table 1 and 2, that the Saclay data on the cross sections for $(\gamma, 2n)$ reactions disagree with Livermore data, since the cross sections $\sigma(\gamma, 2n)$ are underestimated in relation to the cross sections $\sigma(\gamma, n)$: some neutrons from the cross sections $\sigma(\gamma, 2n)$ were unjustifiably included in the cross section $\sigma(\gamma, n)$. The mutual correction of the Livermore and Saclay data that was applied in [2] returned the "missing" neutron contribution to the cross section $\sigma(\gamma, 2n)$ after the extraction of the respective contribution from the cross sections $\sigma(\gamma, n)$; that is, this correction procedure pushed the Saclay and Livermore data toward each other.

2. OBJECTIVE AND ABSOLUTE CRITERIA OF THE EVALUATION OF THE RELIABILITY OF DATA ON CROSS SECTIONS FOR PARTIAL REACTIONS

At the same time, obvious indications of a physically incorrect behavior of partial-reaction cross sections obtained in Livermore were revealed. First of all, this concerns the cross sections $\sigma(\gamma, n)$, for which one can trace the presence of regions of negative values. As a characteristic example, Fig. 2*a* shows the cross section for the reaction $^{116}\mathrm{Sn}(\gamma, n)$ [11]. Its behavior is quite bizarre: instead of showing a typical smooth decrease behind the GDR maximum, the cross section in question decreases sharply, taking "unphysical" negative values in the energy range of 21–26 MeV; as the energy grows further, the cross section exhibits a local maximum, whereupon it again proves to be in the region of negative values.

An unphysical character of the behavior of the cross section for the reaction $^{116}\mathrm{Sn}(\gamma, n)$ is fully confirmed by the data in Fig. 2*b*, which shows one of the specially proposed transitional photoneutron-multiplicity functions, F_2.

These functions,

$$F_1 = \sigma(\gamma, n)/\sigma(\gamma, xn) = \sigma(\gamma, n)/[\sigma(\gamma, n) + 2\sigma(\gamma, 2n) + \ldots + 3\sigma(\gamma, 3n) + \ldots], \quad (1)$$

$$F_2 = \sigma(\gamma, 2n)/\sigma(\gamma, xn), \quad (2)$$

$$F_3 = \sigma(\gamma, 3n)/\sigma(\gamma, xn)\ldots, \quad (3)$$

were first introduced (despite their simplicity and clear meaning) in [12, 13] as objective and absolute criteria of the degree to which the procedure for sorting

Table 1. Ratio of the integrated cross sections, $\sigma_L^{int}/\sigma_S^{int}$, for various reactions on the ^{159}Tb nucleus [3]

E^{int}, MeV	Reaction		
	(γ, xn)	(γ, n)	$(\gamma, 2n)$
20.0	$2340/2480 = 0.94$	$1370/1800 = 0.76$	$485/352 = 1.37$
27.4	$3170/3200 = 0.99$	$1390/1950 = 0.71$	$870/610 = 1.43$

Table 2. Comparison [2] of the ratios of the integral cross sections, $\sigma_L^{int}/\sigma_C^{int}$ (MeV mb), for (γ, n), $(\gamma, 2n)$, and (γ, xn) reactions from the Livermore and Saclay experiments

Nucleus	$\sigma_S^{int}(\gamma, n)/\sigma_L^{int}(\gamma, n)$, rel. units	$\sigma_S^{int}(\gamma, 2n)/\sigma_L^{int}(\gamma, 2n)$, rel. units	$\sigma_S^{int}(\gamma, xn)/\sigma_L^{int}(\gamma, xn)$, rel. units
^{51}V	1.07	0.79	1.07
^{75}As	1.21	1.22	1.21
^{89}Y*	1.25	0.87	1.2
^{90}Zr	1.26	0.73	1.25
^{115}In*	0.97	0.76	0.97
^{116}Sn	1.10	0.92	1.10
^{117}Sn*	1.02	0.93	1.02
^{118}Sn*	1.07	0.86	1.07
^{120}Sn*	1.00	0.86	0.99
^{124}Sn*	0.93	0.94	0.93
^{127}I	1.34	1.07	1.33
^{133}Cs*	1.10	0.86	1.11
^{159}Tb*	1.07	0.71	1.07
^{165}Ho*	1.20	1.05	1.20
^{181}Ta*	1.25	0.89	1.25
^{197}Au*	1.00	0.69	1.00
^{208}Pb*	1.21	0.77	1.21
^{232}Th	0.84	0.69	0.84
^{238}U	0.76	0.79	0.81

* Nuclei previously studied in [9].

neutrons in multiplicity was reliable and authentic (more precisely, unreliable and inauthentic) in a given experiment. By definition, the functions F_1, F_2, F_3, ... cannot assume values greater than 1.0, 0.5, 0.33, ..., respectively; if these functions go beyond these absolute limits, this means that the sorting of neutrons in multiplicity was erroneous. The appearance of regions of obviously unauthentic (negative in many cases) values in reaction cross sections (primarily those that were underestimated for one reason or another) is a direct consequence of this.

