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NUCLEI
Experiment

Evaluation of Reliable Cross Sections of Photoneutron Reactions on ^{103}Rh and ^{165}Ho Nuclei

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Abstract—With the aim of studying the reasons for the discrepancies between the cross sections determined for total and partial photoneutron reactions from various experiments in beams of quasimonoenergetic annihilation photons, data on such cross sections are analyzed for ^{103}Rh and ^{165}Ho target nuclei. Objective physical criteria of data reliability are used in this analysis. It is shown that significant systematic uncertainties the methods of photoneutron multiplicity sorting that were used in those experiments result in the unreliability of experimental data on the cross sections of $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ partial reactions over wide regions of photon energies. New cross sections of photoneutron reactions on ^{103}Rh and ^{165}Ho nuclei and data reliability criteria are obtained by employing the experimental—theoretical method developed earlier for evaluating partial reaction cross sections. The evaluated photoneutron reaction cross sections are compared with experimental data.

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1. INTRODUCTION

The cross sections of partial [first of all, $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$] and total [$(\gamma, sn) = (\gamma, 1n) + (\gamma, n) + (\gamma, 3n) + \ldots$ and $(\gamma, xn) = (\gamma, 1n) + 2(\gamma, n) + 3(\gamma, 3n) + \ldots$] photoneutron reactions [1–4] are widely used both in fundamental and applied nuclear physics studies and in various applications in many realms, such as astrophysics, geology, chemistry, and medicine. Data of this kind were mostly obtained by means of the method of photoneutron multiplicity sorting in beams of quasimonoenergetic annihilation photons at the Lawrence Livermore National Laboratory (USA) and at the Saclay Nuclear Research Centre (CEA, France) [1, 2, 4], as well as using bremsstrahlung photons [3, 4].

Between the photoneutron reaction cross sections obtained in different experiments, there are significant discrepancies, both in shape and in magnitude, which are well known to specialists. In general, the discrepancies between the results of experiments performed in beams of quasimonoenergetic photons and of bremsstrahlung photons came as no surprise in view of the application of substantially different data processing procedures in deriving these results. In experiments of the first type, the cross sections of all partial reactions were measured directly by the method based on the multiplicity sorting of neutrons originating from such reactions and implemented with the aid of dedicated detectors [1, 2]. The (γ, xn) cross section was measured directly in experiments of the second type. The total photoneutron cross section $\sigma(\gamma, sn)$ was determined by introducing corrections in $\sigma(\gamma, xn)$ that were calculated on the basis of statistical nuclear reaction theory. The cross sections for $(\gamma, 2n)$ and $(\gamma, 3n)$ reactions were determined by means of respective difference procedures.

On the other hand, substantial discrepancies between the results of the Livermore and Saclay experiments, where the conditions of data acquisition and analysis were similar, were surprising and, for many years, have attracted the attention of researchers. For example, significant systematic discrepancies between the cross sections of $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions obtained in both laboratories for 19 nuclei (^{51}V, ^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, $^{116-118,120,124}$Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, and ^{238}U) were revealed [5–9]. It was found that, as a rule, $(\gamma, 1n)$ cross sections were larger in Saclay, while, the $(\gamma, 2n)$ cross sections were larger in Livermore by about 60% to 100%. It was shown that the average ratios of the integrated partial reaction cross sections obtained in Saclay and Livermore, $R^{\text{int}} = \sigma^{\text{int}}_{\text{S}}/\sigma^{\text{int}}_{\text{L}}$, are $\langle R^{\text{int}}(1n)\rangle \sim 1.08$ for the reactions featuring one neutron and $\langle R^{\text{int}}(2n)\rangle \sim 0.83$ for the reactions featuring two neutrons, the spread of values ranging from about 0.65 to about 1.35. Also, it was indicated that, for some nuclei from the above list (^{75}As, ^{124}Sn,

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and ^{238}U), the ratios of the integrated cross sections proved to be much less than the aforementioned ones and that their hierarchy was opposite to them. The presence of such large discrepancies directed differently, which exceed greatly the attained statistical uncertainties, posed acutely the problem of data reliability for partial reaction cross sections.

At the same time, the average discrepancy between the cross sections of (γ, xn) neutron-production reactions proves to be relatively small, about 10% [5–9]. This means that, in the methods used to determine partial reaction cross sections, there are significant systematic uncertainties stemming from shortcomings of the experimental method of photoneutron multiplicity sorting. Various recommendations were proposed with the aim of curing (taking into account) the aforementioned discrepancies between the partial reaction cross sections, but, unfortunately, they were not based on a systematic approach. Some of them [5] relied on various assumptions on the reasons behind the discrepancies between experimental data for specific nuclei and, in many cases, led to contradictory consequences, reducing the discrepancy between some experimental data—for example, on $(\gamma, 1n)$ cross sections—but increasing them for others—for example, on $(\gamma, 2n)$ cross sections, and vice versa. Other recommendations gave preference, on the basis of some criteria, to the Livermore data and matched with them substantially different Saclay data by rescaling partial reaction cross sections on the basis of consistent experimental data of the cross sections of the (γ, xn) neutron-production reaction [6–9].

With the aim of finding out which experimental data are reliable, the objective physical criteria of reliability of experimental data on cross sections of partial photoneutron reactions and an experimental–theoretical method for evaluating these cross sections [10] by employing these criteria together with quite consistent experimental data on the cross sections of the (γ, xn) neutron-production reaction were proposed.

For objective physical criteria of data the ratios F_i,

$$F_i = \sigma(\gamma, in)/\sigma(\gamma, xn), \quad (1)$$

which, by definition, should never exceed the limiting values of 1.00, 0.50, 0.33, ... for $i = 1, 2, 3, \ldots$, respectively, are used. An excess of the ratios $F_i^{\rm exp}$ above the limiting values would mean that the distribution of neutrons between partial reactions was performed with significant systematic errors, so that the experimental partial reaction cross sections $\sigma(\gamma, in)$ obtained in this way cannot be thought to be reliable. We can supplement the above reliability criteria with yet another one—since all terms of the ratios in (1) are reaction cross sections, physically reliable F_i should have positive values.

