ISSN 1063-7788, Physics of Atomic Nuclei, 2013, Vol. 76, No. 11, pp. 1403–1414. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.V. Varlamov, B.S. Ishkhanov, V.N. Orlin, N.N. Peskov, M.E. Stepanov, 2013, published in Yadernaya Fizika, 2013, Vol. 76, No. 11, pp. 1484–1495.

NUCLEI
Experiment

New Data on (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ Partial Photoneutron Reactions

V. V. Varlamov[1)*], B. S. Ishkhanov[1),2)], V. N. Orlin[1)], N. N. Peskov[1)], and M. E. Stepanov[1),2)]

Received January 14, 2013

Abstract—Systematic discrepancies between the results of various experiments devoted to determining cross sections for total and partial photoneutron reactions are analyzed by using objective criteria of reliability of data in terms of the transitional photoneutron-multiplicity function $F_i = \sigma(\gamma, in)/\sigma(\gamma, xn)$, whose values for $i = 1, 2, 3, \ldots$ cannot exceed by definition 1.00, 0.50, 0.33, …, respectively. It was found that the majority of experimental data on the cross sections obtained for (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions with the aid of methods of photoneutron multiplicity sorting do not meet objective criteria (in particular, $F_2 > 0.50$ for a vast body of data). New data on the cross sections for partial reactions on ^{181}Ta and ^{208}Pb nuclei were obtained within a new experimental–theoretical method that was proposed for the evaluation of cross sections for partial reactions and in which the experimental neutron yield cross section $\sigma^{\rm expt}(\gamma, xn) = \sigma(\gamma, n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + \ldots$, which is free from problems associated with determining neutron multiplicities, is used simultaneously with the functions $F_i^{\rm theor}$ calculated within a combined model of photonuclear reactions.

DOI: 10.1134/S1063778813110148

1. INTRODUCTION

The present study is aimed at exploring in detail the reasons for known systematic discrepancies between the results of various experiments devoted to determining the cross sections for (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ partial photoneutron reactions in the region of giant-dipole-resonance (GDR) energies with the aid of various methods for neutron multiplicity sorting.

The majority of experiments devoted to determining cross sections for partial photoneutron reactions were performed by using quasimonoenergetic annihilation photons at the Lawrence Livermore National Laboratory (Livermore, USA) and at the Centre d'Etudes Nucléaires de Saclay (Saclay, France). In either laboratory, use was made of methods for neutron multiplicity sorting that are based on the assumption that there is a direct relation between this multiplicity and the mean kinetic energy of the neutrons. On the basis of the results obtained by analyzing the partial photoneutron reaction cross sections for nuclei studied in the two laboratories, it was found [1–3] that there are significant systematic discrepancies between the results of various experiments. The neutron yield cross sections,

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

which are independent of neutron multiplicity sorting problems, proved to have quite consistent values, but the Livermore and Saclay data on the cross sections for (γ, n) and $(\gamma, 2n)$ partial reactions exhibited substantial discrepancies of up to 60% [2, 3]. More specifically, the $(\gamma, 2n)$ cross sections in the Livermore experiment are obviously overestimated, while its (γ, n) cross sections are underestimated, but the reverse is observed in the Saclay experiment. Thus, the Livermore-to-Saclay ratios are substantially greater than unity for the $(\gamma, 2n)$ cross sections (about 1.2) and substantially less than unity for the (γ, n) cross sections (about 0.8).

A number of dedicated studies aimed at revealing the reasons for these discrepancies and at developing methods for taking them into account. In [1–3], these problems were considered most comprehensively and consistently. The above systematic discrepancies between data on cross sections for partial photoneutron reactions were interpreted there as a consequence of errors in the method used in Saclay to sort neutrons in multiplicity, and a mutual correction of the data from the two laboratories was proposed as a method

1)Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia.
2)Faculty of Physics, Moscow State University, Moscow, 119991 Russia.
*E-mail: Varlamov@depni.sinp.msu.ru

for putting together these discrepancies. This method relies on an appropriate recalculation of the Saclay data in such a way that they become closer to the Livermore data.

However, the question of how one should correct data that come from only one of the two laboratories and which are much more copious than those from both laboratories remains open within this approach. This situation requires that the approach intended for evaluating cross sections for partial photoneutron reactions be maximally free from problems of experimental methods for neutron multiplicity sorting. As an alternative method for determining cross sections for partial reactions, one could consider the use of an induced activity, in which case it is the final-state nucleus rather than emitted neutrons that serves as an identifier of a specific reaction. Unfortunately, this method cannot be used always because of some serious limitations.

A method that evaluates cross sections for partial reactions by employing both experimental and theoretical means (experimental–theoretical method below) was proposed in [4, 5]. Within this method, the contributions of the partial reactions in question to the experimental cross section in (1) for the total yield of neutrons is determined with the aid of the transitional multiplicity functions $F_i^{\text{theor}} = \sigma^{\text{theor}}(\gamma, in)/\sigma^{\text{theor}}(\gamma, xn)$ calculated within a modern photonuclear-reaction model [6, 7]. It was also shown [4, 5, 8–10] that the transitional multiplicity functions F_i^{expt} obtained from experimental data provide criteria for a simple, clear, and efficient analysis of the reliability of experimental data on cross sections for partial reactions. It was found that, for a large number of nuclei (^{90}Zr, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, and ^{197}Au), the experimental data obtained for the (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ cross sections with the aid of methods for photoneutron multiplicity sorting do not meet the above objective criteria. For these nuclei, we evaluated the cross sections for partial photoneutron reactions on the basis of our experimental–theoretical approach, and the relations between them comply with the model concepts [6, 7].

The present study is devoted to exploring in detail, on the basis of objective criteria, the reliability of experimental data on the cross sections for partial photoneutron reactions on ^{181}Ta and ^{208}Pb nuclei and to evaluating reaction cross sections that are independent of problems of neutron multiplicity sorting.

2. OBJECTIVE CRITERIA OF THE RELIABILITY OF DATA ON CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS IN TERMS OF THE TRANSITIONAL MULTIPLICITY FUNCTIONS F_i

We have indicated above that, in order to get rid of the dependence of the cross sections for partial photoneutron reactions on the flaws in the experimental methods for neutron multiplicity sorting, our group proposed in [4, 5] the experimental–theoretical approach to evaluating these cross sections. Within this approach, one employs, as input experimental information, only data on the reaction cross section $\sigma^{\text{expt}}(\gamma, xn)$ (1), which is independent of the neutron multiplicity, and separates reactions characterized by different neutron multiplicities with the aid of the transitional multiplicity functions

$$F_i^{\text{theor}} = \sigma^{\text{theor}}(\gamma, in)/\sigma^{\text{theor}}(\gamma, xn) \quad (2)$$
$$= \sigma^{\text{theor}}(\gamma, in)/[\sigma(\gamma, n) + 2\sigma(\gamma, 2n) + \ldots$$
$$+ 3\sigma(\gamma, 3n) + \ldots]^{\text{theor}},$$

which are calculated within a modern photonuclear-reaction model [6, 7].