From the point of view of an analysis of reliability versus unreliability of data on reaction cross sections, the functions $F_1(E)$ and $F_3(E)$ are of no special interest: for the function F_1, this is so because of triviality, since it reflects the relatively simple and physically comprehensible behavior of only the cross section $\sigma(\gamma, n)$—below the $(\gamma, 2n)$ threshold $B2n$, $F_1 = 1$,

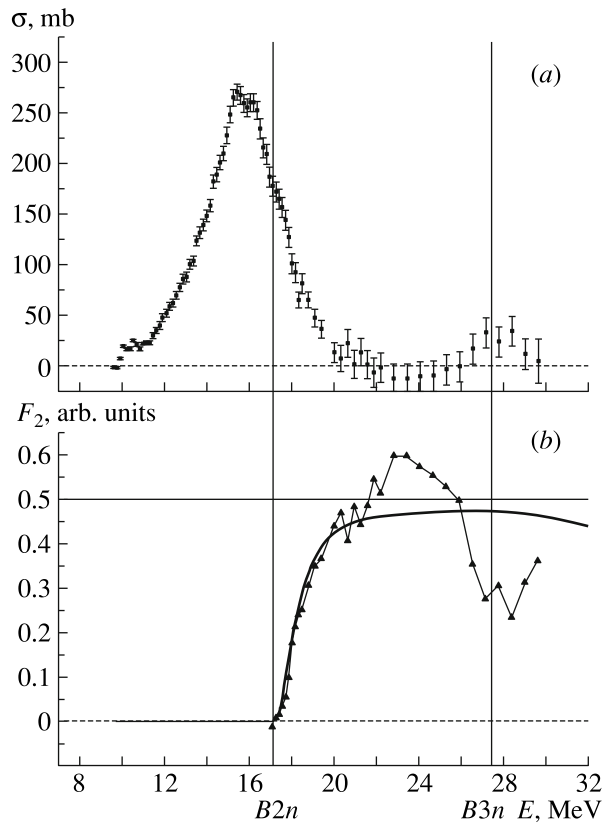

Fig. 2. Unphysical behavior of the experimental [11] cross sections for the reaction ^{116}Sn(γ, n) from the Livermore experiment: (a) experimental cross section for this reaction and (b) energy dependences of the special transitional multiplicity functions $F_{2L}^{\rm expt}$ (closed triangles) and $F_2^{\rm theor}$ (curve) [7, 8].

while, above it, where the $(\gamma, 2n)$ channel is open, this function decreases in accordance with the behavior of the cross section $\sigma(\gamma, 2n)$; for the function F_3, the same can be said in view of the relatively simple (as simple as in the preceding case) behavior of the cross section $\sigma(\gamma, 3n)$ in the energy region of $E > B3n$, as well as in view of the scantiness of respective experimental information.

At the same time, the function $F_2(E)$, is a highly convenient and efficient tool for analyzing the reliability and authenticity of data for three reactions simultaneously, (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$, in energy regions where two of them (sometimes all three) manifest themselves.

The properties that render the function $F_2(E)$ so convenient are the following:

(i) By definition (2), $F_2(E)$ can take values in excess of 0.5 at no energies.

(ii) The deviation of $F_2(E)$ from the value of 0.5 in the region of low energies is due to the presence of the (γ, n) cross section $\sigma(\gamma, n)$.

(iii) The deviation of $F_2(E)$ from the value of 0.5 in the region of energies above the $(\gamma, 3n)$ threshold $B3n$ is due to the contribution of $3\sigma(\gamma, 3n)$.

From Fig. 2b, one can clearly see that it is precisely the energy range between about 21 and 26 MeV where the cross section for the reaction ^{116}Sn(γ, n) has physically unreliable negative values and where, simultaneously, $F_2^{\rm expt} > 0.5$, which is illegitimate by definition. This is obviously indicative of the unreliability and inauthenticity of data on the cross section $\sigma(\gamma, 2n)$ and, accordingly (because of the absence of the third reaction), data on the cross section $\sigma(\gamma, n)$ that were determined in this energy region.

Figure 2b also gives the curve $F_2^{\rm theor} = \sigma^{\rm theor}(\gamma, 2n)/\sigma^{\rm theor}(\gamma, xn)$ obtained on the basis of the modern preequilibrium exciton model [7, 8] of photonuclear reactions, which relies on employing nuclear-level densities calculated within the Fermi gas model and on taking into account the influence of phenomena caused by nuclear deformations and by the isospin splitting of GDR on processes of GDR formation and decay. One can clearly see that the behavior of $F_2^{\rm theor}$ is physically adequate: above the $(\gamma, 2n)$ threshold $B2n$, $F_2^{\rm theor}$ grows, approaching some limiting value [associated with the magnitude of the tail of the cross section $\sigma(\gamma, n)$], but it does not reach the boundary value of 0.5; at energies above $B3n$, this function decreases smoothly because of the appearance of the contribution of $3\sigma(\gamma, 3n)$.