To date, the method outlined above has been applied to studying the majority of nuclei explored jointly in Livermore and Saclay (^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, $^{116-118,120,124}$Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{181}Ta, ^{197}Au, and ^{208}Pb), as well as many other ones (for example, ^{63,65}Cu, ^{76,78,80,82}Se, ^{91,94}Zr, ^{139}La, ^{145,148}Nd, ^{133}Cs, $^{186-192}$Os, and ^{209}Bi) [10–20]. It turned out that, in many cases, the experimental cross sections of partial photoneutron reactions did not satisfy the proposed physical data reliability criteria: there were many physically forbidden negative values of cross sections of various partial reactions—first of all, $(\gamma, 1n)$ reactions, for which the values of $F_i^{\rm exp}$ exceeded the aforementioned upper limits. The difference in the procedures used in Livermore and Saclay to identify events featuring different numbers of neutrons was found to be the main reason for significant discrepancies between partial reaction cross sections obtained at these two laboratories. A comparison of the evaluated and experimental reaction cross sections indicates that an unjustifiable overestimation of $(\gamma, 1n)$ cross sections at one laboratory (primarily in Saclay) and a respective unjustifiable overestimation of $(\gamma, 2n)$ cross section at the other laboratory (Livermore) was due to significant systematic uncertainties in the method of neutron multiplicity sorting. They led to an unreliable redistribution of a noticeable number of neutrons between channels characterized by different multiplicities.

With the aim of evaluating partial reaction cross sections that would satisfy the proposed objective physical reliability criteria, the experimental–theoretical method for evaluating partial reaction cross sections was proposed [10]. The experimental values of the cross section of the (γ, xn) neutron-production reaction, which are nearly unaffected by problems associated with neutron multiplicity sorting since they include all neutrons emitted in this reaction, are used to determine the contributions of partial reactions as

$$\sigma^{\rm eval}(\gamma, in) = F_i^{\rm theor}\sigma^{\rm exp}(\gamma, xn). \quad (2)$$

The transition neutron multiplicity functions in the form of the ratios $F_i^{\rm theor}$ (1) are calculated on the basis of the combined photonuclear reaction model (CPNRM) proposed in [21, 22].

This model is based on the preequilibrium exciton model. It employs nuclear level densities calculated within the Fermi gas model and takes into account the influence of nuclear deformations and isospin splitting of the giant dipole resonance (GDR) on the formation and decay of GDR states. As a

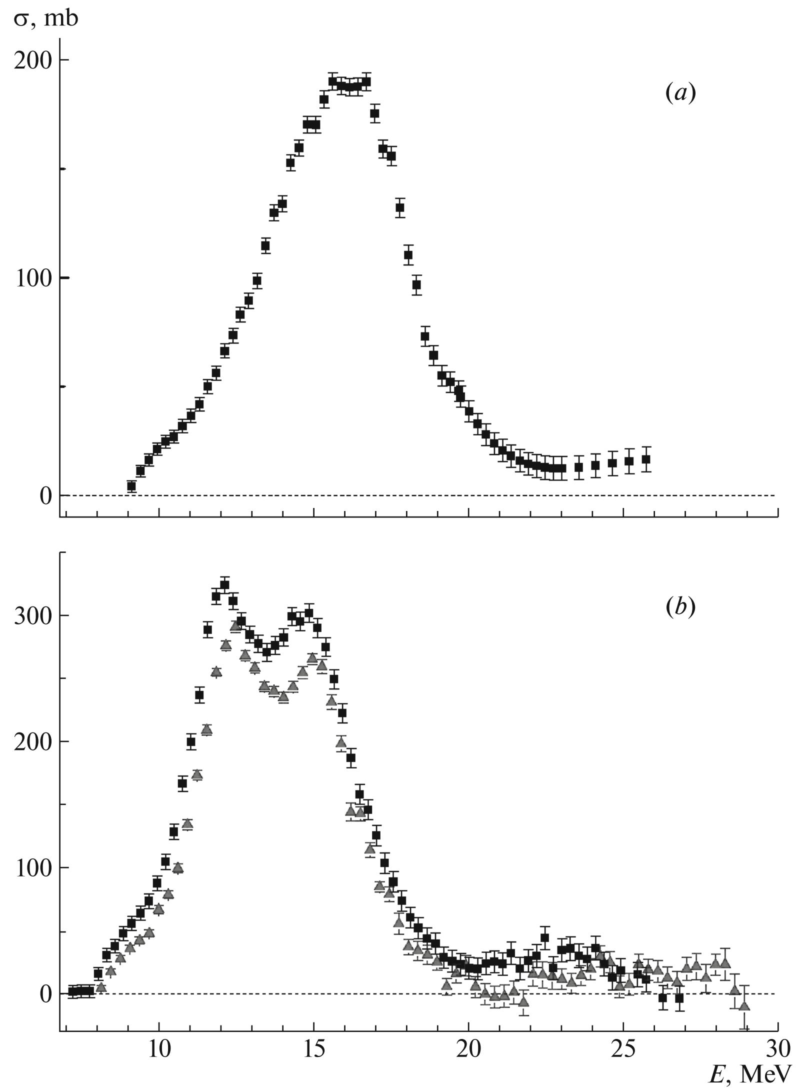

Fig. 1. Cross sections of $(\gamma, 1n)$ reactions on (a) ^{103}Rh [23] and (b) ^{165}Ho nuclei according to data from (closed triangles) [24] and (closed boxes) [25] versus E_γ.

result, the combined photonuclear reaction model describes successfully experimental data on cross sections of neutron production reactions for a large number of medium-heavy and heavy nuclei and makes it possible to calculate cross sections of partial reactions in a way free from problems of experimental neutron multiplicity sorting. New evaluated cross sections of partial (and total) photoneutron reactions were obtained for a large number of nuclei presented above.

For ^{181}Ta [13], ^{197}Au [20], and ^{209}Bi [19] nuclei, the evaluated cross sections for partial and total reactions were compared in detail with the results obtained by means of an alternative method for separating processes involving different numbers of neutrons—the activation method implemented in beams of bremsstrahlung photons. It was found that the reaction cross sections evaluated on the basis of our experimental-theoretical method agree with results of activation experiments (but disagree noticeably with the results of experiments performed with the aid of the method of neutron multiplicity sorting) and are therefore reliable. The results of this comparison give sufficient grounds to conclude that noticeable discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ may also be indicative of the unreliability of experimental data. For general objective physical criteria of reliability of data on cross sections of partial photoneutron reactions, we can therefore take the following ones: the ratios $F_i^{\rm exp}$ should not exceed the above upper limits, $\sigma^{\rm exp}(\gamma, in)$ and $F_i^{\rm exp}$ corresponding to them should not assume negative values, and the discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ should be insignificant.