The functions $F_{1,2,3}^{\text{theor}}$ obtained on the basis of model calculations exhibit a concrete behavior that is physically clear, and a comparison of this behavior with the behavior of the functions

$$F_i^{\text{expt}} = \sigma^{\text{expt}}(\gamma, in)/\sigma^{\text{expt}}(\gamma, xn) \quad (3)$$
$$= \sigma^{\text{expt}}(\gamma, in)/[\sigma(\gamma, n) + 2\sigma(\gamma, 2n) + \ldots$$
$$+ 3\sigma(\gamma, 3n) + \ldots]^{\text{expt}},$$

obtained on the basis of experimental data makes it possible to draw conclusions on the reliability of experimental data.

In Fig. 1, the functions F_i^{theor} are contrasted against the functions $(F_i^{\text{expt}})_{\text{S}}$ and $(F_i^{\text{expt}})_{\text{L}}$ obtained for, respectively, the Saclay [11] and Livermore [12] data for the ^{181}Ta nucleus. It is noteworthy that F_1 and F_3 are of no particular interest—the former by virtue of its triviality and the latter because of a small amount of data on $(\gamma, 3n)$ cross sections—but that F_2 makes it possible to analyze straightforwardly and efficiently the reliability of experimental data on the cross sections for three partial photoneutron reactions simultaneously. The most important property of the function F_2 is that, according to the definition in Eqs. (2) and (3), it cannot exceed 0.50 in magnitude under any conditions: its value above this absolute limit would mean a physically incorrect determination of cross sections for respective partial reactions.

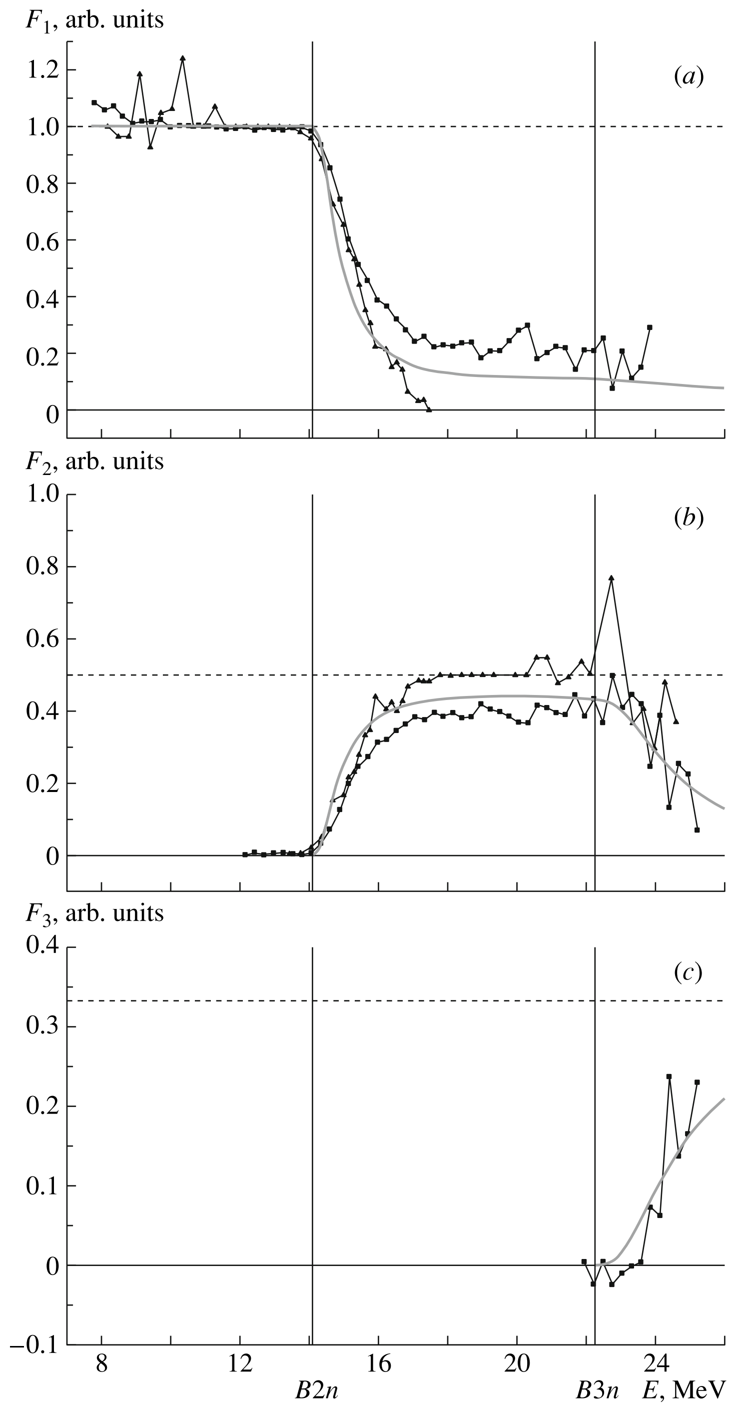

Fig. 1. Transitional functions F_i^{expt} obtained for (closed boxes) Saclay [11] and (closed triangles) Livermore [12] experimental data for the ^{181}Ta nucleus along with (solid curve) the results of the calculations from [4, 5] for F_i^{theor}: (*a*) F_1, (*b*) F_2, and (*c*) F_3.

The main special features of a physically justifiable behavior of the functions $F_{1,2,3}$ are the following:

(i) The function F_1 is equal to unity in the energy region extending up to the threshold $B2n$ for the respective $(\gamma, 2n)$ reaction, whereupon it decreases in accordance with the competition of the increasing $(\gamma, 2n)$ cross section and the decreasing (γ, n) cross section, tending to zero, in just the same way as $\sigma(\gamma, n)$.