A detailed analysis of the effects being discussed was performed for partial-reaction cross sections obtained in Livermore [4], Saclay [5], and Moscow [6] (in a beam of bremsstrahlung photons) for the ^{159}Tb nucleus. Figure 3 illustrates a comparison of the respective transitional photoneutron-multiplicity functions $F_2^{\rm expt}$ and $F_2^{\rm theor}$.

2.1. Theoretical Data

According to the definition in (2), $F_2^{\rm theor}(E) = 0$ for $E < B2n = 14.9$ MeV; starting from $E = B2n$, $F_2^{\rm theor}(E)$ grows and, in the vicinity of $E = B3n = 23.7$ MeV, reaches a value of about 0.46 [which is caused by the contribution of the tail of the cross section $\sigma(\gamma, n)$]; starting from $E = B3n$, $F_2^{\rm theor}(E)$ decreases in accordance with the appearance of the contribution from $3\sigma(\gamma, 3n)$.

2.2. Moscow Data

In the region extending up to $E \sim 18$ MeV, the function $F_{2M}^{\rm expt}(E)$ is rather close to $F_2^{\rm theor}(E)$. In the region of $E > 18$ MeV, $F_{2M}^{\rm expt}(E)$ exceeds $F_2^{\rm theor}(E)$,

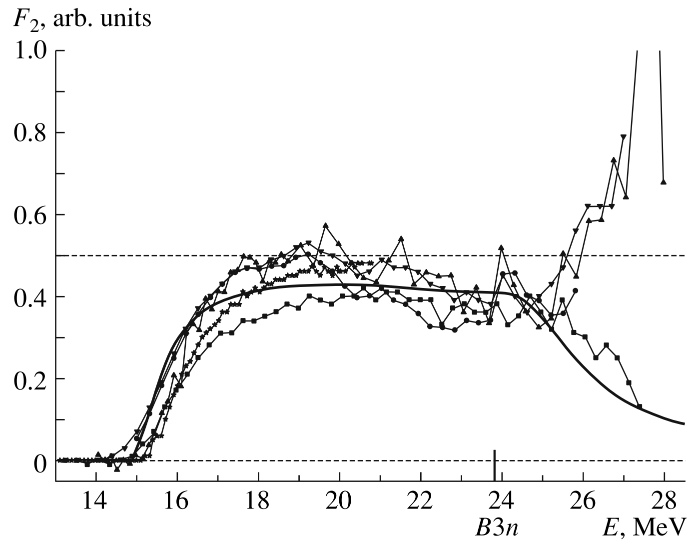

Fig. 3. Transition photoneutron-multiplicity function F_2 for the ^{159}Tb nucleus: (closed triangles) $F_{2L}^{\rm expt}$, Livermore [4]; (closed boxes) $F_{2S}^{\rm expt}$, Saclay [5]; (stars) $F_{2M}^{\rm expt}$, Moscow [6]; (closed circles) $F_2^{\rm eval}$ [2], global evaluation on the basis of the Saclay data; (inverted closed triangles) $F_2^{\rm eval}$ [2], global evaluation on the basis of the Livermore data; and (curve) $F_2^{\rm theor}$, results of the theoretical calculations from [7, 8].

approaching the absolute limit of 0.5 at $E \sim 21$ MeV. This suggests the absence of a sizable contribution from the cross section $\sigma(\gamma, n)$ and, accordingly, an overestimation of data on the cross section $\sigma(\gamma, 2n)$ in disagreement with the behavior of $F_2^{\rm theor}(E)$.

2.3. Saclay Data

Over the entire region studied in those experiments, the behavior of the function $F_{2S}^{\rm expt}(E)$ is by and large quite justifiable physically, but this function is systematically smaller than $F_2^{\rm theor}(E)$. This behavior complies well with the aforementioned underestimation in the Saclay data (Tables 1 and 2) for the cross sections $\sigma(\gamma, 2n)$ {and with the respective obvious overestimation in Saclay data [2] for the cross section $\sigma(\gamma, n)$}.

It should be noted that, since the function F_2 is defined as the ratio of the partial-reaction cross section $\sigma(\gamma, 2n)$ to the cross section $\sigma(\gamma, xn)$ for the total neutron yield and since the latter is characterized by an amplitude of about 2000 to 2500 mb, a small difference of $F_{2C}^{\rm expt}(E) - F_2^{\rm theor}(E) = 0.05$–0.10 corresponds to quite a sizable (100 to 250 mb) discrepancy between the cross sections $\sigma(\gamma, 2n)$.

