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NUCLEI
Experiment

New Data on Photoneutron Reaction Cross Sections for ^{76,78,80,82}Se Nuclei

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Abstract—The problem of reliability of the cross section data obtained for partial photoneutron reactions on ^{76,78,80,82}Se nuclei in beams of quasimonoenergetic annihilation photons by means of neutron multiplicity sorting is discussed by employing objective physical criteria. It is shown that, because of substantial systematic uncertainties, experimental data on the $(\gamma, 1n)$ and $(\gamma, 2n)$ cross sections are unreliable. New data satisfying the reliability criteria are obtained for the partial photoneutron reaction cross sections for ^{76,78,82}Se nuclei by an experimental—theoretical method for evaluating such cross sections and are compared with experimental data and with data evaluated earlier for the isotope ^{80}Se. The evaluated integrated cross sections for the total photoneutron reactions on ^{76,78,80,82}Se nuclei are compared with the predictions of the Thomas—Reiche—Kuhn classical dipole sum rule.

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1. INTRODUCTION

Cross sections for photoneutron reactions leading to the emission of various numbers of particles are widely used in fundamental nuclear physics studies, as well as in various applications in the realms of nuclear physics, astrophysics, geology, chemistry, and medical sciences [1—3]. These are, primarily $(\gamma, 1n)$, $(\gamma, 1n1p)$, $(\gamma, 2n)$, and $(\gamma, 3n)$, reactions. The majority of relevant data were obtained by means of photoneutron multiplicity sorting in beams of quasimonochromatic annihilation photons at the Lawrence Livermore National Laboratory (USA) and at the Nuclear Research Centre in Saclay (France) [1, 2, 4].

Significant systematic discrepancies were found [5—7] in the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ cross sections for 19 nuclei from ^{51}V to ^{232}Th that were studied in these two laboratories. It turned out that, as a rule, the $(\gamma, 1n) + (\gamma, 1n1p)$ cross sections were larger (by about 60% to 100%) in Saclay, while the $(\gamma, 2n)$ cross sections were on the contrary larger in Livermore. For the aforementioned nuclei, the average value of the ratio of the integrated reaction cross sections obtained in Saclay and Livermore is 1.08 in the case of $(\gamma, 1n) + (\gamma, 1n1p)$ reactions and 0.84 in the case of $(\gamma, 2n)$ reactions. At the same time, the average discrepancy between the cross sections for the neutron yield reaction

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

turns out to be about 10%. This means that, in the cross sections for the above partial reactions, there are significant systematic uncertainties associated with drawbacks of the method based on photoneutron multiplicity sorting.

An experimental—theoretical method for evaluating partial reaction cross sections was proposed in [8] with the aim of finding out which data are reliable. In employing this method, the experimental cross section that corresponds to the neutron yield reaction (1) and which is independent of problems inherent in the method of neutron multiplicity sorting since it takes into account all neutrons emitted in this reaction is separated for the partial reaction contributions,

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

by using the transition neutron multiplicity functions

$$F_i^{\text{theor}} = \sigma^{\text{theor}}(\gamma, in) / \sigma^{\text{theor}}(\gamma, xn), \quad (3)$$

calculated on the basis of the combined photonuclear-reaction model (CPNRM) proposed in [9, 10]. The preequilibrium exciton model is based on employing nuclear level densities calculated within the Fermi gas model. It takes into account the effect exerted by the nuclear deformation and by the isospin splitting of the giant dipole resonance (GDR) on processes of GDR formation and decay. The model describes successfully experimental data on the cross sections for neutron yield reactions on a large number of

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medium mass and heavy nuclei and permits evaluating cross sections for partial reactions in a way free from shortcomings of neutron multiplicity sorting.

The ratios $F_i^{\rm theor}$ in (3) were calculated for (γ, in) partial reactions at specific neutron multiplicities of $i = 1, 2, 3, \ldots$. It was shown that the analogous experimental ratios obtained for a specific reaction could be used as objective physical criteria of the reliability of data [8]. According to the definition of the above ratios in (3), they can never exceed the limits of 1.00, 0.50, 0.33, …for, respectively, $i = 1, 2, 3, \ldots$. If the ratios $F_i^{\rm exp}$ exceed the above limiting values, then the distribution of neutrons among the partial reactions in the respective experiment involved significant systematic uncertainties, so that the resulting reaction cross sections are unreliable.

The reliability criteria formulated in the way outlined above should be supplemented with the condition requiring that physically reliable values of the ratios F_i be positive since all terms in these ratios are reaction cross sections.

For a large number of medium mass and heavy nuclei (including ^{63,65}Cu, ^{80}Se, ^{91,94}Zr, ^{115}In, $^{112-124}$Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, ^{181}Ta, $^{186-192}$Os, ^{197}Au, ^{208}Pb, and ^{209}Bi), it was shown in [6–8, 11–16] that, in many cases, the experimental cross sections for partial photoneutron reactions do not satisfy the proposed physical criteria of data reliability. They exhibit a large number of physically forbidden negative cross section values for various reactions—first of all, $(\gamma, 1n) + (\gamma, 1n1p)$ reactions—and/or values for (γ, in) reactions such at which the ratios $F_i^{\rm exp}$ exceed the aforementioned upper limits.