(ii) The function F_2 is equal to zero in the energy region extending up to the threshold $B2n$, whereupon it increases in accordance with the competition of the decreasing (γ, n) cross section and the increasing $(\gamma, 2n)$ cross section, approaching the absolute limit of const $= 0.50$ from below without reaching

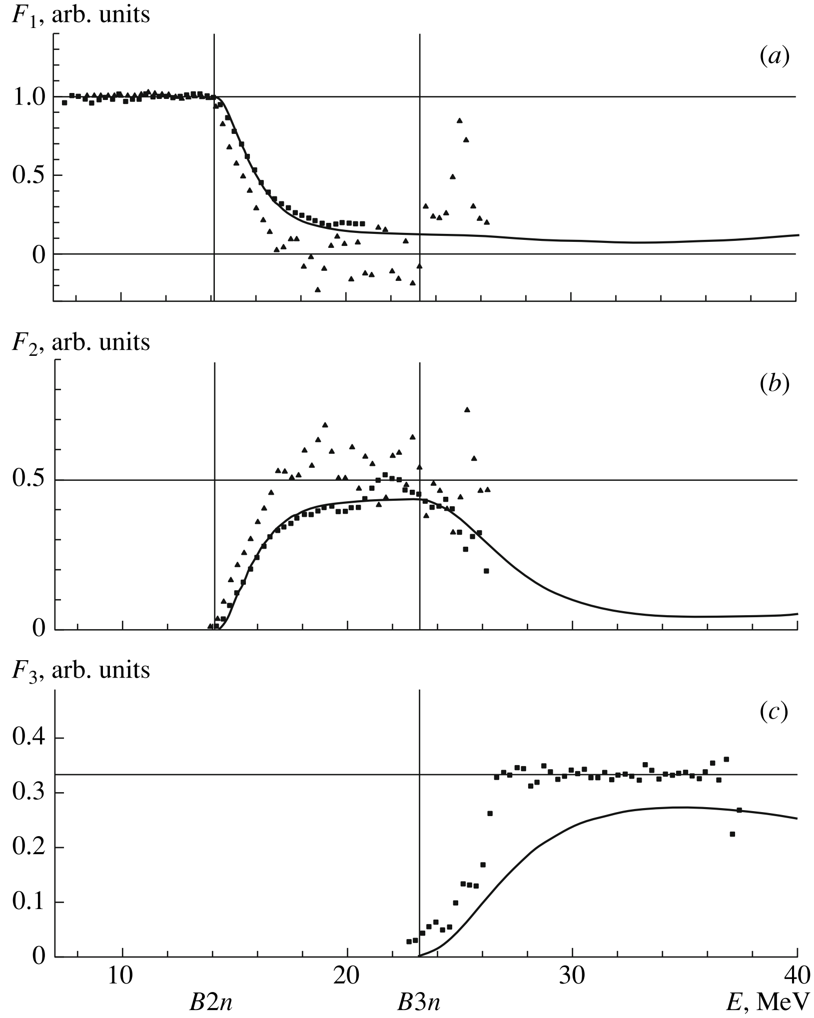

Fig. 2. As in Fig. 1, but for the ^{208}Pb nucleus. The displayed closed boxes and closed triangles represent, respectively, Saclay [13] and Livermore [14] experimental data.

it anywhere; at energies in excess of the threshold $B3n$ for the respective $(\gamma, 3n)$ reaction, this function decreases in accordance with the contribution of $3\sigma(\gamma, 3n)$.

(iii) The function F_3 is equal to zero in the energy region extending up to the the threshold $B3n$, whereupon it increases in accordance with the competition of the decreasing (γ, n) and $(\gamma, 2n)$ cross sections and the increasing cross section $\sigma(\gamma, 3n)$.

Figure 1 clearly demonstrates that the Saclay and Livermore data $[(F_i^{\rm expt})_{\rm S}$ and $(F_i^{\rm expt})_{\rm L}$, respectively] for ^{181}Ta differ substantially not only from each other but also from theoretical data $(F_i^{\rm theor})$.

The deviation of $(F_{1,2}^{\rm expt})_{\rm S}$ from $F_{1,2}^{\rm theor}$ indicates that, in the energy region below the threshold $B3n$ for the respective $(\gamma, 3n)$ reaction, the cross section $\sigma(\gamma, n)$ is overestimated, while the cross section $\sigma(\gamma, 2n)$ is underestimated in relation to the respective theoretical cross sections, even though the functions $(F_{1,2}^{\rm expt})_{\rm S}$ fall within the region of physically justifiable values. In the region of energies above $B3n$, $(F_2^{\rm expt})_{\rm S}$ exceeds substantially $F_2^{\rm theor}$, while $(F_3^{\rm expt})_{\rm S}$ proves to be in the region of physically incorrect negative values, whence we conclude that the cross section $\sigma(\gamma, 3n)$ is unjustifiably underestimated.

The deviation of $(F_i^{\rm expt})_{\rm L}$ from $F_i^{\rm theor}$ is more significant. At energies in the vicinity of 17.5 MeV, $(F_1^{\rm expt})_{\rm L}$ decreases sharply to zero (which suggests that there are no neutrons of multiplicity equal to unity at high energies); accordingly, $(F_2^{\rm expt})_{\rm L} = 0.50$ at energies in the range between about 17.5 and 20.5 MeV. At high energies, $(F_2^{\rm expt})_{\rm L}$ features physically incorrect (above 0.50) values of about 0.57, 0.56, 0.55, and 0.73. The behavior of the functions

