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NUCLEI
Experiment

Data on Photoneutron Reactions from Various Experiments for ^{133}Cs, ^{138}Ba and ^{209}Bi Nuclei

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Abstract—Basic methods for determining cross sections for photoneutron partial reactions are examined. They are obtained directly in experiments with quasimonoeneregetic annihilation photons or from the cross section for the $(\gamma, xn) = (\gamma, 1n) + 2(\gamma, 2n) + 3(\gamma, 3n) + \ldots$ neutron-yield reaction in experiments with bremsstrahlung photons by introducing corrections based on statistical nuclear-reaction theory. The difference in the conditions of these experiments, which leads to discrepancies between their results because of sizable systematic errors, is analyzed. Physical criteria are used to study the reliability of data on the photodisintegration of ^{133}Cs, ^{138}Ba, and ^{209}Bi nuclei. The cross sections for partial and total reactions satisfying the reliability criteria are evaluated within the experimental—theoretical method ($\sigma^{\rm eval}(\gamma, in) = F_i^{\rm theor} \times \sigma^{\rm expt}(\gamma, xn)$) on the basis of the experimental cross sections $\sigma^{\rm expt}(\gamma, xn)$ and the results of the calculations within the combined model of photonuclear reactions.

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1. INTRODUCTION

Experimental data on cross sections for photonuclear reactions are broadly needed in various fields of science and technologies—from fundamental nuclear physics to various applications. Along with data on nuclear reactions induced by neutrons, charged particles, and heavy ions, such data are included in the EXFOR international database of nuclear reactions [1–3]. This database developed and maintained by the IAEA Nuclear Data Centers Network [4] and is well known to users [5]. The well-developed search systems of various versions of this database (Photonuclear Experiment Data Center, Institute of Nuclear Physics, Moscow State University, Russia; IAEA Nuclear Data Section, Austria; and National Nuclear Data Center, United States of America) permit immediate and efficient data processing. In many cases, a comparison of the results of different experiments reveals previously unknown systematics of these results and makes it possible to find systematic discrepancies between them, to perform an analysis of reasons behind them, and develop methods for removing them. In the region of photonuclear reactions, such investigations are of great importance since the conditions under which different experiments with gamma rays are performed are strongly different. This is due primarily to the absence of monoenergetic photons, with the result that experimentalists have to use various methods for producing quasimonoenergetic photons whose effective spectrum could be interpreted as that which is close to a monoenergetic spectrum. A significant difference in the methods for obtaining data is the reason for substantial systematic errors that exceed greatly statistical errors and which manifest themselves in severalfold distinctions between reaction cross sections determined in different experiments. In this situation, the use of available data is possible only with using for objective reliability criteria and with the aid of methods for data evaluation that satisfy these criteria.

The objective of the present study is to analyze experimental data on cross sections for partial photoneutron reactions on ^{133}Cs, ^{138}Ba, and ^{209}Bi nuclei, for which the aforementioned effects of the influence of substantial systematic errors in experiments on the reliability of their results manifest themselves quite clearly and to evaluating new reliable cross sections for partial photoneutron reactions.

2. SYSTEMATIC ERRORS AND DISCREPANCIES BETWEEN THE RESULTS OF PHOTONUCLEAR EXPERIMENTS

The majority of cross sections for photonuclear reactions were obtained [6–9] in experiments of two types that were performed in bremsstrahlung-photon beams and in beams of quasimonoenergetic photons

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produced in the in-flight annihilation of relativistic positrons.

The quantity that one measures directly in experiments with bremsstrahlung photons is not the cross section $\sigma(E)$ sought for the reaction under study with an energy threshold E_{thr} but the reaction yield

$$Y(E_m) = \alpha \int_{E_{\text{thr}}}^{E_m} W(E_m, E)\,\sigma(E)\,dE, \qquad (1)$$

which is the folding of the sought reaction cross sections $\sigma(E)$ with the continuous photon spectrum $W(E_m, E)$ bounded from above at an endpoint energy E_m. The yield is measured at several values of the endpoint energy E_m, whereupon the respective set of integral equations (1) is solved with respect to $\sigma(E)$ by means of one of the methods developed in such a way that the effective spectrum could be interpreted as that which is close to a quasimonoenergetic spectrum (that is, has a shape close to the shape of a rather narrow Gaussian spectrum) [10].

Since the determination of reaction cross sections in experiments with bremsstrahlung photons is performed by means of a procedure for solving the inverse problem specified by Eqs. (1), a method for determining cross sections "directly" in experiments was proposed as an alternative. This method is based on obtaining quasimonoenergetic photons of energy $E_\gamma = E_{e^+} + 0.511$ MeV that are produced in the annihilation of fast positrons in a thin target from a small-Z material. Since the positron-annihilation process is accompanied by the emission of bremsstrahlung photons, information about the reaction cross section $\sigma(E)$ is extracted in three steps in experiments with photons from the annihilation process [8, 9]: (i) measurement of the yield $Y_{e^+}(E_m)$ (1) for the reaction under study induced by annihilation and bremsstrahlung photons, (ii) measurement of the yield $Y_{e^-}(E_m)$ (1) for the reaction induced by bremsstrahlung from electrons, and (iii) derivation (after respective normalization and under the assumption that the bremsstrahlung spectra generated by positrons and electrons are identical) of the difference of the experimental yields $Y_{e^+}(E_m)$ and $Y_{e^-}(E_m)$ and an interpretation of this difference as the sought reaction cross section

$$Y_{e^+}(E_m) - Y_{e^-}(E_m) = Y(E_m) \approx \sigma(E_m). \qquad (2)$$

There are distinct systematic discrepancies between the results of experiments with bremsstrahlung and annihilation photons. First of all, they are due to a significant difference between the methods for deducing information about the cross sections for the reactions under study and about the effective spectra of photons inducing these reactions: as a rule, reaction cross sections from experiments with annihilation photons are substantially smoother in shape and somewhat smaller in magnitude than the respective reaction cross sections from experiments with bremsstrahlung photons. On average, the difference in absolute value between the cross sections obtained for the yield reaction (3) in different experiments is about 12% [11, 12]. The discrepancies between data obtained at different laboratories, the reasons behind these discrepancies, and methods for taking them into account and for overcoming them were considered in sufficient detail elsewhere [11–13].

The procedure used in the majority of experiments devoted to photonuclear reactions relied on directly detecting photoneutrons, which are products of these reactions. In this method, the experimental results are plagued by additional systematic uncertainties associated with determining the photoneutron multiplicity.