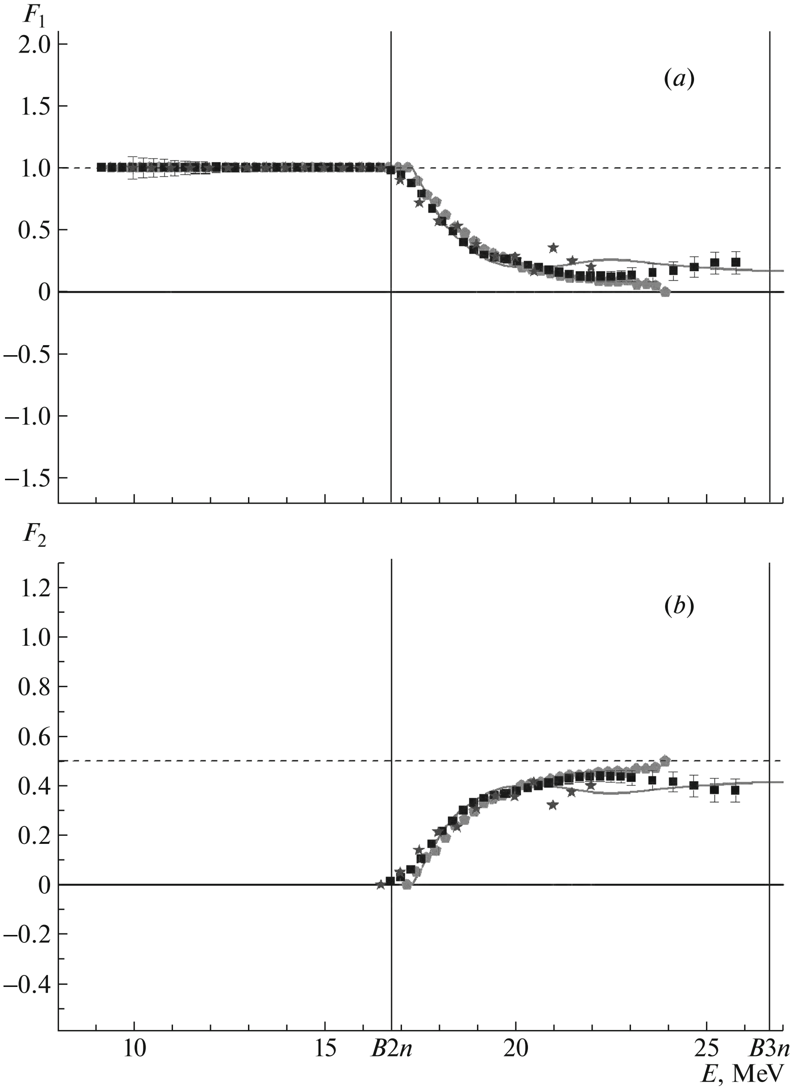

Fig. 2. Ratios $F_1^{\rm exp}$ and $F_2^{\rm exp}$ obtained for the isotope ^{103}Rh by employing experimental data {from (boxes) [23], (stars) [26], and (pentagons) [27]} along with their calculated counterparts $F_1^{\rm theor}$ and $F_2^{\rm theor}$ {from (curves) [21, 22]}. Thin vertical lines indicate the thresholds $B2n$ and $B3n$ for, respectively, $(\gamma, 2n)$ and $(\gamma, 3n)$ reactions. The notation in the figures that follow is identical to that used here.

2. ANALYSIS OF RELIABILITY OF EXPERIMENTAL DATA ON CROSS SECTIONS OF PARTIAL PHOTONEUTRON REACTIONS

In the present study, simultaneous analysis and evaluation of partial reaction cross sections $\sigma(\gamma, in)$ satisfying the above physical reliability criteria are performed for two medium-heavy nuclei, of which one (^{103}Rh) was investigated only in Saclay [23], while the other (^{165}Ho) was investigated in both laboratories [24, 25].

The energy dependences of the $(\gamma, 1n)$ cross sections of the two nuclei in question are given in Fig. 1. One can clearly see that all values of the Saclay cross section $\sigma(\gamma, 1n)_{\rm S}$, without exception, for either nucleus are positive. For the ^{165}Ho nucleus, the Livermore cross sections $\sigma(\gamma, 1n)_{\rm L}$ are significantly smaller than $\sigma(\gamma, 1n)_{\rm S}$. In the region of the main cross-section maximum (from about 12 to 16 MeV), the discrepancy becomes as large as about 50 mb, the cross section magnitude there being about 300 mb. Starting from moderately low energies of about 20 MeV, the cross section $\sigma(\gamma, 1n)_{\rm L}$ becomes close to zero; moreover, it takes physically forbidden negative values at some neutron energies. This analysis of the experimental reaction cross sections $\sigma(\gamma, 1n)$ obtained in Saclay and Livermore demonstrates the need for obtaining reliable experimental data on cross sections of partial reactions on the nuclei being considered.