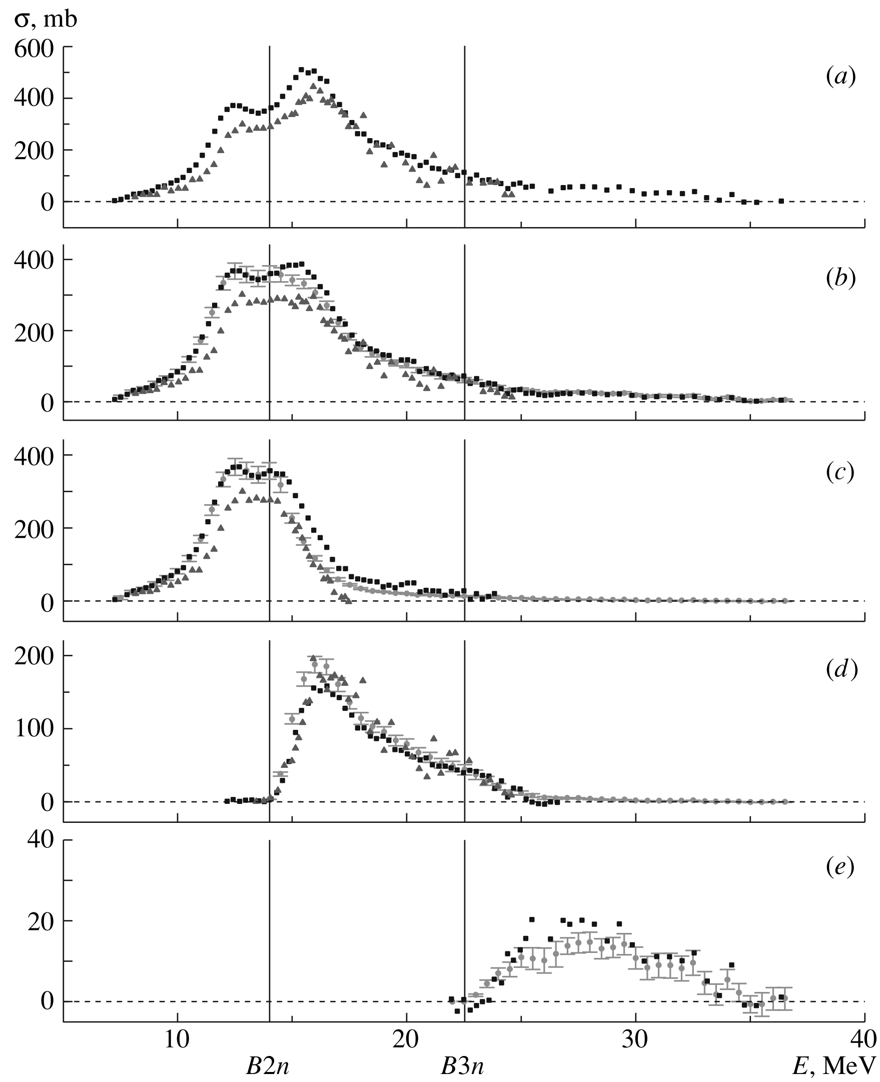

Fig. 3. Evaluated (closed circles with error bars) and experimental (closed boxes for Saclay data [11] and closed triangles for Livermore data [12]) cross sections for total and partial photoneutron reactions on ^{181}Ta nuclei: (*a*) $\sigma(\gamma, xn)$, (*b*) $\sigma(\gamma, sn)$, (*c*) $\sigma(\gamma, n)$, (*d*) $\sigma(\gamma, 2n)$, and (*e*) $\sigma(\gamma, 3n)$.

$(F_{1,2}^{\rm expt})_{\rm L}$ suggests that the cross section $\sigma(\gamma, n)$ is underestimated, while the cross section $\sigma(\gamma, 2n)$ is overestimated.

Figure 2 shows similar data for the ^{208}Pb nucleus [13, 14]. One can clearly see that the functions $(F_{1,2}^{\rm expt})_{\rm L}$ deviate strongly from the functions $F_{1,2}^{\rm theor}$, and the character of these deviations indicates that the (γ, n) cross section is underestimated, featuring physically incorrect negative values. The $(\gamma, 2n)$ cross section is overestimated, leading to physically unjustifiable values of $(F_2^{\rm expt})_{\rm L} > 0.50$ in the energy range between about 17 and 23 MeV. At the same time, the proximity of $(F_{1,2}^{\rm expt})_{\rm S}$ and $F_{1,2}^{\rm theor}$ suggests that, in the region of energies extending up to $B3n$, the cross sections $\sigma(\gamma, n)$ and $\sigma(\gamma, 2n)$ were determined in Saclay quite reliably. This is not so for the cross section $\sigma(\gamma, 3n)$ since $(F_3^{\rm expt})_{\rm S}$ and $F_3^{\rm theor}$ differ sizably, $(F_3^{\rm expt})_{\rm S}$ being very close to the absolute upper boundary (0.33) nearly over the entire energy range studied experimentally (from about 26 to 37 MeV).

Figures 1 and 2 clearly show that the experimental cross sections for the (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions on ^{181}Ta and ^{208}Pb nuclei, as well as the respective reactions on ^{90}Zr, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, and ^{197}Au nuclei, which were studied previously in [4, 5, 8–10], do not meet the proposed objective reliability criteria. In view of this, the problem of deriving (evaluating) cross sections for partial reactions under conditions

Table 1. Basic features [center of gravity, $E^{\text{c.g.}}$, and integrated (up to $E^{\text{int}} = 35.0$ MeV) cross section σ^{int}] of evaluated cross sections for total and partial photoneutron reactions on ^{181}Ta nuclei along with Saclay and Livermore experimental data

Reaction	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb
	Evaluated data		Saclay data [11]		Livermore data [12]	
(γ, xn)	16.7 (1)*	4078.2 (9.3)*	16.7 (1)	4078.2 (9.3)	16.2 (10)	3068.3 (63.1)
(γ, sn)	15.8 (1)	3021.9 (36.1)	15.8 (1)	3124.3 (30.8)	15.3 (1)	2199.7 (46.3)
(γ, n)	13.9 (1)	1956.3 (31.0)	14.0 (7)	2189.5 (21.5)	13.3 (8)	1315.7 (20.7)
$(\gamma, 2n)$	18.4 (1)	958.3 (17.4)	18.3 (1)	797.4 (20.0)	18.3 (1)	887.0 (41.7)
$(\gamma, 3n)$	28.4 (1)	107.3 (6.3)	28.5 (3)	137.4 (100)		

* Cross section used as an input for evaluations and obtained on the basis of Saclay experimental data [11].

free from difficulties in determining the multiplicity of neutrons comes to be of paramount importance.

3. NEW APPROACH FOR THE EVALUATION OF CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS

As was indicated in the Introduction, a new method for evaluating the cross sections for partial photoneutron reactions was proposed in [4, 5] in order to sidestep problems associated with experimentally determining neutron multiplicities. The experimental–theoretical method in question relies on employing experimental information only about the neutron yield cross section (1), which is independent of problems of neutron multiplicity sorting. The contributions of partial reactions to the cross section for the total reaction in question are determined with the aid of the transition multiplicity functions $F_i^{\text{theor}} = \sigma^{\text{theor}}(\gamma, in)/\sigma^{\text{theor}}(\gamma, xn)$ calculated within a combined preequilibrium model of photonuclear reactions [6, 7]—specifically, the preequilibrium exciton model relying on the use of Fermi gas nuclear-level densities and taking into account nuclear-deformation effects and the isospin splitting of the respective giant dipole resonance. The evaluated reaction cross sections are obtained according to the relation

$$\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}}\sigma^{\text{expt}}(\gamma, xn). \qquad (4)$$

The competition of the evaluated cross sections for partial reactions complies with the concepts of the modern model of photonuclear reactions, while their sum agrees with the experimental cross section in (1).

Table 2. Ratios of the integrated cross sections σ^{int} for total and partial reactions on ^{181}Ta nuclei according to calculations performed up to the energy of $E^{\text{int}} = 25$ MeV on the basis of evaluated data and on the basis of Saclay and Livermore experimental data

Reaction	$\sigma^{\text{int}}_{\text{eval}}/\sigma^{\text{int}}_{\text{S}}$ [11]	$\sigma^{\text{int}}_{\text{eval}}/\sigma^{\text{int}}_{\text{L}}$ [12]
(γ, xn)	1	1.24 (3813.8/3068.3)
(γ, sn)	0.96 (2867.3/2998.4)	1.30 (2867.3/2199.7)
(γ, n)	0.88 (1922.4/2189.5)	1.46 (1922.4/1315.7)
$(\gamma, 2n)$	1.16 (929.1/797.9)	1.05 (929.1/887.0)

3.1. Photodisintegration of ^{181}Ta Nuclei

In Fig. 3, the cross sections evaluated in the way outlined above for partial reactions on ^{181}Ta nuclei are compared with experimental data from [11, 12]. In Fig. 3*a*, the experimental cross section (1) obtained according to the Saclay data [11] for the neutron yield reaction ^{181}Ta(γ, xn) and used as an input for evaluations is presented as an evaluated cross section. Figure 3*b* gives additionally the total photoneutron reaction cross sections

$$\sigma(\gamma, sn) = \sigma(\gamma, n) + \sigma(\gamma, 2n) + \sigma(\gamma, 3n) + \ldots \qquad (5)$$

obtained by summing evaluated cross section for partial reactions. In Table 1, we present basic features of all cross sections in Fig. 3 according to calculations for energy regions extending up to 35 MeV.