A direct detection of neutrons in experiments with bremsstrahlung photons may give only the cross section for the neutron-yield reaction

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

which includes contributions from the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions. They are of importance from the point of view of studying the formation and decay of giant-dipole-resonance (GDR) states, mechanisms of photon interaction with nuclei, and various special features of electromagnetic interactions of nuclei; in addition, they form the cross section for the total photoneutron reaction

$$(\gamma, sn) = (\gamma, 1n) + (\gamma, 2n) + (\gamma, 3n) + \ldots. \qquad (4)$$

For medium-mass and heavy nuclei, the latter cross section is directly related to the photoabsorption cross section.

Since the energy thresholds $B1n$, $B2n$, $B3n$, ... for partial photoneutron reactions are rather close to one another, several of these reactions prove to be possible simultaneously over broad regions of photon energies. Within the direct-detection method, a single neutron from the $(\gamma, 1n)$ reaction is detected one time, either neutron from the $(\gamma, 2n)$ reaction is detected two times, each neutron from the $(\gamma, 3n)$ reaction is detected three times, and so on. As a result, each partial reaction proves to be represented in the summed cross section $\sigma(\gamma, xn)$ for the neutron-yield reaction (3) with the respective neutron-multiplicity factor. Thus, we see that, in order to break down the (γ, xn) neutron-yield reaction into partial reactions, it is necessary to know the multiplicity with which the detected neutron was produced in this reaction. Herein lies the well-known problem of photoneutron multiplicity sorting.

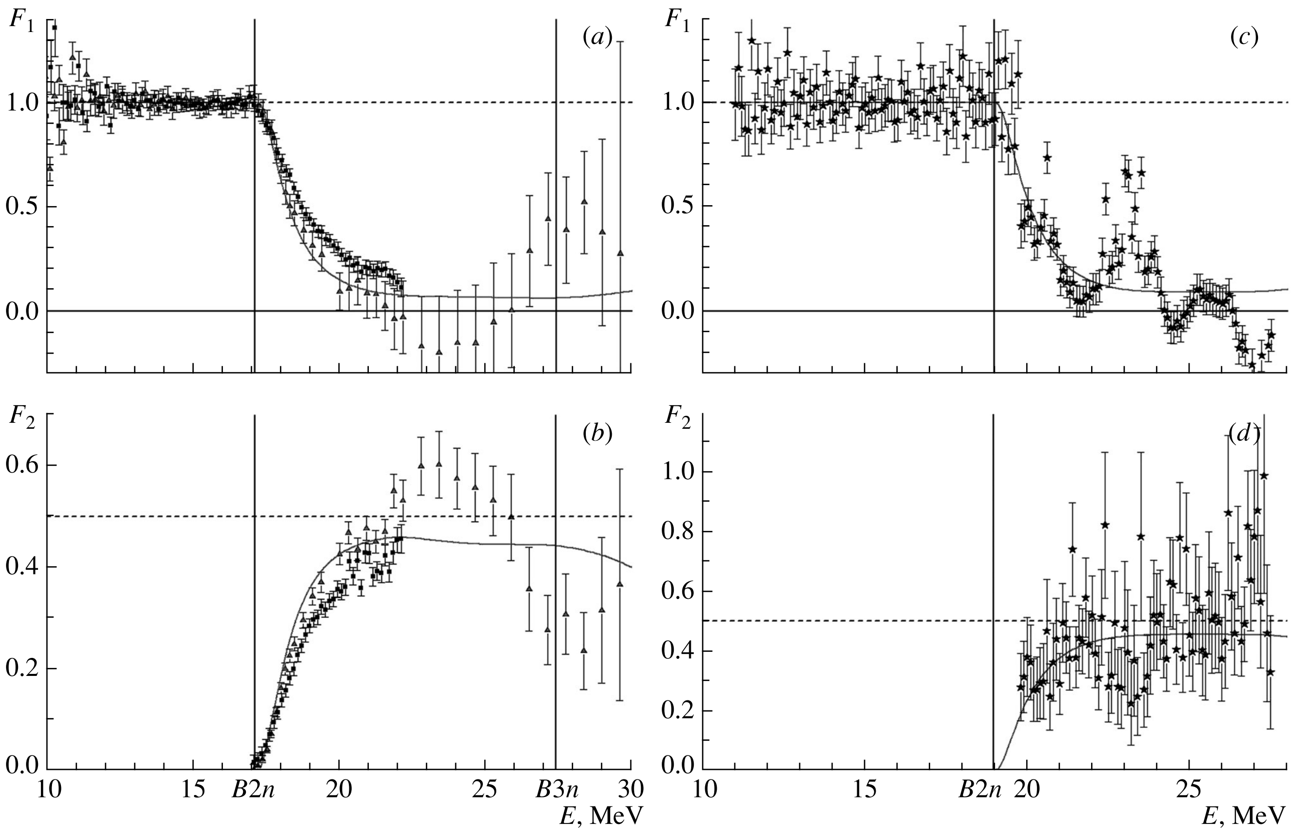

Fig. 1. Comparison of the energy dependences of the functions F_1^{expt} and F_2^{expt} obtained on the basis of the results of the experiments with annihilation photons for the (a, b) ^{116}Sn nucleus and the experiment with bremsstrahlung photons for the (c, d) ^{112}Sn nucleus with the function F_i^{theor} calculated on the basis of the model proposed in [20–22] (curve). The points on display represent the results obtained in (triangles) Livermore [18] and (squares) Saclay [19] and at (stars) Institute of Nuclear Physics, Moscow State University [23].

The procedure used in experiments with bremsstrahlung photons to determine cross sections for partial reactions was described in detail earlier in [11–13]. First, the cross section for the neutron-yield reaction (3) is determined, whereupon corrections are introduced in it according to statistical nuclear-reaction theory, This makes it possible to obtain the cross section for the total photoneutron reaction (4) and to evaluate thereupon cross sections for partial reactions.

In experiments with annihilation photons, their spectrum is quasimonoenergetic, which permits a direct determination of partial-reaction cross sections by the method of photoneutron multiplicity sorting. On the basis of assumptions on a direct relation between the multiplicity of neutrons from the different reactions and their kinetic energy, one determines $\sigma(\gamma, 1n)$, $\sigma(\gamma, 2n)$, and $\sigma(\gamma, 3n)$ and then obtains from them, via the respective summation, both $\sigma(\gamma, sn)$ and $\sigma(\gamma, xn)$, which are determined by expressions (3) and (4).

The overwhelming majority of respective data were obtained at the Lawrence Livermore National Laboratory (USA) and at the Saclay Center of Nuclear Research (France). In both laboratories, the cross sections for partial reactions were determined by the same method of photoneutron multiplicity sorting via experimentally measuring their kinetic energies, but specific implementations of the method were different. Because of this, there are significant (up to 100%) systematic discrepancies between experimental data for 19 nuclei studied in the two laboratories [12, 13]. In summary, the $(\gamma, 1n)$ cross sections have greater values in Saclay, while the $(\gamma, 2n)$ cross sections have greater values in Livermore.