2.4. Livermore Data

The behavior of $F_{2L}^{\rm expt}(E)$ differs markedly from the behavior of $F_2^{\rm theor}(E)$ and $F_{2S}^{\rm expt}(E)$. Below $E \sim$ 16.5 MeV, the functions $F_{2L}^{\rm expt}(E)$ and $F_2^{\rm theor}(E)$ are close. In the range of $E \sim 16.5$–18.0 MeV, $F_{2L}^{\rm expt}(E)$ increases sharply, strongly deviating from $F_2^{\rm theor}(E)$ and approaching the absolute limit of 0.5. This means than the cross section $\sigma(\gamma, n)$ approaches zero at $E \sim 17.5$ MeV. In the range of $E \sim 18.0$–21.5 MeV, $F_{2L}^{\rm expt}(E)$ undergoes oscillations about the limit of 0.5, some of its values being negative, $F_{2L}^{\rm expt}(E) >$ 0.5 (region of physically inauthentic values). The cross section $\sigma(\gamma, 2n)$ was strongly overestimated, and a decrease at high energies [a tail of the cross section $\sigma(\gamma, n)$] was absent. In the range of $E <$ 21.5–25.5 MeV, the function $F_{2L}^{\rm expt}(E)$ exhibits a well-pronounced dip [which corresponds to a distinct maximum in the cross section for the reaction 159Tb(γ, n); it is similar to that which is observed in the cross section for the reaction ^{116}Sn(γ, n)—see Fig. 2*a*]. At $E \sim 25.0$ MeV, $F_{2L}^{\rm expt}(E)$ becomes close to $F_2^{\rm theor}(E)$, and this suggests the "restoration of the tail" of the cross section $\sigma(\gamma, n)$. At E higher than an energy value of about 25.0 MeV, $F_{2L}^{\rm expt}(E)$ does not decrease because of the opening of the $(\gamma, 3n)$ channel, but it increases fast and once again comes into the region of physically inauthentic values ($F_2 > 0.5$), reaching the value of $F_2 = 2.0$ [this means that a partial contribution, the cross section $\sigma(\gamma, 2n)$, is twice as large as the total cross section $\sigma(\gamma, xn)$!]. Such exotic values of $F_{2L}^{\rm expt}(E)$ indicate unambiguously that, in this region of energies, the discrimination between neutrons of multiplicity 2 and 3 was absolutely incorrect. Since the $(\gamma, 3n)$ cross section was not determined in Livermore, all neutrons from it were erroneously attributed to the respective reaction $(\gamma, 2n)$.

The results obtained in [2] by simultaneously correcting the Saclay and Livermore data, $F_2^{\rm eval}$, indicate that allowance for the uncertainty in the Saclay data on the $(\gamma, 2n)$ cross section moves them toward the Livermore data [$F_{2\rm S}^{\rm eval}(E)$ for the Saclay data has all flaws analogous to the aforementioned flaws in the function $F_{2\rm L}^{\rm expt}(E)$ for the Livermore data].

A preliminary analysis of experimental cross sections for (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions that was performed with the aid of the transitional photoneutron-multiplicity function $F_2(E)$ for a large number of nuclei in the mass number range of $A = 90$–208 reveals that, for the most part, such data are unreliable and inauthentic. The regions where (γ, n) cross sections take physically unacceptable negative values, which are directly related to the regions of $F_2(E)$ values in excess of the boundary value of 0.5, and which are indicative of the inauthenticity of data on cross sections both for (γ, n) and for $(\gamma, 2n)$ partial reactions were found in data for the following nuclei: ^{90}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, and ^{208}Pb.

This analysis indicates that, by and large, experimental data obtained for cross sections for partial photoneutron reactions by applying various methods for sorting neutrons in multiplicity are unreliable and inauthentic, since the dependence of the multiplicity of neutrons on their mean energy is not likely to be direct and unambiguous, in contrast to what is assumed in these methods.

The unreliability and inauthenticity of partial-reaction cross sections obtained from the cross sections for total reactions from relations of statistical theory may stem from a more intricate character of nuclear-photodisintegration processes than what is assumed in the simple statistical model. This is suggested by a comparison of these results with the results obtained on the basis of the modern preequilibrium model, which takes into account nuclear deformations and effects of the isospin splitting of GDR in the nucleus being considered.

3. EVALUATING CROSS SECTIONS FOR PARTIAL REACTIONS UNDER CONDITIONS FREE FROM FLAWS IN EXPERIMENTAL METHODS FOR DETERMINING PHOTONEUTRON MULTIPLICITIES

With the aim of obtaining reliable and authentic data on cross sections for partial photoneutron reactions, we proposed an experimental–theoretical approach. In this approach, one takes, for input experimental information, the cross sections $\sigma^{\rm expt}(\gamma, xn)$ for the total neutron yield, which are independent of the neutron multiplicity, and describes the competition between different channels of GDR decay and the separation of reactions characterized by different neutron multiplicities in terms of the transitional photoneutron-multiplicity function $F_2^{\rm theor}$ calculated within the preequilibrium model of photonuclear reactions that relies on the use of nuclear-level densities calculated within the Fermi gas model and which takes into account effects associated with nuclear deformations and with the isospin splitting of GDR [7, 8].