A comparison of experimental and evaluated cross sections for both total and partial reactions is of considerable interest from the point of view of the problem of reliability of data. Table 2 gives the respective ratios of integrated cross sections according to calculations performed up to an energy of $E^{\text{int}} = 25$ MeV.

The following conclusions can be drawn from these ratios:

(i) For the (γ, n) cross section, the Saclay data [11] prove to be overestimated by 12%, while the Livermore data [12] are underestimated by 46%. This corresponds to the behavior of the function $(F_1^{\rm expt})_{\rm S}$ (see Fig. 1*a*).

(ii) For the $(\gamma,2n)$ cross section, the Saclay data [11] prove to be underestimated by 16%, and this corresponds to the behavior of the function $(F_2^{\rm expt})_{\rm S}$ (see Fig. 1*b*).

(iii) For the same reaction, the Livermore data [12] also prove to be underestimated (by 5%), which, at first glance, does not comply with the behavior (see Fig. 1*b*) of the function $(F_2^{\rm expt})_{\rm L}$ (over almost the whole energy region studied experimentally, this function have values close to the absolute upper boundary of 0.50).

The observed underestimation of the cross section $\sigma(\gamma,2n)$ calls for a dedicated analysis along with an analysis of the behavior of the function $(F_2^{\rm expt})_{\rm L}$ [12]. Since the relations

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

$$\sigma(\gamma,n)=\sigma(\gamma,sn)-\sigma(\gamma,2n), \quad (7)$$

hold for the reactions from Table 2 in the energy region being considered, it is of particular interest to trace the variations in the integrated cross section ratio $\sigma^{\rm int}_{\rm eval}/\sigma^{\rm int}_{\rm L}$ [12] under study in response to the transitions $(\gamma,xn)\to(\gamma,sn)\to(\gamma,n)$, upon which the fraction of the (γ,n) cross section grows—$2\sigma(\gamma,2n)$ is added to it in $\sigma(\gamma,xn)$, $\sigma(\gamma,2n)$ is added in $\sigma(\gamma,sn)$, and nothing is added in $\sigma(\gamma,n)$ (the respective fraction is 100%).

Its obvious that, if the ratios of the cross sections for partial reactions in experimental and evaluated data were close, the ratios $\sigma^{\rm int}_{\rm eval}/\sigma^{\rm int}_{\rm L}$ would also be close for all of the reactions considered here. However, the data in Table 2 clearly show that the greater the fraction of the cross section for the (γ,n) partial reaction in the cross section for the total reaction, the higher the degree to which the latter is underestimated ($1.24\to1.30\to1.46$). Upon the subsequent transition $(\gamma,n)\to(\gamma,2n)$ to the cross section $\sigma(\gamma,2n)$, in which the fraction of the cross section $\sigma(\gamma,n)$ is naturally equal to zero, the ratio $\sigma^{\rm int}_{\rm eval}/\sigma^{\rm int}_{\rm L}$ decreases sharply to 1.05: an experimentally observed underestimation of the cross section $\sigma(\gamma,2n)$ appears to be nearly one-tenth as great as the underestimation of the cross section $\sigma(\gamma,n)$. This means that the physically incorrect behavior of the function $(F_2^{\rm expt})_{\rm L}$ (see Fig. 1*b*) is due to a very large (46%) underestimation of the number of multilicity-1 neutrons in the (γ,xn) cross section [denominator of the ratio in (3)] rather than to unjustifiably associating extra neutrons of multiplicity 2 with the $(\gamma,2n)$ reaction [numerator in the ratio in (3)]—moreover, there is small (5%) deficit of such neutrons. The reasons for this are not clear, but it is the very large, physically unjustifiable, underestimation of the cross section for the reaction ^{181}Ta$(\gamma,n)^{180}$Ta [12] (this underestimation was also highlighted in discussing Fig. 2*a*) that is responsible for a substantial (by 25%) underestimation that was found in the case of the cross section for the reaction ^{181}Ta(γ,xn) and which is clearly seen in Fig. 3*a*.

The data in Table 1 show that, in accordance with the behavior of the function $(F_3^{\rm expt})_{\rm S}$ (see Fig. 1*c*), there are sizable discrepancies between the evaluated and experimental $(\gamma,3n)$ cross sections.

Since the discrepancies between the evaluated and experimental (that is, those that were obtained by means of neutron multiplicity sorting) cross sections for the respective reactions on ^{181}Ta nuclei are quite sizable, it is of particular interest to compare those cross sections with the results of alternative experiments in which a specific reaction is identified without determining neutron multiplicities. As was indicated in the Introduction, such an identification can be performed by the final-state nucleus within the induced-activity method. Unfortunately, there are rather many cases in which this method is unapplicable since the radioactive decay of the final-state nucleus should have features appropriate for performing respective measurements, but, in the case of the ^{181}Ta nucleus, it is possible to perform the alternative experiments in question.

The required investigations of this type were performed in [15] at the racetrack microtron of the Institute of Nuclear Physics (Moscow State University) at maximum electron energy of 67.7 MeV (this is a new generation electron accelerator). A high quality of the electron beam employed, the use of a high-purity germanium detector in order to record photons, and the application of updated software to processing the experimental energy spectra of photons made it possible to perform a high-precision comparative investigation of partial reactions leading to the production of one [in the reaction ^{181}Ta$(\gamma,n)^{180}$Ta] to seven [in the reaction ^{181}Ta$(\gamma,7n)^{174}$Ta] neutrons. The quality of those experiments was so high that it permitted observing and quantitatively studying processes in which final nuclei of various reactions arose not only in the ground state but also in isomeric states—for example, the isotopes ^{178g,m}Ta originating from the reaction ^{181}Ta$(\gamma,3n)^{178}$Ta.