In [14–17], experimental data on partial-reaction cross sections for a large number of nuclei from experiments performed in annihilation-photon beams and processed by the method of photoneutron multiplicity sorting were analyzed by using specially proposed physical criteria of reliability of data. For such criteria, use was made of the neutron-multiplicity transition functions

$$F_i = \sigma(\gamma, in)/\sigma(\gamma, xn) \quad (5)$$

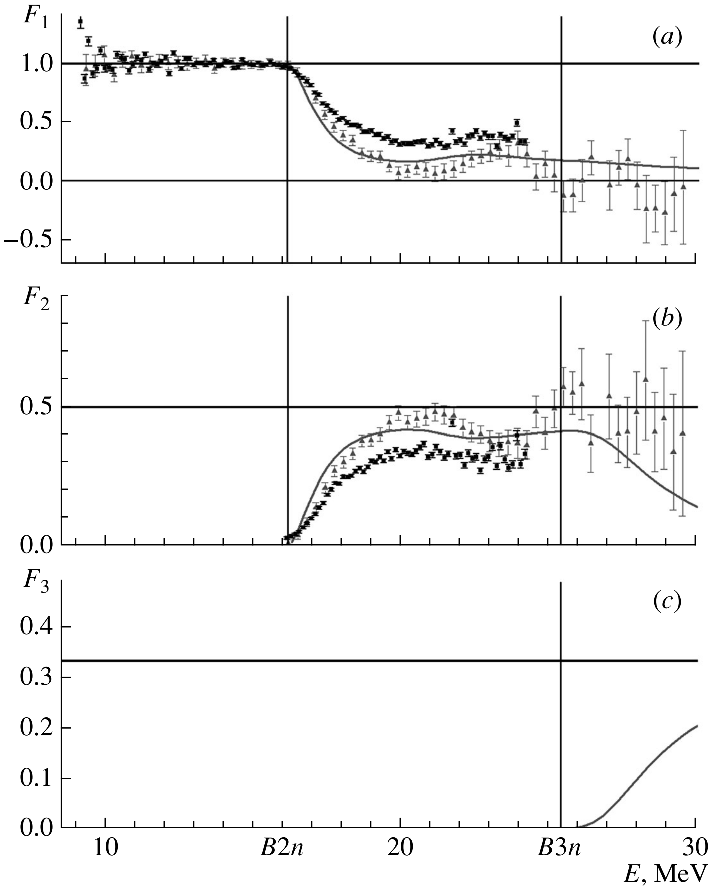

Fig. 2. Comparison of the functions F_i^{theor} calculated within the model proposed in [20–22] (curves) for $i = (a)$ 1, (b) 2, and (c) 3 with the functions F_i^{expt} obtained for the isotope ^{133}Cs on the basis of experimental data. The points on display represent the results obtained in (squares) Saclay [19] and (triangles) Livermore [24]. In view of the absence of experimental data, only F_3^{theor} is presented in Fig. 2*c*.

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

which make it possible to find out reliably whether systematic errors are present in experimental data. The most pronounced manifestations of such errors are the following: (i) In many regions of photon energies, the values of F_i (5) exceed their limits that are physically admissible by definition of these functions and which are $1.00, 0.50, 0.33, \ldots$ for, respectively, $i = 1, 2, 3, \ldots$. (ii) For some partial reactions, predominantly for $(\gamma, 1n)$, the cross sections take physically forbidden negative values.

The analysis performed in [14–17] revealed that significant systematic errors found in the cross sections for $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions were due to shortcomings of the photoneutron-multiplicity-sorting methods used in the experiments under discussion and based on the results obtained by measuring the kinetic energies of photoneutrons. Figures 1*a* and 1*b* give rather typical examples of a comparison of the energy dependences of the functions F_1 and F_2 obtained on the basis of Livermore [18] and Saclay [19] experimental data for the ^{116}Sn nucleus with the results of the calculations based on the model proposed in [20–22]. One can see that, from the point of view of reliability, the Saclay data exhibit sizable deviations from the results of the theoretical calculations. At the same time, it is obvious that, in the energy range between about 21.5 and 26.0 MeV, the Livermore data are unreliable, since $F_1 < 0$ and $F_2 > 0.50$. It is worth noting that the two signatures of unreliability of the data obviously correlate with each other. As was shown in [14–17], this was due to an unjustifiable transfer of a significant fraction of neutrons of multiplicity one from the $(\gamma, 1n)$ cross section to the cross section for the $(\gamma, 2n)$ reaction, which should be formed by neutrons of multiplicity two. As a result, the former cross section unjustifiably decreases to the appearance in it (and, accordingly, in F_1) negative values forbidden physically, while the latter increases, also unjustifiably, to values at which the function