3.1. Preequilibrium Exciton Model of Photonuclear Reactions on the Basis of Nuclear-Level Densities Calculated in the Fermi Gas Model

In the energy region of GDR ($E_\gamma \leqslant 30$ MeV), where electric GDR, which is a coherent mixture of single-particle–single-hole ($1p1h$) $E1$ excitations, is formed via the interaction of a nucleus with electromagnetic radiation, the interaction of a photon only with one-nucleon nuclear currents [14] is considered as a dominant process determining photoabsorption on this nucleus. The two-nucleon photoabsorption mechanism comes to be dominant in the region of $E_\gamma \geqslant 40$ MeV; within this mechanism, an excited nucleon exchanges a virtual pion with the neighboring nucleon, whereby the transfer of the absorbed-photon energy and momentum involves a correlated proton–neutron pair rather than a single nucleon.

For medium-mass and heavy nuclei, the cross section for GDR excitation can be reliably calculated on the basis of a semimicroscopic model [7]. The quasideuteron component of the photoabsorption cross section can be found within a refined version of the Levinger quasideuteron model [14, 15].

The exciton model [16–18], in which some corrections were introduced, was used in describing the nucleon-emission stage, which follows photoabsorption. In particular, the influence of isospin effects was taken into account in considering the GDR reaction channel, since the $T_>$ component of GDR decays predominantly through the proton channel. This is especially important for proton-rich nuclei, which have a significant $T_>$ component of GDR. Isospin effects were taken into account by modifying exciton densities in the $T_>$ channel of the reaction and the density of compound states of the final nucleus with the aid of respective substitutions in relations for the energies of nuclear states. These substitutions permit taking into account the decrease in the density of $T_>$

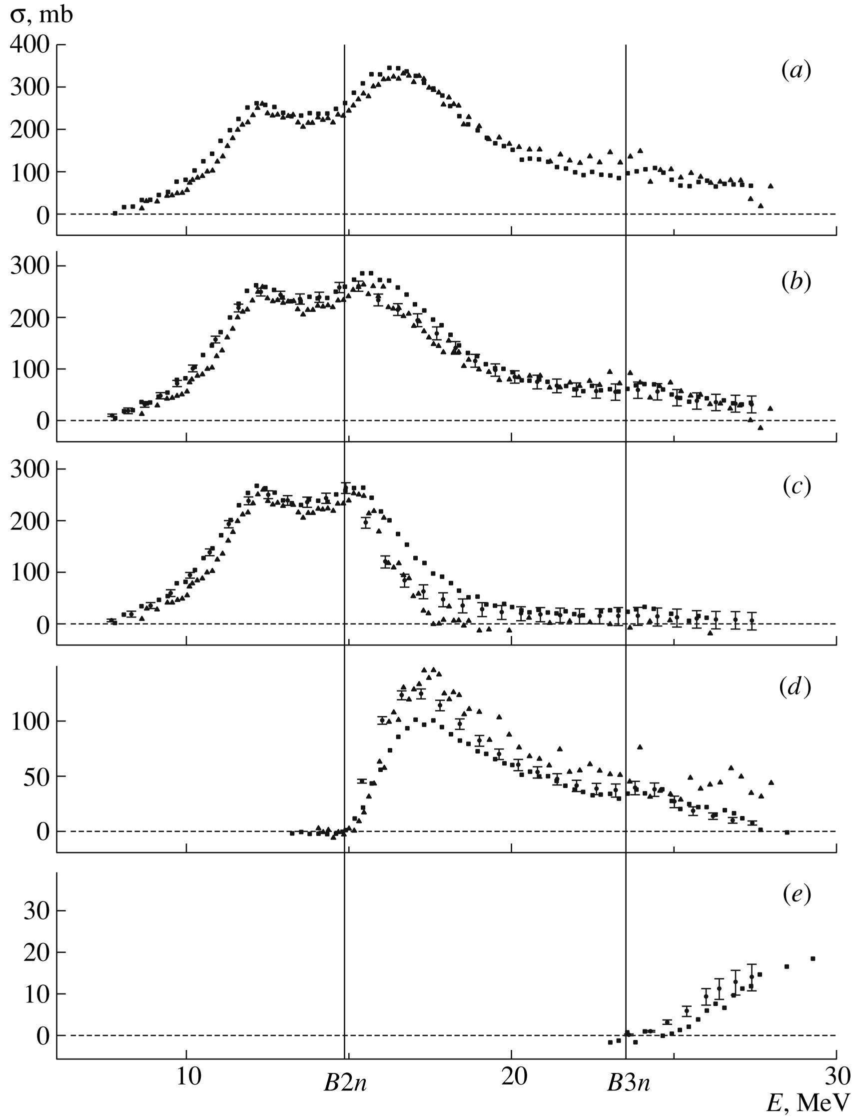

Fig. 4. Evaluated (points with error bars) and experimental {(closed triangles) Livermore [4] and (closed boxes) Saclay [5] cross sections for total and partial photoneutron reactions on the ^{159}Tb nucleus}: (a) $\sigma(\gamma, xn)$, (b) $\sigma(\gamma, sn)$, (c) $\sigma(\gamma, n)$, (d) $\sigma(\gamma, 2n)$, and (e) $\sigma(\gamma, 3n)$.

states in relation to the total densities because of their shift upward along the energy scale.