In Table 3, the results of the experiment reported in [15] and performed by the induced-activity method are compared with the results of the experiments under discussion, which were performed with the aid of the method of sorting photoneutrons in multiplicity in Saclay [11] and in Livermore [12], as well as against our data evaluated on the basis of the

Table 3. Results of experiments performed for the ^{181}Ta nucleus with the aid of induced-activity and neutron-sorting (in multiplicity) methods along with data evaluated for the respective $(\gamma, 2n)$ and (γ, n) reactions

Cross-section and yield ratios	Experiment			Evaluation
	Saclay [11]	Livermore [12]	Induced activity [15]	Our present study
$\sigma(\gamma,2n)/\sigma(\gamma,n)$	0.36 (797.4/2189.5)	0.67 (887.0/1315.7)		0.49 (958.3/1956.3)
$Y(\gamma,2n)/Y(\gamma,n)$	0.24	0.42	0.34 ± 0.07	0.33*
$\sigma(\gamma,3n)/\sigma(\gamma,n)$	0.063 (137.4/2189.5)			0.055 (107.3/1956.3)
$Y(\gamma,3n)/Y(\gamma,n)$	0.02		0.023–0.025**	0.018*

* Yield ratios evaluated in our study for the respective reactions on the basis of their cross sections.
** Total yield of the reaction $^{181}\mathrm{Ta}(\gamma,3n)^{178}\mathrm{Ta}$ leading to the production of the final nucleus in the ground state and in the isomeric state.

new experimental–theoretical approach. The data from [15] are presented for the ratios of the $(\gamma, 2n)$ and (γ, n) yields defined as the convolution of the $(\gamma, 2n)$ and (γ, n) cross sections with the respective photon spectra. The data given in Table 3 on the relative yields of the $(\gamma, 2n)$ and (γ, n) partial reactions, as well as on the relative yields of the the $(\gamma, 3n)$ and (γ, n) partial reactions, make it possible to draw the following conclusions:

(i) The yield ratio (0.33) obtained on the basis of evaluated data for the (γ, n) and $(\gamma, 2n)$ partial reactions on ^{181}Ta nuclei agrees well with the ratio (0.34) deduced from the results of the experiment reported in [15] and performed by the induced-activity method—that is, a method free from the flaws in experimental methods of photoneutron multiplicity sorting.

(ii) The yield ratio $Y(\gamma, 2n)/Y(\gamma, n)$ obtained on the basis of Saclay data (0.24) is substantially smaller than the experimental and evaluated results (0.34 and 0.33, respectively); this indicates that the Saclay data on the yield of the reaction $^{181}\mathrm{Ta}(\gamma, 2n)^{179}\mathrm{Ta}$ are substantially underestimated, while the data on the cross section for the reaction $^{181}\mathrm{Ta}(\gamma, n)^{180}\mathrm{Ta}$ are overestimated.

(iii) The yield ratio $Y(\gamma, 2n)/Y(\gamma, n)$ obtained on the basis of the Livermore data (0.42) is substantially greater than the experimental and evaluated results (0.34 and 0.33, respectively), the evaluated and experimental cross sections for the reaction $^{181}\mathrm{Ta}(\gamma, 2n)^{179}\mathrm{Ta}$ being relatively close (within 6%—see Table 3); this indicates that the experimental cross section for the reaction $^{181}\mathrm{Ta}(\gamma, n)^{180}\mathrm{Ta}$ is substantially underrated (by 25%), which is also reflected in the underestimation of the $^{181}\mathrm{Ta}(\gamma, xn)$ total neutron yield.

(iv) The yield ratio $Y(\gamma, 3n)/Y(\gamma, n)$ deduced from the Saclay data proves to be close both to the evaluated result and to data from the experiment performed by the induced-activity method, and this is indicative of quite a satisfactory separation of multiplicity-2 and multiplicity-3 neutrons in the cross section for the reaction $^{181}\mathrm{Ta}(\gamma, 3n)^{178}\mathrm{Ta}$ in the experiment reported in [11]. The results there are unsatisfactory only in the energy range between about 22 and 24 MeV, where the experimental cross section contains physically incorrect negative values.

It is noteworthy that the evaluated data on the cross section for the reaction $^{181}\mathrm{Ta}(\gamma, 2n)^{179}\mathrm{Ta}$ also comply with the results deduced previously in [1, 2] from a simultaneous analysis of Saclay [11] and Livermore [12] data on the photodisintegration of ^{181}Ta nuclei and with the results obtained by studying the (e, xn), (e, n), and $(e, 2n)$ reactions on these nuclei, in which case the (e, xn) cross section was determined by counting the number of emitted neutrons, while the (e, n) cross section was measured by the induced-activity method. After the respective normalization of the experimental cross sections $\sigma(e, xn)$ and $\sigma(e, n)$, the cross section for the reaction $^{181}\mathrm{Ta}(e, 2n)$ was obtained by using the obvious relation

$$\sigma(e, 2n) = \frac{1}{2}(\sigma(e, xn) - \sigma(e, n)). \quad (8)$$

It was found that, although a comparison of data on the absolute values of the cross sections $\sigma(e, 2n)$ and $\sigma(\gamma, 2n)$ was impossible, the Livermore data [12] on the cross section $\sigma(\gamma, 2n)$ are quite consistent with the results of the independent alternative experiment, while the respective Saclay data from [11] prove to be substantially underestimated.

Thus, the investigations performed for the ^{181}Ta nucleus suggest the following:

Table 4. Integrated cross sections according to evaluated data on the total and partial photoneutron reactions on ^{208}Pb nuclei along with Livermore and Saclay experimental data

	$E^{\text{int}} = B2n = 14.1$ MeV	$E^{\text{int}} = B3n = 23.2$ MeV	$E^{\text{int}} = 40.0$ MeV
(γ, xn)			
Evaluation*	1811.1 (15.4)	3820.8 (41.6)	4592.9 (55.0)
Saclay [13]	1811.1 (15.4)	3820.8 (41.6)	4592.9 (55.0)
Livermore [14]	1432.9 (11.8)	3186.7 (47.5)	3581.6 (74.9)
(γ, sn)			
Evaluation	1791.8 (11.1)	3270.9 (16.4)	3663.1 (25.8)
Saclay [13]	1811.1 (11.3)	3299.4 (29.3)	3587.8 (32.5)
Livermore [14]	1431.0 (12.1)	2508.2 (36.9)	2671.8 (55.0)
(γ, n)			
Evaluation	1791.4 (11.2)	2699.6 (13.2)	2774.7 (13.2)
Saclay [13]	1810.7 (12.0)	2817.1 (41.6)	2875.6 (55.9)
Livermore [14]	1432.3 (9.2)	1922.0 (57.9)	1960.5 (89.6)
$(\gamma, 2n)$			
Evaluation		571.2 (7.7)	714.5 (10.8)
Saclay [13]		530.0 (18.2)	615.7 (33.0)
Livermore [14]		670.9 (32.0)	860.9 (49.3)
$(\gamma, 3n)$			
Evaluation			165.5 (13.9)
Saclay [13]			197.2 (13.8)
Livermore [14]			

* Saclay experimental data [13] used as inputs for evaluations.