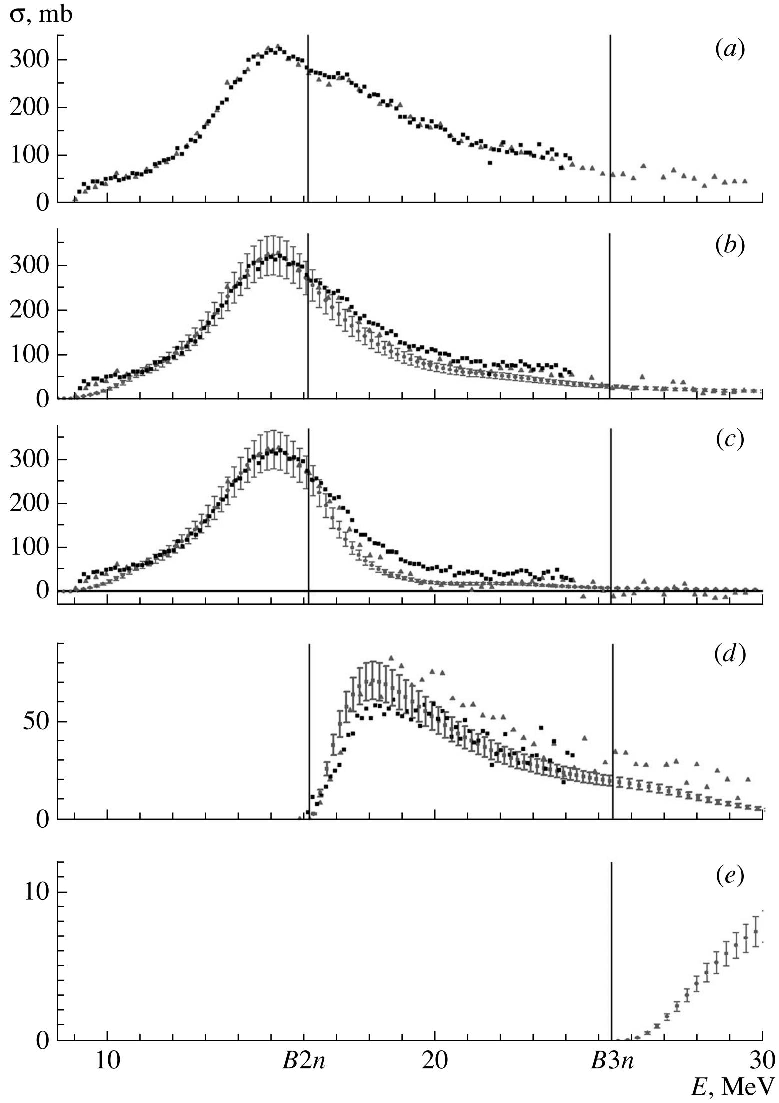

Fig. 3. Comparison of cross sections (circles) estimated for the total photoneutron reactions, (*a*) $\sigma(\gamma, xn)$ and (*b*) $\sigma(\gamma, sn)$, and for partial photoneutron reactions, (*c*) $\sigma(\gamma, 1n)$, (*d*) $\sigma(\gamma, 2n)$, and (*e*) $\sigma(\gamma, 3n)$ on the ^{133}Cs nucleus with experimental data obtained in (squares) Saclay [19] and (triangles) Livermore [24].

F_2 has physically unreliable values in excess of 0.50. It is also noteworthy that the function F_2 decreases systematically starting from an energy of about 23 MeV, which is well below the threshold $B3n$ for the $(\gamma, 3n)$ reaction. This is also indicative of an unreliable sorting of neutrons whose multiplicities are two and three.

Figures 1*c* and 1*d* show the functions F_1 and F_2 determined for the cross sections measured for photoneutron reactions on ^{112}Sn nuclei in the experiment with bremsstrahlung photons [23]. As was indicated above, the cross sections for partial reactions can be determined in such an experiment only by measuring the cross section for the neutron-yield reaction (3) and by introducing in it corrections based on statistical nuclear-reaction theory. Such data are relatively scanty, but, even to them, one can apply the physical reliability criteria introduced above. Figure 1 shows that, similarly to what we have in the example of the ^{116}Sn nucleus in Figs. 1*a* and 1*b*, the data in the energy range between about 24 and 25 MeV and at higher energies of about 26 MeV are questionable from the point of view of reliability of the attribution of neutrons to channels of multiplicity one and two. This is likely due to an insufficiently accurate description of special features of decay channels for highly excited GDR states within a simple statistical model. This is also confirmed by a more successful description of cross sections for total photoneutron reactions within the combined model proposed in [20–22], where basic points of statistical theory are supplemented with tak-

Table 1. Integrated values of the evaluated cross sections for the total and partial photoneutron reactions on ^{133}Cs nuclei along with Saclay [19] and Livermore [24] experimental data

Reaction	$\sigma^{\rm int}$, MeV mb		
	evaluated data	experimental data	
		Livermore [24]	Saclay [19]
$E^{\rm int} = B2n = 16.2$ MeV			
$(\gamma, xn)^*$	1110.8 ± 36.3	$1140.5 \pm 9.6^*$	1137.3 ± 25.6
(γ, sn)	1107.8 ± 36.2	1139.6 ± 9.6	1136.3 ± 25.5
$(\gamma, 1n)$	1110.1 ± 36.3	1137.4 ± 9.7	1135.3 ± 25.5
$E^{\rm int} = B3n = 25.4$ MeV			
$(\gamma, xn)^*$	2294.8 ± 47.7	$2543.8 \pm 17.3^*$	2598.0 ± 61.1
(γ, sn)	1919.0 ± 42.9	2089.8 ± 36.9	2229.4 ± 50.6
$(\gamma, 1n)$	1543.9 ± 39.8	1630.7 ± 19.2	1860.9 ± 50.6
$(\gamma, 2n)$	375.1 ± 9.5	452.6 ± 8.8	367.9 ± 3.4
$E^{\rm int} = 29.5$ MeV			
$(\gamma, xn)^*$	2463.0 ± 48.2	$2453.0 \pm 48.2^*$	
(γ, sn)	2009.5 ± 43.0	2193.4 ± 20.4	
$(\gamma, 1n)$	1568.2 ± 39.8	1625.7 ± 28.1	
$(\gamma, 2n)$	429.2 ± 9.8	556.4 ± 17.0	
$(\gamma, 3n)$	11.9 ± 0.7		

* Livermore experimental data reported in [24] and used as inputs in our evaluations.

Table 2. Integrated values of the evaluated cross sections for total and partial photoneutron reactions on the isotope ^{138}Ba along with experimental data from [25]

Reaction	$\sigma^{\rm int}$, MeV mb	
	evaluated data	experimental data [25]
$E^{\rm int} = B2n = 15.5$ MeV		
$(\gamma, xn)^*$	936.1 ± 6.6	$936.1 \pm 6.6^*$
(γ, sn)	957.4 ± 28.9	935.7 ± 6.6
$(\gamma, 1n)$	956.3 ± 28.9	935.1 ± 6.6
$E^{\rm int} = B3n = 24.6$ MeV		
$(\gamma, xn)^*$	2433.2 ± 14.3	$2433.2 \pm 14.3^*$
(γ, sn)	1940.1 ± 43.5	1998.9 ± 12.6
$(\gamma, 1n)$	1442.7 ± 33.7	1565.1 ± 15.7
$(\gamma, 2n)$	492.1 ± 10.9	433.9 ± 7.3
$(\gamma, 3n)$		
$E^{\rm int} = 27.1$ MeV		
$(\gamma, xn)^*$	2538.4 ± 17.6	$2538.4 \pm 17.6^*$
(γ, sn)	2036.1 ± 44.1	2041.6 ± 14.5
$(\gamma, 1n)$	1459.8 ± 33.7	1548.3 ± 18.7
$(\gamma, 2n)$	564.0 ± 11.4	490.4 ± 9.7
$(\gamma, 3n)$	4.0 ± 0.3	7.1 ± 3.9

* Experimental data reported in [25] and used as inputs in our evaluations.

ing into account effects of nuclear deformations and isospin GDR splitting.