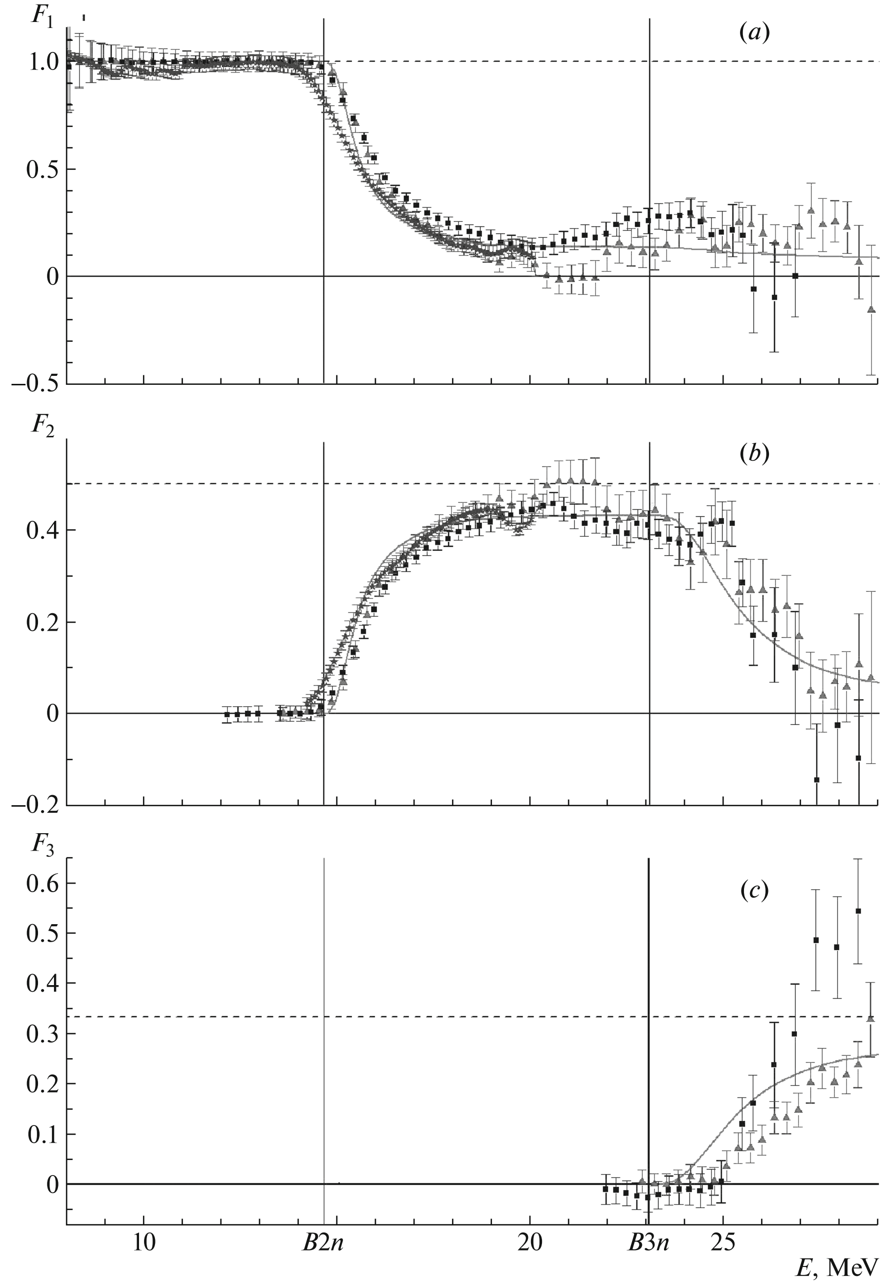

Fig. 3. Ratios F_1^{exp}, F_2^{exp}, and F_3^{exp} obtained for the isotope ^{165}Ho by employing experimental data {from (triangles) [24], (boxes) [25], and (stars) [28]} along with their calculated counterparts F_1^{theor}, F_2^{theor}, and F_3^{theor} {from (curves) [21, 22]}.

As was indicated in the preceding section, the neutron multiplicity transition functions in the form of the ratios F_i given by Eq. (1) were proposed [10] for use as objective physical criteria of reliability of data on cross sections for partial photoneutron reactions. Figures 2 and 3 illustrate a comparison of the energy dependences of F_i^{exp} and F_i^{theor} [21, 22] for the two nuclei being considered.

For the ^{103}Rh nucleus (see Fig. 2), the ratios F_i^{exp} obtained on the basis of Saclay data [23] and the results of two experiments reported in [26, 27] and performed in beams of bremsstrahlung photons are presented. One can see that F_i^{exp} and F_i^{theor} agree for all of these experiments at all energies, with the exception of the those in the range between about 21 and 24 MeV, where the F_1^{exp} values are significantly lower than the values of F_1^{theor}, while the F_2^{exp} values are, on the contrary, significantly higher than the values of F_2^{theor}.

Table 1. Integrated cross sections $\sigma^{\rm int}$ (in mb MeV units) based on evaluated cross sections of total and partial photoneutron reactions of the ^{103}Rh nucleus along with experimental data [23]

	$E^{\rm int} = B2n = 16.7$ MeV	$E^{\rm int} = 21.0$ MeV	$E^{\rm int} = 24.0$ MeV	$E^{\rm int} = 26.0$ MeV
		(γ, xn)		
[23]*	757.8 ± 5.7	1635.8 ± 9.1	1822.0 ± 11.0	1966.1 ± 13.5
Evaluation	776.9 ± 33.0	1648.9 ± 49.7	1822.1 ± 50.7	1949.9 ± 51.9
		(γ, sn)		
[23]	757.8 ± 5.7	1385.6 ± 8.5	1491.6 ± 10.1	1578.9 ± 12.2
Evaluation	747.4 ± 39.0	1391.4 ± 55.6	1507.8 ± 57.9	1594.4 ± 60.2
		$(\gamma, 1n)$		
[23]	757.4 ± 5.7	1135.6 ± 8.5	1161.5 ± 10.1	1192.0 ± 12.2
Evaluation	747.4 ± 36.0	1157.5 ± 46.6	1204.1 ± 47.5	1233.1 ± 48.3
		$(\gamma, 2n)$		
[23]		258.4 ± 5.8	338.6 ± 6.4	395.4 ± 7.4
Evaluation		234.0 ± 12.0	303.8 ± 13.8	361.3 ± 15.9

* Integrated cross sections obtained by employing data from [23], which were used in the evaluation procedure based on Eq. (2).

The relationships between $F_i^{\rm theor}$ [21, 22] and $F_i^{\rm exp}$ [24, 25, 28] for the ^{165}Ho nucleus (see Fig. 3) are substantially more diverse.

By means of bremsstrahlung gamma radiation [28], experimental data on $F_1^{\rm exp}$ and $F_2^{\rm exp}$ were obtained only up to an energy of about 20 MeV. They deviate noticeably from their theoretical counterparts $F_1^{\rm theor}$ and $F_2^{\rm theor}$. For example, $F_1^{\rm exp}$ is significantly less than $F_1^{\rm theor}$ at energies below about 16 MeV and is significantly greater that at higher energies. As might have been expected, the hierarchy of $F_2^{\rm exp}$ and $F_2^{\rm theor}$ is inverse.

In the energy range from the $(\gamma, 2n)$ threshold $B2n = 14.7$ MeV to an energy of about 25 MeV, the ratios $F_1^{\rm exp}$ obtained on the basis of Saclay data exceed significantly $F_1^{\rm theor}$. The largest positive deviations at energies around 25.5 MeV and the largest negative deviations at energies between about 25.5 and 29.0 MeV (physically forbidden negative values of $F_1^{\rm exp}$ being present) are seen. Accordingly, $F_2^{\rm exp}$ values obtained from Saclay data are smaller than $F_2^{\rm theor}$ values, maximum deviations and negative values arising at energies in excess of about 25 MeV. In this energy region, the values of $F_3^{\rm exp}$ exceed significantly not only $F_3^{\rm theor}$ but also the physical limit of 0.33 admissible by definition.