(i) The cross section obtained for the reaction ^{181}Ta$(\gamma, n)^{180}$Ta in the Saclay experiment [11] is substantially overestimated (by 12%), while the respective cross section for the reaction ^{181}Ta$(\gamma, 2n)^{179}$Ta is substantially underestimated (by 16%) with respect to the evaluated data; therefore, neither is reliable.

(ii) The cross section obtained for the reaction ^{181}Ta$(\gamma, n)^{180}$Ta in the Livermore experiment [12] is substantially underestimated (by 46%), while the respective cross section for the reaction ^{181}Ta$(\gamma, 2n)^{179}$Ta is also somewhat underestimated (by 5%) with respect to the evaluated data; therefore, neither is reliable.

Our investigations give sufficient grounds to conclude that the evaluated cross sections for the (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions on ^{181}Ta nuclei are not consistent with the results of the experiments that employed the method of neutron multiplicity sorting [11, 12], but that they agree with the results of various experiments [2, 15] that employed the induced-activity method.

3.2. Photodisintegration of the ^{208}Pb Nucleus

The results obtained for the ^{181}Ta nucleus aggravate substantially the problem of reliability of experimental data. These results suggest that, in contrast

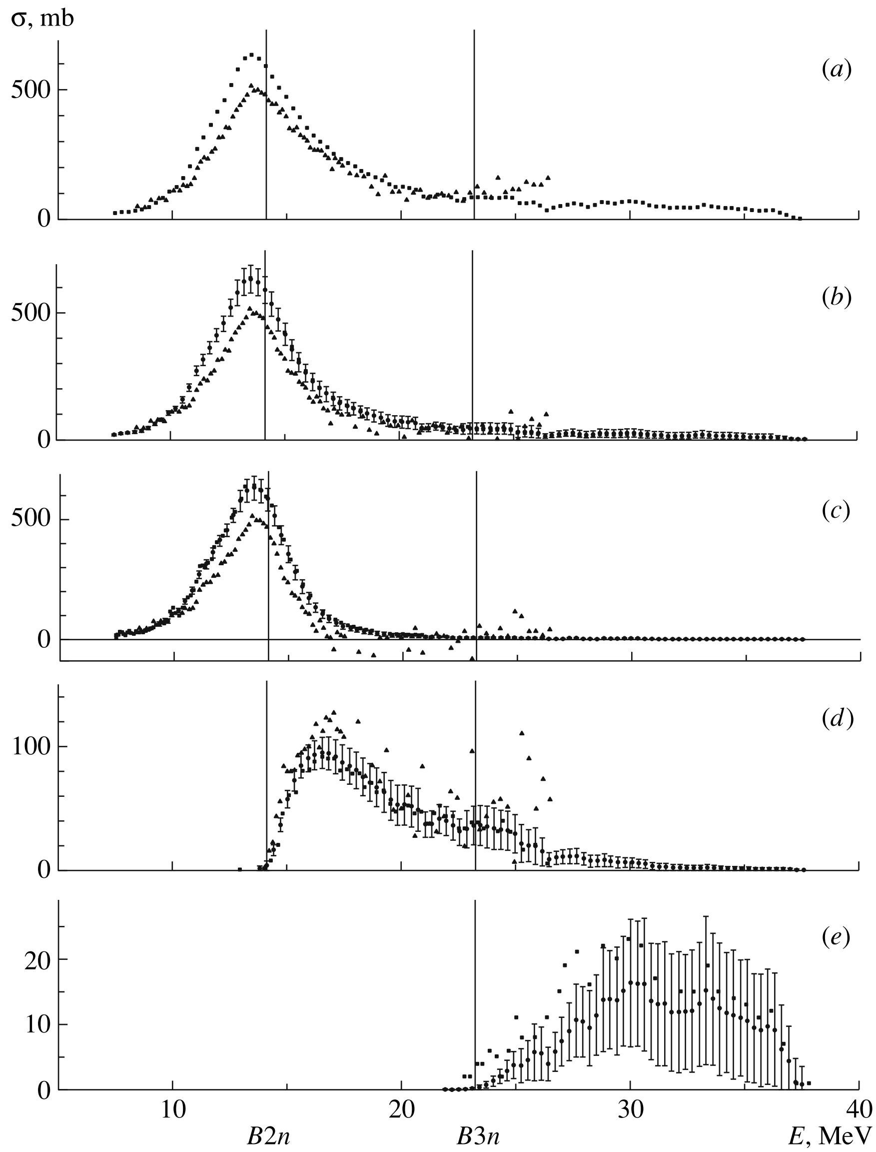

Fig. 4. As in Fig. 3, but for the ^{208}Pb nucleus. The closed boxes and triangles represent, respectively, the Saclay [13] and Livermore [14] experimental data.

to many cases studied previously in [4, 5, 8–10], a physically unjustifiable behavior of the multiplicity function obtained on the basis of the Livermore data ($F_2 \geqslant 0.50$) is due to a very strong (46%) underestimation of the number of multiplicity-1 neutrons rather than to an overestimation of the number of multiplicity-2 neutrons (moreover, there is a modest underestimation of 5% here).

The behavior of the functions $F_{1,2}$ (see Figs. 2*a* and 2*b*) indicate that data on the photodisintegration of ^{208}Pb nuclei aggravate still further the problem of studying the reliability of neutron multiplicity sorting since these data do not fit in the the picture that combines the cases that were studied previously—the overestimation (underestimation) of the cross sections $\sigma(\gamma, n)$ and the underestimation (overestimation) of the cross sections $\sigma(\gamma, 2n)$ in the Saclay (Livermore) experiments.

Figures 4*c* and 4*d* and Table 4 give a clear idea of how well the Saclay experimental cross sections [13] agree with the evaluated data on the respective (γ, n) and $(\gamma, 2n)$ reactions and of how strongly the Livermore experimental cross sections [14] deviate from these evaluated data. In accordance with the behavior of the function F_3 (see Fig. 2*c*), the evaluated $(\gamma, 3n)$ cross section is substantially smaller than the Saclay experimental cross section [13].

4. POSSIBLE REASONS FOR THE DISTORTION OF INFORMATION ABOUT CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS IN EXPERIMENTS THAT EMPLOY THE SORTING OF NEUTRONS IN MULTIPLICITY

The results obtained by studying cross sections for partial photoneutron reactions on ^{90}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, ^{181}Ta, ^{197}Au and ^{208}Pb nuclei are indicative of the following:

(i) For all nuclei with the exception of ^{208}Pb, the cross sections measured for the (γ, n) and $(\gamma, 2n)$ reactions in the Saclay experiments are, respectively, overestimated and underestimated, which complies with the behavior of the functions $F_{1,2,3}$. For ^{208}Pb, a reliable relationship of the cross sections for partial reactions is observed.