The analysis of experimental data on cross sections for partial photoneutron reactions from various experiments that was performed in [14–17] by using physical reliability criteria indicates that, in many cases, the procedure on neutron multiplicity sorting was performed with substantial systematic errors, with the result that such data are unreliable. The systematic errors of neutron multiplicity sorting, which was used in obtaining almost all of the data on cross sections on partial photoneutron reactions can be avoided in experiments performed, for example, by the activation method or in experiments where product neutrons are detected in the coincidence mode. Since the implementation of such experiments is nontrivial and since they are not always possible, the problem of developing methods for evaluating data on cross sections describing partial photoneutron reactions and satisfying the above reliability criteria becomes highly important.

3. EXPERIMENTAL–THEORETICAL METHOD FOR EVALUATING PARTIAL-PHOTONEUTRON-REACTION CROSS SECTIONS CONSISTENT WITH PHYSICAL RELIABILITY CRITERIA

From the foregoing, it is clear that cross sections for partial photoneutron reactions should be evaluated by a method that is free both from the shortcomings of the experimental methods of neutron multiplicity sorting and from the limitations of statistical theory in describing the competition between channels of the decay of GDR states. Such a method was proposed in [14, 15] on the basis of combining experimental data on the cross sections for the neutron-yield reaction (3) alone, which are independent of the problems of neutrons multiplicity sorting, with the relations of the combined model of photonuclear reactions [20–22]. The preequilibrium exciton model employs nuclear-level densities calculated on the basis of the Fermi gas model, takes into account both nuclear deformations and isospin GDR splitting, and makes it possible to describe cross sections for the

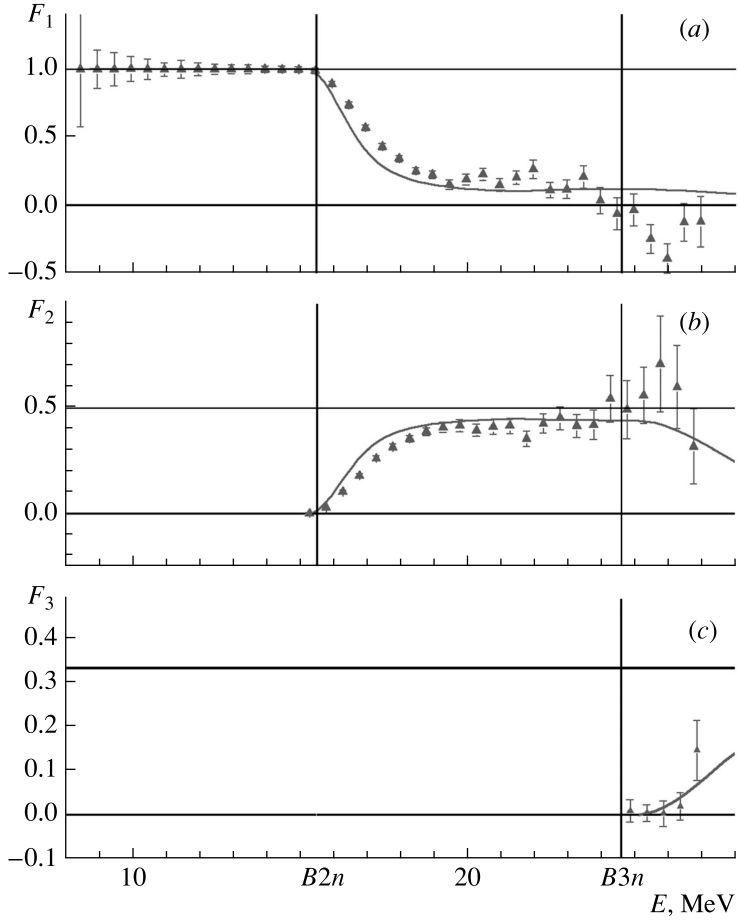

Fig. 4. Comparison for $i = (a)\,1, (b)\,2$, and $(c)\,3$ of the theoretical functions F_i^{theor} calculated on the basis of the model developed in [20–22] (curve) with the functions F_i^{expt} obtained for the isotope ^{138}Ba on the basis of experimental data (triangles represent Livermore data from [25]).

neutron-yield reaction in the region of medium-mass and heavy nuclei. Within the proposed experimental–theoretical method for evaluating cross sections for partial photoneutron reactions, the relationships between the evaluated cross sections $\sigma^{\text{eval}}(\gamma, in)$ are established in accordance with the fundamentals of the model used (F_i^{theor}); that is,

$$\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}} \times \sigma^{\text{expt}}(\gamma, xn). \qquad (6)$$

Their respective sum $\sigma^{\text{eval}}(\gamma, xn)$ coincides with $\sigma^{\text{expt}}(\gamma, xn)$. For a large number of nuclei, this method was used to evaluate the cross sections obtained for the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions in beams of quasimonoenergetic annihilation photons by using the method of of photoneutron multiplicity sorting. For several tin isotopes, the estimations in question were performed [14] on the basis of data obtained not only in experiments with annihilation photons by means of photoneutron multiplicity sorting but also in experiments with bremsstrahlung photons by means of the introduction of corrections in the cross section for the neutron-yield reaction (3) in accordance with statistical nuclear-reaction theory.

The presence of the substantial systematic errors that are being discussed here and which are caused by the misinterpretation of multiplicities of detected neutrons was found in all cases.

4. EVALUATION OF CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS

4.1. Data on the Isotope ^{133}Cs

The energy dependences obtained for the neutron-multiplicity transition functions $F_{1,2}^{\text{expt}}$ (5) on the basis of Saclay [19] and Livermore [24] experimental data for the ^{133}Cs nucleus are compared in Fig. 2 with the function F_i^{theor} calculated on the basis of combined model of photonuclear reactions [20–22].

One can see that, in the energy region extending to $B3n = 25.4$ MeV, both the Saclay [19] and the