In addition, yet another correction to the exciton model was used: an increase in the lifetime of the doorway dipole state because of its collectivization in the GDR region was taken into account. This leads to a decrease in the yield for large number of nucleons (because of an extremely high energy carried away from the nucleus involved by the first emitted particle). The collectivization of doorway dipole states in the GDR region occurs to some extent because of the residual-interaction-induced mixing of different $1p1h$ configurations. This reduces the probability for their decay to $2p2h$ states, since the coupling of coherent $1p1h$ states to the majority of such states is quite weak; the former interact primarily with collective states that belong to the *dipole phonon plus surface quadrupole phonon* type and whose number is modest. Owing to this, the probability for the process in which a nucleon escapes directly from a doorway state, carrying away a high energy, grows. As a result, the yields of the secondary, tertiary, etc., nucleons decreases.

The concepts outlined above formed the basis of a model for describing the competition between channels of GDR decay. This model was used to describe cross sections for multiparticle photonucleon reactions. A detailed description of basic relations of the model [7, 8], which were used to calculate cross sections for partial reactions including (γ, n),

Table 3. Properties of gamma radiation from final nuclei formed in partial reactions on ^{181}Ta and ^{196}Au nuclei according to investigations by the induced-activity method

Reaction	$E^{\max}$, MeV	$T_{1/2}$	E_γ, keV
$^{181}\mathrm{Ta}(\gamma,n)^{180}\mathrm{Ta}$	67.7	8.154 h	93.326
			103.557
$^{181}\mathrm{Ta}(\gamma,2n)^{179}\mathrm{Ta}$		1.82 yr	63.0
$^{197}\mathrm{Au}(\gamma,n)^{196}\mathrm{Au}$	29.1	6.1669 d	426.0
$^{197}\mathrm{Au}(\gamma,2n)^{195}\mathrm{Au}$		186.098 d	98.85

(γ,np), $(\gamma,2n)$, $(\gamma,2np)$, $(\gamma,3n)$, and $(\gamma,3np)$ was given in [19].

3.2. Evaluating Data on Cross Sections for Partial Reactions by Employing Transitional Photoneutron-Multiplicity Functions

Within the model described above, we calculated cross sections for photonuclear reactions involving the production various numbers of nucleons and constructed the transitional multiplicity functions $F_1^{\rm theor}(E)$, $F_2^{\rm theor}(E)$, and $F_3^{\rm theor}(E)$.

With the aid of these functions and on the basis of experimental data on the cross section $\sigma^{\rm expt}(\gamma,xn)$ for the total photoneutron yield, we evaluated reliable data on the cross sections for partial reactions; that is,

$$\sigma^{\rm eval}(\gamma,n)=F_1^{\rm theor}\sigma^{\rm expt}(\gamma,xn), \quad (4)$$

$$\sigma^{\rm eval}(\gamma,2n)=F_2^{\rm theor}\sigma^{\rm expt}(\gamma,xn), \quad (5)$$

$$\sigma^{\rm eval}(\gamma,3n)=F_3^{\rm theor}\sigma^{\rm expt}(\gamma,xn). \quad (6)$$

Within this new approach, we evaluated the cross sections that describe (γ,n) and $(\gamma,2n)$ partial reactions and which are free from the aforementioned drawbacks of experimental data for the following nuclei: ^{90}Zr and ^{115}In [20], ^{112,114,116,117,118,119,120,122,124}Sn [12], ^{159}Tb [3], ^{197}Au [13], and ^{208}Pb.

In Fig. 4, the cross sections evaluated within the new experimental–theoretical approach for partial photoneutron reactions on ^{159}Tb nuclei are contrasted against the experimental data obtained in Saclay and Livermore.

One can clearly see that, in accordance with the foregoing, the evaluated cross sections for partial reactions prove to be intermediate between the unjustifiably overestimated and unjustifiably underestimated experimental cross sections and that the competition between them corresponds to Eqs. (1)–(3) validated physically within the theoretical model used.

3.3. Comparison of Data Obtained within the New Approach with the Results of Modern Experiments Based on the Induced-Activity Method

Obviously, sizable discrepancies between the evaluated data call for independent tests that would use the results of experiments free from the aforementioned flaws in the methods for determining photoneutron multiplicities. Such independent tests may be implemented on the basis of determining absolute (or relative) relationships between cross sections (or yields) for partial reactions by the induced-activity method. In such experiments, the separation of partial reactions relies on identification by characteristic gamma radiation (measurement of the energy spectra of gamma rays deexciting final nuclei), not requiring a determination of photoneutron multiplicities.