Livermore data on $F_1^{\rm exp}$ agree fairly well with $F_1^{\rm theor}$ in the energy region extending up to about 20 MeV and in the energy range between about 22.0 and 23.5 MeV. In the energy range between about 20 and 22 MeV, the values of $F_1^{\rm exp}$ are close to zero and are significantly smaller than the values of $F_1^{\rm theor}$, while, in the region of energies above about 23.5 MeV, the former exceed significantly the latter. The relationships between $F_2^{\rm exp}$ and $F_2^{\rm theor}$ are inverse with respect to the relationships between $F_1^{\rm exp}$ and $F_1^{\rm theor}$. In the energy range between about 20 and 22 MeV, the values of $F_2^{\rm exp}$ exceed significantly $F_2^{\rm theor}$ and prove to be close to limiting (by definition) value of 0.50. Over the whole energy region studied in the experiments under analysis, the values of $F_3^{\rm exp}$ are significantly smaller than the values of $F_3^{\rm theor}$.

Such discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ show that the reliability of the experimental data under analysis on the cross sections $\sigma(\gamma, in)$ for either of the above two nuclei is questionable.

3. EVALUATION OF NEW RELIABLE REACTION CROSS SECTIONS BY THE EXPERIMENTAL–THEORETICAL METHOD

With the aim of overcoming the problems associated with the unreliability of experimental cross sections of partial cross sections, the experimental–theoretical method was proposed [10] for obtaining evaluated partial reaction cross sections that are independent of systematic uncertainties inherent in the experimental neutron multiplicity sorting

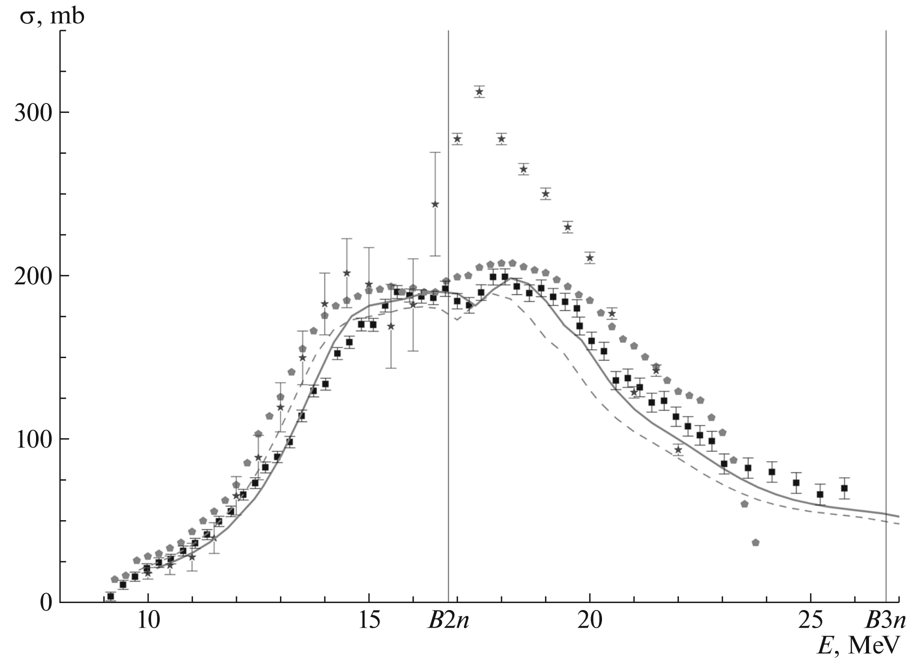

Fig. 4. Comparison of (dashed curve) uncorrected and (solid curve) corrected theoretical data [21, 22] on the cross sections of the photoneutron-production reaction ^{103}Rh(γ, xn) with experimental data from (boxes) [23], (stars) [26], and (pentagons) [27].

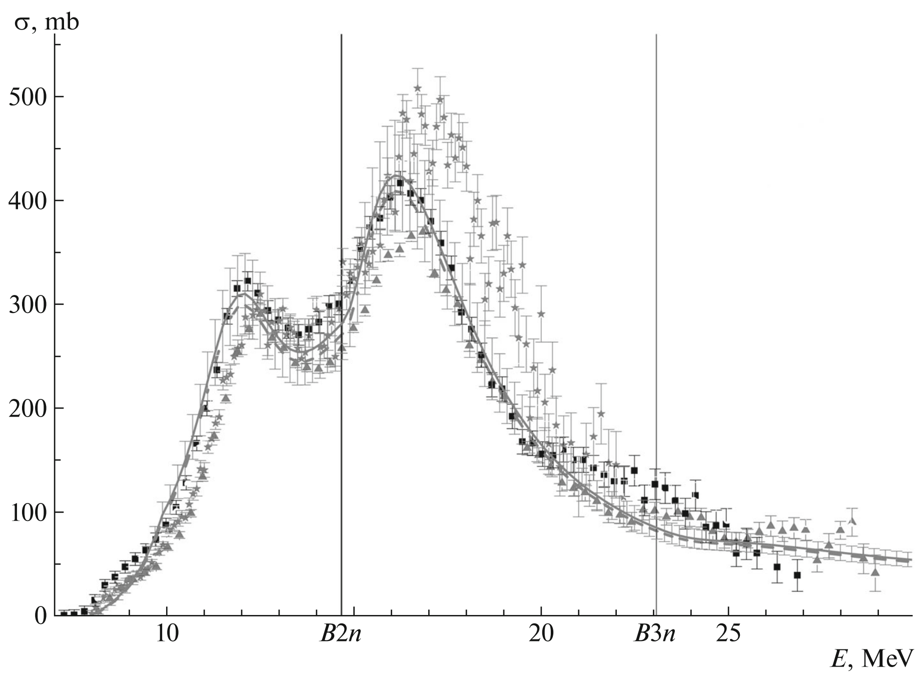

Fig. 5. Comparison of (dashed curve) uncorrected and (solid curve) corrected theoretical data [21, 22] on the cross sections of the photoneutron-production reaction ^{165}Ho(γ, xn) with experimental data from (triangles) [24], (boxes) [25], and (stars) [28].

method. Within this method, the ratios of the partial cross sections are determined by model concepts ($F_i^{\rm theor}$), while their sum, $\sigma^{\rm eval}(\gamma, xn)$, is taken to be $\sigma^{\rm exp}(\gamma, xn)$ according to Eq. (2).