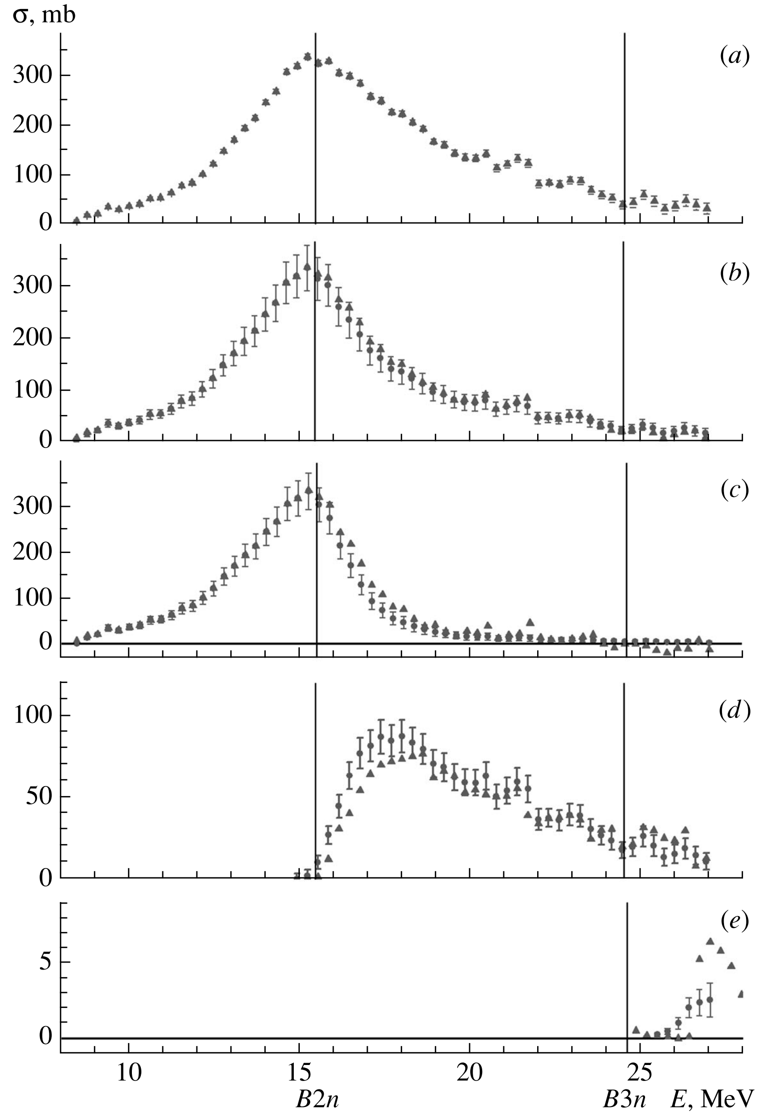

Fig. 5. Evaluated (closed circles) cross sections for the total photoneutron reactions, (*a*) $\sigma(\gamma, xn)$ and (*b*) $\sigma(\gamma, sn)$, and the partial photoneutron reactions, (*c*) $\sigma(\gamma, 1n)$, (*d*) $\sigma(\gamma, 2n)$, and (*e*) $\sigma(\gamma, 3n)$ on ^{138}Ba nuclei (the triangles represent Livermore experimental data from [25]).

Livermore [24] experimental data are compatible with the reliability criteria introduced in (5). However, the results of the two experiments deviate substantially both from each other and from the evaluated data, the directions of these deviations from the estimates being opposite to each other. At all energies, the $F_{1,2}^{\text{expt}}$ values obtained on the basis of Saclay data do not exceed the limiting values of the physical reliability criteria. In two energy regions (between about 25 and 26 MeV and between 28 and 30 MeV), the F_1^{expt} values based on Livermore data do not satisfy the reliability criteria (although the errors in the F_1^{expt} values are quite large, these values are systematically negative). In the region of energies above about 25 MeV, the values of F_2^{expt} deviate substantially from F_2^{theor}, and some of them prove to be greater than 0.50. It is noteworthy that the changes in the dependences of F_1^{expt} and F_2^{expt} correlate clearly with each other—an increase in one of them corresponds to a decrease in the other, and vice versa.

In Fig. 3, the cross sections estimated for the $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, and (γ, sn) reactions on the isotope ^{133}Cs within the experimental–theoretical approach [see Eq. (3)] are presented along with the cross section determined experimentally [24] for the (γ, xn) reaction in (3) and used as input information for our evaluation procedure according to Eq. (6) and along with data from [19]. Table 1 gives data on the evaluated integrated cross sections for partial

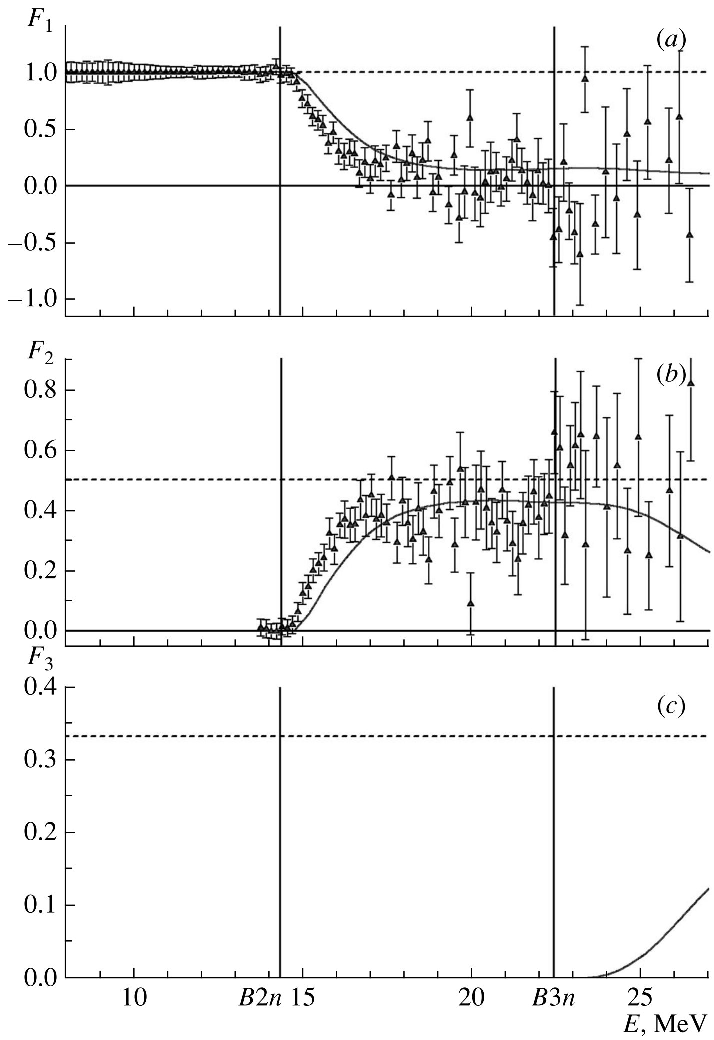

Fig. 6. As in Fig. 4, but for the isotope ^{209}Bi (the triangles represent Livermore experimental data from [26]). For want of experimental data, only the function $F_3^{\rm theor}$ is given in Fig. 6*c*.

photoneutron reactions on ^{133}Cs nuclei. The following preliminary comment is in order. The integrated cross section that was determined for the $(\gamma, 1n)$ reaction on the basis of Livermore data and which was calculated up to the energy of 25.4 MeV (1630.7 MeV mb) proves to be larger than its counterpart calculated up to the energy of 29.5 MeV (1625.7 MeV mb). This stems directly from the fact that, in the energy range between about 25.4 and 29.5 MeV, the cross section in question takes physically forbidden negative values (see Fig. 4*c*). In view of this, it is reasonable to discuss the relationship between the evaluated and experimental cross sections for energies not exceeding 25.4 MeV.