Investigations of this type were conducted at the racetrack microtron installed at the Institute of Nuclear Physics (Moscow State University) and characterized by a maximum energy of 67 MeV. A high quality of an electron beam from this new-generation electron accelerator and the use of a high-purity germanium detector for photon detection and of modern software for processing the experimental energy spectra of photons make it possible to perform presently an accurate and reliable comparative investigation of partial reactions involving the production of up to six or seven nucleons.

Table 3 gives data on the energies of lines in the energy spectra of photons deexciting final nuclei and on the respective half-lives of final nuclei formed upon the interaction of incident photons with ^{181}Ta and ^{197}Au nuclei. It can clearly be seen that ^{180,179}Ta and ^{196,195}Au final nuclei can be reliably identified, so that partial reactions leading to the production of one and two nucleons can be reliably separated.

In Table 4, data evaluated within the new approach for the yields of partial photoneutron reactions on ^{181}Ta and ^{197}Au nuclei are contrasted against both the results of the Livermore and Saclay experiments discussed above and performed with quasimonochromatic photons and the results of modern experimental investigations performed by means of the induced-activity method, which are free from the drawbacks of methods for neutron separation by multiplicity.

The data presented in Table 4 for the relative yields of partial reactions indicate the following:

(i) In relation to the results obtained with the aid of the induced-activity method, the Saclay experimental data on the $(\gamma,2n)$ cross section were unjustifiably underestimated (0.24 instead of 0.34 in the case of the ^{181}Ta nucleus and 0.12 instead of 0.17 in the case of the ^{197}Au nucleus), while the Livermore data were unjustifiably overestimated (0.42 and 0.18, respectively).

Table 4. Comparison of experimental results and evaluated data from the application of different methods

Reaction	Ratio of yields of reactions $(\gamma, 2n)$ and (γ, n)				
	Experiment			Model	Evaluation (mutual matching)
	Saclay	Livermore	Moscow (induced activity)		
$^{181}Ta(\gamma, 2n)^{179}Ta$	0.24 [5]	0.42 [22]	0.34 ± 0.07	0.29 [7, 8]	0.37 [2]
$^{197}Au(\gamma, 2n)^{195}Au$	0.12 [21]	0.18 [23]	0.17 ± 0.03	0.15 [13]	0.17 [2]

Table 5. Comparison of basic features [center of gravity $E^{\text{c.g.}}$ and integrated (up to $E^{\text{int}} = 27.4$ MeV) cross section σ^{int}] of evaluated [3] and experimental [5] cross sections for reactions on the ^{159}Tb nucleus

Reaction	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb
	evaluated data		Saclay data [4]	
(γ, xn)	16.84 ± 0.06	3200 ± 30	16.84 ± 0.06	3200 ± 30
(γ, sn)	15.78 ± 0.02	2383 ± 9	15.98 ± 0.07	2570 ± 20
(γ, n)	14.04 ± 0.02	1642 ± 7	14.6 ± 0.08	1950 ± 20
$(\gamma, 2n)$	19.40 ± 0.03	715 ± 5	19.88 ± 0.08	610 ± 10
$(\gamma, 3n)$	26.29 ± 0.04	26 ± 1	26.80 ± 43	16.0*

* The value of 46 MeV mb is indicated up to $E^{\text{int}} = 29.3$ MeV.

(ii) As a consequence, the experimental data on the (γ, n) cross section were unjustifiably overestimated in Saclay and unjustifiably underestimated in Livermore.

(iii) The proposed experimental–theoretical approach makes it possible to deduce data on the $(\gamma, 2n)$ cross section that comply well with data obtained by the induced-activity method (0.29 and 0.34 in the case of the ^{181}Ta nucleus and 0.15 and 0.17 in the case of the ^{197}Au nucleus); therefore, this approach yields reliable and authentic data on cross sections for partial reactions.

It is noteworthy that the mutual matching of the Saclay and Livermore data in [2] also led to intermediate and, hence, more reliable results (0.37 and 0.34 in the case of the ^{181}Ta nucleus and 0.17 and 0.17 in the case of the ^{197}Au nucleus).

4. PHYSICAL IMPLICATIONS OF THE EVALUATION OF RELIABLE AND AUTHENTIC CROSS SECTIONS FOR PARTIAL REACTIONS

Particular attention should be paid to the circumstance that the cross sections evaluated for partial reactions under conditions free from the drawbacks of experimental methods for photoneutron separation in multiplicity differ (see Table 5) quite sizably from the experimental cross sections. These deviations lead to serious physical implications.