Within the procedure for evaluating $F_i^{\rm theor}$, the respective theoretical total cross sections $\sigma^{\rm theor}(\gamma, xn)$ were slightly corrected in order to render them maximally close to $\sigma^{\rm exp}(\gamma, xn)$. For example, the cross

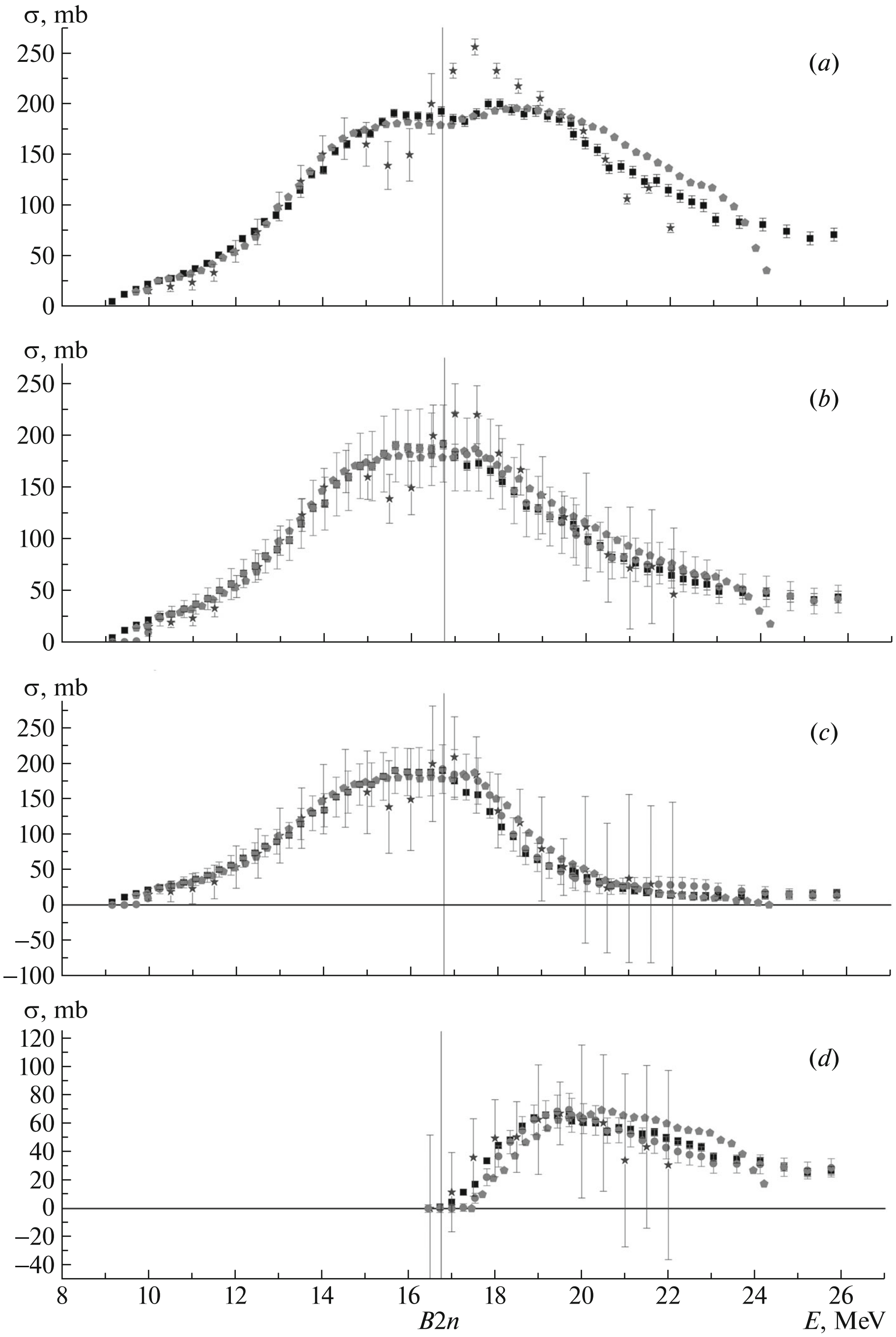

Fig. 6. Comparison of (circles) evaluated and (boxes [23], stars [26], and pentagons [27]) experimental cross sections of reactions occurring on the isotope ^{103}Rh: (*a*) $\sigma(\gamma, xn)$, (*b*) $\sigma(\gamma, sn)$, (*c*) $\sigma(\gamma, 1n)$, and (*d*) $\sigma(\gamma, 2n)$. In Fig. 6*a*, the evaluated cross section is in perfect agreement with the original experimental cross section [23].

section $\sigma^{\text{theor}}(\gamma, xn)$ for the ^{103}Rh nucleus (see Fig. 4) was shifted with respect to the experimental cross section from [23] along the energy scale toward higher energies by 0.40 MeV and was multiplied by the factor of 1.10. In the case of the ^{165}Ho nucleus, the respective values for the cross section $\sigma^{\text{theor}}(\gamma, xn)$ are 1.07 MeV and 0.10. The corrected results for the ^{165}Ho nucleus are given in Fig. 5. In the region of the main maximum, the theoretical cross section is the most close to the Saclay experimental data from [25], and this is the reason why we use them in our evaluation procedure on the basis of Eq. (2).

The energy dependences of the evaluated cross sections of photoneutron reactions are shown in Fig. 6 along with experimental data for the ^{103}Rh.