The data in Table 1 indicate that the cross sections evaluated for both partial reactions differ substantially from the respective experimental cross sections. In contrast to the situation around a large number of nuclei studied earlier (^{63,65}Cu, ^{80}Se, $^{91-96}$Zr, ^{115}In, $^{112-124}$Sn, ^{159}Tb, ^{181}Ta, $^{186-192}$Os, ^{197}Au, and ^{207,208}Pb) for which the cross sections for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions deviated from the evaluated cross sections in opposite directions, the cross sections evaluated for the ^{133}Cs nucleus are smaller than their experimental counterparts for both partial reactions. For the $(\gamma, 1n)$ reaction, the discrepancy is 7% ($\sigma^{\rm int} = 1543.9$ and 1630.7 MeV mb), while, for the $(\gamma, 2n)$ reaction, it is 21% (375.1 versus 452.6 MeV mb). The discrepancies between the evaluated and experimental integrated cross sections that were calculated for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions up to the energy of 29.5 MeV prove to be 4 and 30%, respectively.

The evaluated cross section for the $(\gamma, 3n)$ reaction is presented in Table 1 and in Fig. 3*e*, but there are no experimental data on this reaction. The experimental–theoretical method makes it possible

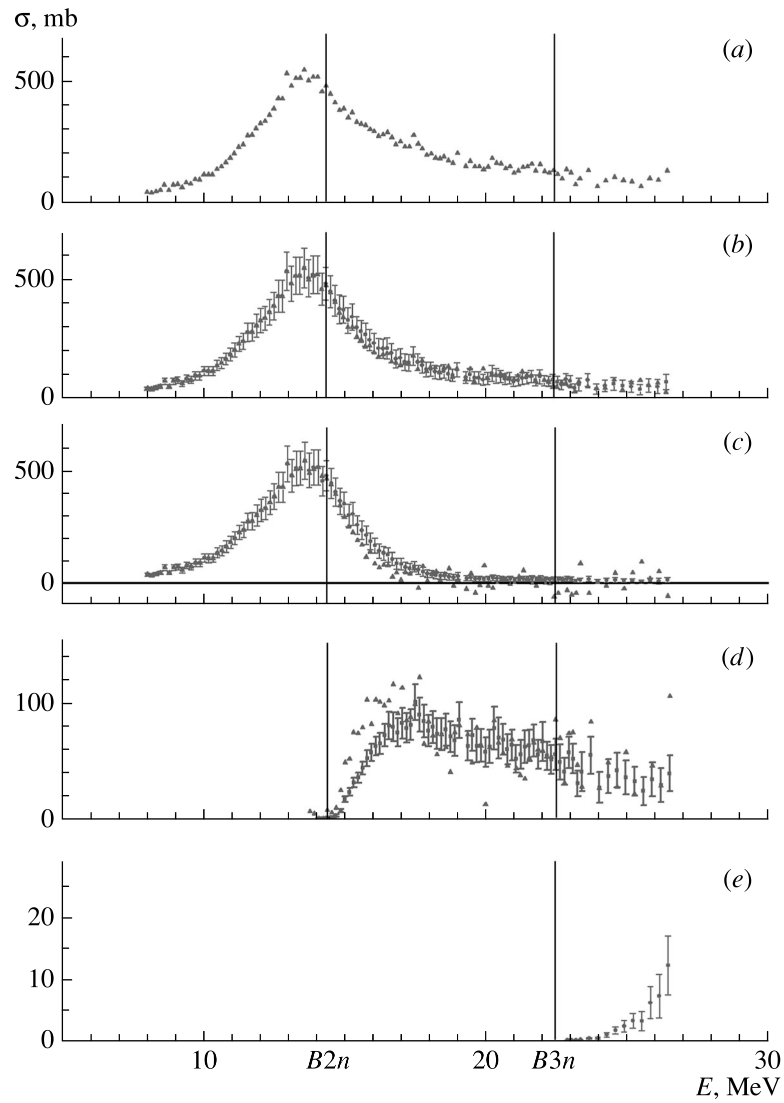

Fig. 7. Comparison of (circles) evaluated and (triangles representing Livermore data from [25]) experimental cross sections for the total and partial photoneutron reactions on ^{209}Bi nuclei: $(a)\,\sigma(\gamma, xn)$, $(b)\,\sigma(\gamma, sn)$, $(c)\,\sigma(\gamma, 1n)$, $(d)\,\sigma(\gamma, 2n)$, and $(e)\,\sigma(\gamma, 3n)$.

to evaluate, on the basis of the experimental cross section for the neutron-yield reaction in (3), cross sections describing various multineutron reactions and satisfying the reliability criteria. This is important since, for the ^{133}Cs nucleus, the cross section for the $(\gamma, 3n)$ reaction was not measured experimentally because of serious problems encountered in determining the neutron multiplicity at energies higher than $B3n = 25.4$ MeV. Figure 2 shows that, in this energy region, experimental data from [19] on the partial photoneutron reactions that were studied deviate substantially from evaluated data and simultaneously do not satisfy the above reliability criteria since $F_1^{\rm expt} < 0$ and $F_2^{\rm expt} > 0.50$.

4.2. Data on the Isotope ^{138}Ba

Only data obtained in Livermore [25] have been published thus far for the ^{138}Ba nucleus. In Fig. 4, the energy dependences obtained on the basis of these data for the neutron-multiplicity transition functions $F_{1,2,3}^{\rm expt}$ (5) are compared with the function $F_i^{\rm theor}$ calculated on the basis of the model proposed in [20–22]. One can see that, in just the same way as in the case of data for the ^{133}Cs nucleus, the values obtained for these functions from Livermore data do not satisfy the reliability criteria at energies higher than some 24.5 MeV, showing a clear-cut correlation between negative values of the function F_1 and F_2 values that exceed 0.50.