By way of example, we indicate that, in relation to the data obtained in Saclay, the integrated cross section that was evaluated for the reaction $^{159}Tb(\gamma, 2n)$ increased by 15% (715 instead of 610), while the integrated cross section for the reaction $^{159}Tb(\gamma, n)$ decreased by 19% (1642 instead of 1950). Therefore, the cross-section ratio $\sigma^{\text{int}}(\gamma, 2n)/\sigma^{\text{int}}(\gamma, n)$, which is of great interest from the point of view of evaluating a number of fundamental physics effects—for example, the relationship between direct and statistical processes in GDR decay—increased in the case of the ^{159}Tb nucleus by 27% (715/1642 instead of 610/1950). Naturally, the increase in the contribution of the $(\gamma, 2n)$ cross section entails a sizable (nearly by 9%—2383 instead of 2570) decrease in the integrated cross section for the total photoneutron reaction $(\gamma, sn) = (\gamma, n) + (\gamma, 2n) + (\gamma, 3n) + \ldots$, the latter making a dominant contribution [the contributions of photoproton reactions are added to the (γ, sn) cross section] to the integrated cross section for total photoabsorption.

In relation to the Livermore data, the integrated cross section that was evaluated for the $(\gamma, 2n)$ channel decreased by 22% (715 instead of 870), while its counterpart for the (γ, n) channel increased by

18% (1642 instead of 1390). Accordingly, the cross-section ratio $\sigma^{\rm int}(\gamma,2n)/\sigma^{\rm int}(\gamma,n)$ decreased by 30% (715/1642 instead of 870/1390). Concurrently, the integrated (γ,sn) cross section increased by 4% (2383 instead of 2300).

5. CONCLUSIONS

The following conclusions can be drawn from the results of the present investigations.

It has been found that the relationships between the cross sections determined in different laboratories for (γ,n) and $(\gamma,2n)$ partial photoneutron reactions on many nuclei differ substantially from the relationships between the cross sections $\sigma(\gamma,xn)$ for the total yield of neutrons. These distinctions have a pronounced systematic character: data on the transitional multiplicity function $F_2^{\rm expt} = \sigma^{\rm expt}(\gamma,2n)/\sigma^{\rm expt}(\gamma,xn)$ indicate that, in Livermore (Saclay), the cross sections were obviously overestimated (underestimated) for the $(\gamma,2n)$ channel and underestimated (overestimated) for the (γ,n) channel.

From our analysis of the energy dependences of the transitional photoneutron-multiplicity function $F_2^{\rm expt}(E)$, it has been found that the $(\gamma,2n)$ cross sections obtained in Livermore are overestimated in nearly all of the energy regions studied there, this overestimation being so strong in some regions that the values of $F_2^{\rm expt}(E)$ exceeds the physically admissible (by definition) limit of 0.5. This unjustifiable overestimation of the $(\gamma,2n)$ cross section naturally leads to the respective underestimation of the (γ,n) cross section, with the result that it takes, in many cases physically inauthentic (frequently negative) values. Thus, we can state with confidence that the experimental method used to discriminate between neutrons of multiplicity 1 and 2 was erroneous. The presence of physically inauthentic values of the function $F_2^{\rm expt}(E)$ (about 1.5 to 2.0) in some cases—for example, in the case of the ^{159}Tb nucleus—in the energy region of $E > B3n$ indicates unambiguously that there were errors in the experimental separation of neutrons with multiplicities of 2 and 3 as well.

Our analysis has also shown that the experimental cross sections determined in Livermore and Saclay for (γ,n), $(\gamma,2n)$,and $(\gamma,3n)$ partial reactions, as well as for the (γ,sn) total reaction, are neither reliable nor authentic because the separation of photoneutrons between these partial reactions was incorrect. In all probability, the flaws in the experimental methods for sorting photoneutrons in multiplicity stem from a violation of the assumption that the relation between the mean energy of neutrons and their multiplicity is unambiguous.

Within the new experimental—theoretical approach [3, 12, 13, 19, 23] and on the basis of the experimental cross sections $\sigma(\gamma,xn)$ for the total neutron yield and information obtained for the competition between different channels of GDR decay ($F_1^{\rm theor}$, $F_2^{\rm theor}$, and $F_3^{\rm theor}$) within the modern model of photonuclear reactions [7, 8], we have evaluated the cross sections for (γ,n), $(\gamma,2n)$, and $(\gamma,3n)$ partial reactions and the cross section $\sigma(\gamma,sn)$ for the total photoneutron reaction on ^{90}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, and ^{197}Au nuclei. The results of this evaluation are free from the drawbacks of the experimental methods for neutron separation in multiplicity and are more reliable than experimental data.

We have shown that the evaluated cross sections for partial and total photoneutron reactions differ substantially both from the Livermore and from the Saclay experimental data obtained under conditions of incorrectly sorting neutrons in multiplicity. This calls for revisiting many physics effects whose role was evaluated by using the absolute values of the cross sections for partial photoneutron reactions and/or their ratios. Such effects include, first of all, the relationship between direct and statistical processes in the excitation and decay of highly excited nuclear states, the relationship between the components of the configuration and isospin splitting of GDR, and the exhaustion of the dipole sum rule [in the case where one approximates the total-photoabsorption cross section $\sigma(\gamma,abs)$ by the cross section $\sigma(\gamma,sn)$ for the total photoneutron reaction].

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