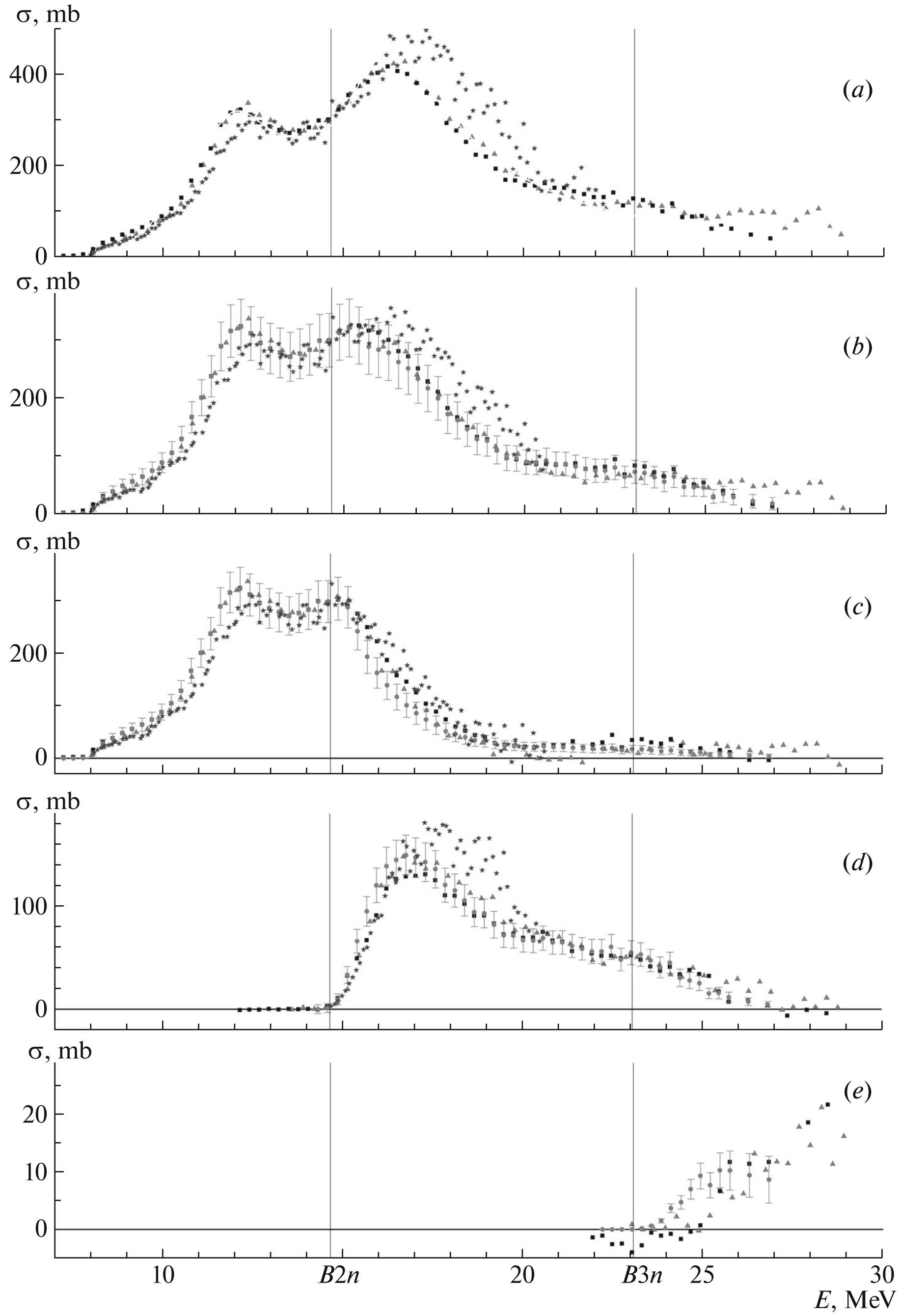

Fig. 7. Comparison of (circles) evaluated and (boxes [24], (stars) [25], and (pentagons) [28]) experimental cross sections of reactions occurring on the isotope ^{165}Ho: (a) $\sigma(\gamma, xn)$, (b) $\sigma(\gamma, sn)$, (c) $\sigma(\gamma, 1n)$, (d) $\sigma(\gamma, 2n)$, and (e) $\sigma(\gamma, 3n)$. In Fig. 7*a*, the evaluated cross section is in perfect agreement with the original experimental cross section [25].

The respective integrated cross sections for various integration limits are given in Table 1. Particular attention is given there to the energy range between 21 and 24 MeV, where (see Fig. 2) the largest discrepancies between the ratios $F_i^{\rm exp}$ and $F_i^{\rm theor}$ obtained from the Saclay and Livermore data are observed. The cross sections measured for all partial and total reactions in bremsstrahlung photon beams differ significantly from the evaluated cross sections. This is likely to be due to large statistical uncertainties in experimental data.

The experimental data obtained in Saclay exhibit clear-cut consequences of an unreliable redistribution of neutrons between partial reactions involving one and two neutrons. One can see that, in the energy region extending up to 26.0 MeV, the experimental

Table 2. Integrated cross sections σ^{int} (in mb MeV units) on the basis of evaluated cross sections of total and partial photoneutron reactions on ^{165}Ho nuclei along with experimental data [24, 25]

	$E^{\text{int}} = B2n = 14.7$ MeV	$E^{\text{int}} = B3n = 23.1$ MeV	$E^{\text{int}} = 27.0$ MeV	$E^{\text{int}} = 28.5$ MeV
		(γ, xn)		
[24]	1248.8 ± 17.6	3353.5 ± 33.6	3742.2 ± 37.8	3867.2 ± 39.8
[25]*	1272.3 ± 12.4	3353.5 ± 24.4	3663.7 ± 31.8	3722.8 ± 36.8
Evaluation	1272.3 ± 12.4	3353.5 ± 24.4	3663.7 ± 31.8	3722.8 ± 36.8
		(γ, sn)		
[24]	1247.5 ± 17.5	2628.4 ± 27.6	2849.6 ± 29.4	2913.4 ± 30.4
[25]	1271.7 ± 11.4	2694.2 ± 27.6	2870.6 ± 26.9	2888.6 ± 30.6
Evaluation	1270.3 ± 29.7	2634.8 ± 41.6	2796.3 ± 43.5	2822.4 ± 44.6
		$(\gamma, 1n)$		
[24]	1245.8 ± 17.6	1899.0 ± 27.1	1973.3 ± 30.1	2003.5 ± 31.9
[25]	1270.4 ± 9.7	2055.8 ± 17.5	2119.2 ± 22.2	2113.4 ± 25.3
Evaluation	1269.6 ± 29.6	1917.4 ± 34.0	1955.2 ± 34.2	1961.0 ± 34.2
		$(\gamma, 2n)$		
[24]		724.6 ± 13.3	850.6 ± 16.8	858.8 ± 18.1
[25]		664.2 ± 8.7	767.0 ± 11.0	762.7 ± 12.2
Evaluation		716.6 ± 16.2	815.5 ± 17.8	822.9 ± 18.0
		$(\gamma, 3n)$		
[24]			20.0 ± 3.3	46.6 ± 4.3
[25]			16.7 ± 5.6	44.9 ± 6.9
Evaluation			24.9 ± 3.8	37.8 ± 6.0