Table 3. Integrated values of the evaluated cross sections, σ^{int}, for the total and partial photoneutron reactions on the isotope ^{209}Bi along with experimental data [26]

Reaction	σ^{int}, MeV mb	
	evaluated data	experimental data [26]
$E^{\text{int}} = B2n = 14.4$ MeV		
$(\gamma, xn)^*$	1818.4 ± 61.9	$1795.1 \pm 11.8^*$
(γ, sn)	1816.4 ± 53.9	1784.7 ± 14.1
$(\gamma, 1n)$	1815.5 ± 61.9	1783.8 ± 13.4
$E^{\text{int}} = B3n = 22.4$ MeV		
$(\gamma, xn)^*$	3261.5 ± 75.3	$3261.5 \pm 25.7^*$
(γ, sn)	2841.7 ± 58.2	2772.6 ± 40.5
$(\gamma, 1n)$	2421.6 ± 33.7	2189.0 ± 33.2
$(\gamma, 2n)$	418.8 ± 12.1	480.7 ± 15.7
$(\gamma, 3n)$		
$E^{\text{int}} = 26.4$ MeV		
$(\gamma, xn)^*$	3738.4 ± 77.2	$3761.5 \pm 44.6^*$
(γ, sn)	3110.0 ± 58.2	3045.7 ± 74.1
$(\gamma, 1n)$	2482.9 ± 66.8	2230.4 ± 58.9
$(\gamma, 2n)$	611.0 ± 13.9	706.9 ± 30.2
$(\gamma, 3n)$	8.2 ± 0.6	

* Experimental data obtained in [26] and used as inputs for our evaluation procedure.

In Fig. 5, the cross sections evaluated within our experimental—theoretical approach [see Eq. (3)] for the $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, and (γ, sn) reactions on the isotope ^{138}Ba are presented along with the cross section measured experimentally for the respective (γ, xn) reaction in [25] and used as input information for our evaluation procedure based on Eq. (6). Table 2 gives data on the cross sections evaluated for the partial photoneutron reactions on the isotope ^{138}Ba. In [25], the cross sections for all of the reactions being discussed, with the exception of the $(\gamma, 3n)$ reaction, were obtained over the energy range extending up to 27.1 MeV. Although the cross section for this reaction was determined experimentally up to still higher energies, only up to the energy of 27.1 MeV can the $(\gamma, 3n)$ cross section be evaluated on the basis of the proposed method.

It is noteworthy that, by and large, the situation around the ^{138}Ba nucleus differs from the situations both around the ^{133}Cs nucleus and around the majority of nuclei studied earlier [14—17]—the evaluated cross section for the $(\gamma, 1n)$ reaction is substantially smaller than its experimental counterpart, while the evaluated cross section for the $(\gamma, 2n)$ reaction is substantially larger that the respective experimental cross section. In the energy range extending up to $B3n = 24.6$ MeV, where there are no (see Fig. 5) negative values of the reaction cross sections, the respective deviations are 8 and 13% (in the region of energies reaching 27.1 MeV, the deviations increase up to 6 and 15%, respectively).

4.3. Data on the Isotope ^{209}Bi

In order to evaluate the cross sections for photoneutron reactions on ^{209}Bi nuclei, use was made of data obtained in Livermore and reported in [26]. For the ^{209}Bi nucleus, data similar to those for the ^{133}Cs and ^{138}Ba nuclei, which were considered above, are given in Figs. 6 and 7 and in Table 3.

From the energy dependences of the functions F_i in Fig. 6, one can see that, in the energy range between about 18.0 and 22.5 MeV, the reliability of the data is questionable because of the appearance of negative values in the cross section for the $(\gamma, 1n)$ reaction. At higher energies, the $(\gamma, 2n)$ cross sections in the data may assume values at which $F_i > 0.50$. Despite the spread of values of the transition functions and despite large errors in the functions F_1^{expt} and F_2^{expt}, there are pronounced correlations between them: if F_1^{expt} assumes a negative value, then the respective value of F_2^{expt} exceeds 0.50. But if, on the contrary, F_1^{expt} has a value that exceeds substantially the theoretical value F_1^{theor}, the respective value of F_2^{expt} is substantially smaller than the theoretical value F_2^{theor}.

The discrepancies between the evaluated and experimental cross sections for the ^{209}Bi nucleus (see Fig. 7) are by and large similar to those that are observed for the ^{138}Ba nucleus—that is, they are also different from those that were observed for the nuclei studied earlier in [14—17]. The evaluated cross section for the $(\gamma, 1n)$ reaction proves to be substantially larger than the respective experimental cross section, while the evaluated cross section for the $(\gamma, 2n)$ reaction is substantially smaller than its experimental counterpart. At energies not higher than $B3n = 22.4$ MeV, the respective deviations are 10 and 15% (in the range of energies reaching 26.4 MeV, the deviations increase in accordance to the aforesaid—to 11 and 16%, respectively).

It is noteworthy that the cross sections evaluated for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions on ^{209}Bi nuclei agree well with yields measured for the respective reactions in the activation experiment that was reported in [27] and in which reactions were identified by the final-state ^{208}Bi and ^{207}Bi nuclei produced in, respectively, the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions rather than by emitted neutrons.

In just the same way as in the case of the ^{133}Cs nucleus, the cross section for the $(\gamma, 3n)$ reaction on the ^{209}Bi nucleus is given in Table 3 and in Fig. 7*d*, even though there are no experimental data for this reaction.

5. CONCLUSIONS

For a large number of nuclei, the experimental cross sections obtained for partial photoneutron reactions in experiments with various sources of photons (quasimonoenergetic annihilation photons and bremsstrahlung gamma-ray emission from electrons) by means of various procedures (neutron-multiplicity sorting and introduction of corrections to the cross section for the neutron-yield reaction) are questionable from the point of view of their reliability, since, in broad energy regions, they do not satisfy objective physical criteria. This is because the cross sections for partial photoneutron reactions have substantial systematic errors caused by shortcomings of the methods for their determination.

In the present study, we have analyzed these drawbacks by considering the example of experimental data obtained for ^{133}Cs, ^{138}Ba, and ^{209}Bi nuclei by means of neutron multiplicity sorting in various experiments with quasimonoenergetic annihilation photons. New data on cross sections characterizing $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions and satisfying physical reliability criteria have been obtained on the basis of the experimental—theoretical evaluation method. For ^{133}Cs and ^{209}Bi nuclei, the $(\gamma, 3n)$ cross sections, which were not determined experimentally earlier, have been estimated for the first time.

The cross sections estimated on the basis of the experimental—theoretical approach both for the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions and for the (γ, sn) total reaction on ^{133}Cs, ^{138}Ba, and ^{209}Bi nuclei deviate substantially from experimental data and, in contrast to them, are free from their systematic uncertainties under study. It is of great interest to compare the cross sections evaluated in this way for the above partial reactions with the results of experiments performed with photon beams of a different type—for example, those obtained upon the inverse Compton scattering of relativistic electrons on a powerful-laser beam. Such experiments were performed at the Conan State University and at the NewSubaru facility in Japan. Similar experiments are now planned at the ELI-NP facility under construction in Romania. This facility is expected to have a monoenergetic-photon beam of a very high quality.

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