(ii) For all nuclei with the exception of ^{181}Ta, the cross sections measured for the $(\gamma, 2n)$ and (γ, n) reactions in the Livermore experiments prove to be, respectively, overestimated and underestimated, which complies with the behavior of the respective functions $F_{1,2,3}$. For ^{181}Ta, a modest (5%) underestimation of the $(\gamma, 2n)$ cross section and a very strong (46%) underestimation of the (γ, n) cross section are observed simultaneously.

Both in the Saclay and in the Livermore experiments, the multiplicity of neutrons was determined from their kinetic energy on the basis of the assumption that both of neutrons in the $2n$ channel have energies smaller that one neutron in the $1n$ channel, but the number of low-energy neutrons proved to be underestimated in the Saclay experiment and, on the contrary, overestimated in the Livermore experiment. Such discrepancies ought to be associated with a means for detecting neutrons of different energies.

In the Saclay experiment, use was made of a large liquid scintillator enriched in gadolinium. Since the production of two neutrons in $(\gamma, 2n)$ reactions occurs within a characteristic short nuclear time, there is the possibility in the case on an insufficient time resolution of the setup used that weak signals overlap each other, which must obviously lead to underrating the contribution of the $2n$ channel.

The Livermore experiments relied on the ring-ratio method (concentric counter rings in a paraffin moderator): low-energy neutrons originating from a $(\gamma, 2n)$ reaction must have time to be moderated to the thermal energy of capture by a BF3 counter on their path to the inner ring, while high-energy neutrons originating from the reaction (γ, n) must traverse this ring and undergo moderation on their path to the outer ring. Since, however, it is not mandatory that the path of a fast neutron is rectilinear, such a neutron could return to the inner ring upon traveling along a curvilinear trajectory, and this would obviously lead to overestimating the contribution of the $2n$ channel.

An individual character of the discrepancies being discussed [4, 5, 8–10] suggests that the neutron multiplicity is determined differently at different neutron energies. Investigations performed for the ^{181}Ta nucleus in [15] revealed that, in the photodisintegration of this nucleus at the photon energy of 25 MeV, the first neutron from the respective $(\gamma, 2n)$ reaction has a mean energy of about 4 MeV, while the second neutron has an energy of about 1.4 MeV. At a similar hierarchy of the energies of the first and second neutrons from the respective $(\gamma, 3n)$ reaction, the energy of the second neutron proves to be substantially higher than the energy of the third neutron. In addition, it should be noted that the same nucleus is formed in the (γ, n) reaction after the emission of a single neutron and in the $(\gamma, 2n)$ and $(\gamma, 3n)$ reactions after the emission of the first neutron. Moreover, the same nucleus is produced in the (γ, np) reaction, whose role was not considered in the experiments being discussed. Thus, we have seen that in determining the multiplicity of a neutron, the relation between this multiplicity and the measured kinetic energy of the neutron being considered may be substantially more intricate than that which was assumed in performing the experiments under discussion.

5. CONCLUSIONS

Our objective-criterion-based investigation of the reliability of experimental data obtained in the Saclay and Livermore experiments for cross sections describing partial photoneutron reactions on ^{90}Zr, ^{115}In, ^{112,114,116,117,118,119,120,122,124}Sn, ^{159}Tb, ^{181}Ta, ^{197}Au, and ^{208}Pb nuclei has led to the following conclusions:

(i) Systematic discrepancies between data obtained by using different methods for neutron multiplicity sorting are associated with special features of the methods used to measure the kinetic energy of neutrons.

(ii) The main reason behind the aforementioned discrepancies between the results of the different experiments surveyed above is seated in the intricate relationship between the multiplicity of neutrons and their measured kinetic energy. In view of this, the degree of the discrepancies being discussed become dependent on individual features of the spectra of neutrons from the reactions under study.

(iii) Almost all of the cases of experimental neutron multiplicity sorting that were studied above show that this sorting was physically incorrect. Therefore, the data obtained in this way for partial-photoneutron-reaction cross sections should be revisited and reanalyzed.

(iv) The proposed experimental–theoretical method for evaluating cross sections for partial reactions on the basis of simultaneously employing the (γ, xn) neutron yield cross section and relations of the combined photoneutron-reaction model gives results that disagree with data deduced with aid of photoneutron sorting in multiplicity but agree with data obtained by the induced activity method.

(v) A reliable experimental determination of cross sections for partial photonuclear reactions requires employing alternative direct methods for identifying these reactions—first of all, methods for detecting emitted neutrons in the coincidence mode and the method of induced activity of a final-state nucleus.

ACKNOWLEDGMENTS

We are grateful to T.S. Polevich for her generous help in data treatment and presentation.

This work was funded by a grant (no. 02.120.21.485) for support of leading scientific schools and under a contract (no. 02.740.11.0242) with the Ministry of Education of Science of the Russian Federation (project 1.1: research work of groups from scientific–educational centers) and was supported by the Russian Foundation for Basic Research (project nos. 09-02-00368 and 13-02-00124).

REFERENCES

1. E. Wolynec, A. R. V. Martinez, P. Gouffon, et al., Phys. Rev. C **29**, 1137 (1984).
2. E. Wolynec and M. N. Martins, Rev. Brasil. Fis. **17**, 56 (1987).
3. V. V. Varlamov, N. N. Peskov, D. S. Rudenko, and M. E. Stepanov, Vopr. At. Nauki Tekh., Ser. Yad. Konst., Nos. 1–2, 48 (2003).
4. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, et al., Bull. Russ. Acad. Sci. **74**, 833 (2010).
5. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, et al., Bull. Russ. Acad. Sci. **74**, 842 (2010).
6. B. S. Ishkhanov and V. N. Orlin, Phys. Part. Nucl. **38**, 232 (2007).
7. B. S. Ishkhanov and V. N. Orlin, Phys. At. Nucl. **71**, 493 (2008).
8. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, and A. V. Sopov, Preprint NIIYad. Fiz. MGU-2010-8/864 (Inst. Nucl. Phys., Moscow State Univ., Moscow, 2010).
9. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, et al., Preprint NIIYad. Fiz. MGU-2011-5/869 (Inst. Nucl. Phys., Moscow State Univ., Moscow, 2011).
10. V. V. Varlamov, B. S. Ishkhanov, and V. N. Orlin, Phys. At. Nucl. **75**, 1339 (2012).
11. R. Bergère, H. Beil, and A. Veyssière, Nucl. Phys. A **121**, 463 (1968).
12. R. L. Bramblett, J. T. Caldwell, G. F. Auchampaugh, and S. C. Fultz, Phys. Rev. **129**, 2723 (1963).
13. A. Veyssière, H. Beil, R. Bergère, et al., Nucl. Phys. A **159**, 561 (1970).
14. R. R. Harvey, J. T. Caldwell, R. L. Bramblett, and S. C. Fultz, Phys. Rev. **136**, B126 (1964).
15. B. S. Ishkhanov, V. N. Orlin, and S. Yu. Troshchiev, Phys. At. Nucl. **75**, 253 (2012).