* Integrated cross sections obtained by employing data from [25], which were used in the evaluation procedure based on Eq. (2).

cross section of the $(\gamma, 1n)$ reaction is approximately 3% (1233.1 to 1192.0 mb MeV) smaller than its evaluated counterpart, whereas the experimental cross section of the $(\gamma, 2n)$ reaction is, on the contrary, larger than the evaluated cross section by about 10% (395.3 to 361.3 mb MeV). In the energy region where the discrepancies between F_i^{exp} and F_i^{theor} are the largest (21–24 MeV), the difference between the experimental and evaluated cross sections is also more significant: 56% (46.6 to 29.9 mb MeV) for the $(\gamma, 1n)$ reaction and 16% (80.2 to 69.8 mb MeV) for the $(\gamma, 2n)$ reaction. As a matter of fact, these discrepancies mean the transfer of a considerable number of neutrons from the $(\gamma, 1n)$ reaction to the $(\gamma, 2n)$ reaction.

The circumstance that the relationships between the experimental and evaluated cross sections of the ^{103}Rh nucleus in the data obtained in Saclay differ from those established for a large number of other nuclei studied at that laboratory attracts attention. Instead of a characteristic overestimation of the cross section of the $(\gamma, 1n)$ reaction and an underestimation of the cross section of the $(\gamma, 2n)$ reaction, one observes inverse relationships, which are more characteristic of the Livermore data. In this respect, the situation around the ^{103}Rh nucleus is similar to the situations around the ^{75}As, ^{124}Sn, and ^{238}U nuclei mentioned above. It is noteworthy that those relationships between the Saclay experimental and evaluated data that are characteristic of the Livermore data were also found in [29] for the isotopes ^{76,78,80,82}Se studied in Saclay [30].

This confirms directly one of the basic conclusions drawn in earlier studies [10–20] that the relation between the measured kinetic energy of neutrons and their multiplicity to be determined is indirect and is quite intricate.

The evaluated cross sections of partial and total photoneutron reactions on ^{165}Ho nuclei are given in Fig. 7 along with relevant experimental data, while the respective integrated cross sections are presented in Table 2. In just the same way as in the case of the ^{103}Rh nucleus, the experimental data obtained in beams of bremsstrahlung photons for the cross sections of all partial and total reactions differ significantly from the evaluated data.

A comparison of the evaluated and experimental cross sections indicates once again that there are significant systematic uncertainties in the experimental cross sections of partial reactions. For example, the evaluated integrated cross section for the $(\gamma, 1n)$ reaction in the energy range between $B2n = 14.7$ MeV and $B3n = 23.1$ MeV (643.7 mb MeV) is close to the Livermore data (653.2 mb MeV) but is 22% smaller than the Saclay data (785.4 mb MeV). At the same time, the situation around the cross section of the $(\gamma, 2n)$ reaction is diametrically opposite—the evaluated cross section (98.9 mb MeV) is close to the Saclay data (102.8 mb MeV) but is 27% smaller than the Livermore data (126.0 mb MeV). It is noteworthy that similar discrepancies calculated for higher energies ($E^{\rm int} = 27.0$ and 28.5 MeV) are somewhat smaller both for the Saclay and for the Livermore data. This is due to the presence of physically forbidden negative values in the $(\gamma, 1n)$ cross sections obtained at the Saclay and Livermore laboratories, as well as in the $(\gamma, 2n)$ cross section obtained in Saclay (see Figs. 1 and 3).

Similar discrepancies between the evaluated and experimental integrated cross sections are observed for the $(\gamma, 3n)$ reaction as well. For example, the evaluated cross section in the energy region extending up to $E^{\rm int} = 27.0$ MeV (24.9 mb MeV), where (Fig. 3) there are no negative values, is 25% larger than the Livermore result (20.0 mb MeV). The experimental data obtained in Saclay, which include a large number of negative values, yield a cross section value (16.7 mb MeV) that differs from its evaluated counterpart by about 50%. The relative proximity of the integrated cross sections calculated according to the Livermore and Saclay data that is observed up to the energy of $E^{\rm int} = 28.5$ MeV despite a significant discrepancy between the respective ratios $F_3^{\rm exp}$ (see Fig. 3) is due to the presence of a large number of negative values in the Saclay data.

4. CONCLUSIONS

In order to analyze systematic uncertainties in experimental cross sections of partial photoneutron reactions on ^{103}Rh and ^{165}Ho nuclei, we have made use of objective physical reliability criteria in the form of the ratios $F_i = \sigma(\gamma, in)/\sigma(\gamma, xn)$ of the cross sections for specific partial reactions to the cross section for the neutron-production reaction. By analogy with the results of earlier studies reported in [10–20], we have shown that the experimental cross sections obtained for the $(\gamma, 1n)$ and $(\gamma, 2n)$ partial reactions on both nuclei under study and additionally for the $(\gamma, 3n)$ reaction on the ^{165}Ho nucleus in beams of quasimonochromatic annihilation photons by the method of photoneutron multiplicity sorting are unreliable. Among these data, one observes physically forbidden negative partial cross sections, which correspond to $F_i^{\rm exp}$ values exceeding physically admissible upper limits, as well as large discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$. This incorrectness is due primarily to an unreliable (erroneous) transfer of a noticeable number of neutrons from one partial reaction to another because of significant systematic errors in the procedure for experimentally determining the multiplicity of neutrons on the basis of measurement of their energy.

In view of the aforementioned deviations of the Saclay experimental data for the ^{103}Rh nucleus from typical experimental data obtained for a large number of other nuclei and their similarity to the obviously unreliable Livermore data, it is highly desirable to compare the results of experiments performed by means of the method of neutron multiplicity sorting with the results obtained by different methods for the separation of partial reactions. Alternative experiments may include those performed by the activation method in beams of bremsstrahlung photons [31, 32] and those performed in beams of photons from the inverse Compton scattering of relativistic electrons on a beam from a powerful laser with the aid of a photoneutron detector whose efficiency is nearly independent of energy (see, for example [33]).

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