It was also shown that noticeable discrepancies between the partial reaction cross sections as determined in Livermore and Saclay are due to the use of different procedures for obtaining the number of events featuring one and two neutrons.

A detailed comparison of new evaluated data for ^{181}Ta [12] and ^{209}Bi [16] nuclei with results obtained by measuring the yields of the respective reactions in a bremsstrahlung photon beam by the activation method was performed in [17, 18]. Within this method, which is an alternative to neutron multiplicity sorting, a direct identification of a specific partial reaction relies on information about final state nuclei rather than on data on emitted neutrons. The ratios of the $[(\gamma, xn)$, where $x = 1$–$6]$ cross sections for ^{181}Ta and ^{209}Bi nuclei were determined by simultaneously employing the measured reaction yields and the results of CPNRM calculations. It was found that, although the reaction cross sections evaluated by means of the proposed experimental–theoretical method deviate significantly from experimental results obtained on the basis of neutron multiplicity sorting, they agree with the results of activation experiments and are therefore reliable. This conclusion is confirmed by a detailed comparison in [19] of the evaluated data on the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ cross sections for the ^{197}Au nucleus with experimental data obtained by the activation method in a beam of bremsstrahlung photons [20]. This comparison gives grounds to supplement the above objective physical criteria of reliability of data on partial reaction cross sections with the statement that noticeable discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ may also be indicative of unreliability of experimental data.

Thus, the criteria of reliability of data on the cross sections for partial photoneutron reactions can be formulated in the following general form:

(i) The ratios $F_i^{\rm exp}$ should not have values that exceed the above upper limits.

(ii) $\sigma^{\rm exp}(\gamma, in)$ and respective $F_i^{\rm exp}$ should not take negative values.

(iii) The discrepancies between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ should not be noticeable.

Earlier, it was shown [15] that the experimental data in [21] on the cross sections for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ partial reactions on ^{80}Se nuclei are not reliable. In the region of energies above some 24 MeV, one observes negative cross section values for the former and cross section values for which $F_2 > 0.50$ for the latter. The evaluated data were compared with experimental data, and it was shown that the discrepancies were due primarily to unreliably (erroneously) redistributing a noticeable number of neutrons between the two partial reactions in question.

The present study is devoted to an analysis of reliability of experimental cross sections from [21] on partial photoneutron reactions on the isotopes ^{76,78,82}Se.

2. ANALYSIS OF RELIABILITY OF CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS BY MEANS OF OBJECTIVE PHYSICAL CRITERIA

As was indicated above, the ratios of the cross sections for specific partial reactions to the cross section for the neutron yield reaction,

$$F_i^{\rm exp} = \sigma^{\rm exp}(\gamma, in)/[\sigma^{\rm exp}(\gamma, 1n) + \sigma^{\rm exp}(\gamma, 1n1p) + 2\sigma^{\rm exp}(\gamma, 2n) + 3\sigma^{\rm exp}(\gamma, 3n) + \ldots]. \quad (4)$$

were proposed in [8] as objective physical criteria of reliability of data on the cross sections for partial photoneutron reactions.

With the aid of the proposed reliability criteria, it was shown in [6–8, 11–16] that, for a large number

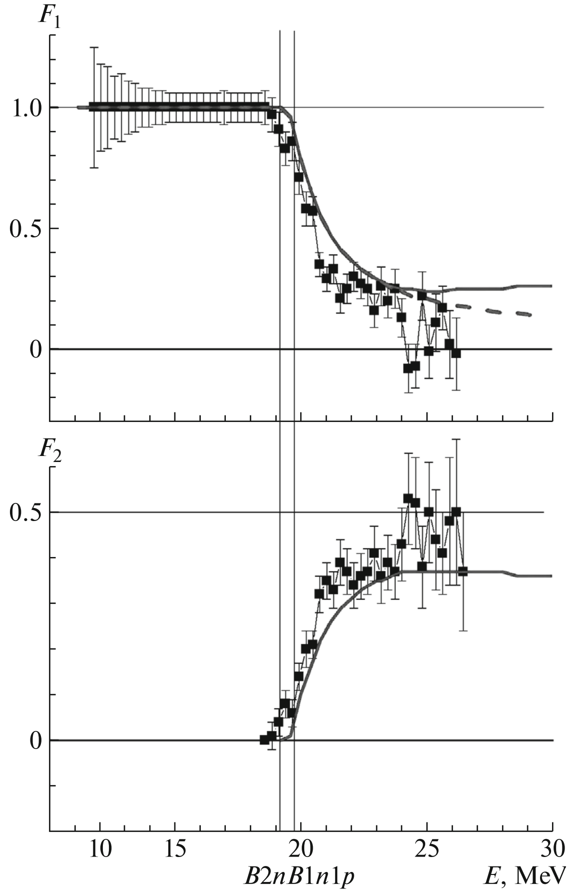

Fig. 1. Ratios F_1^{exp} and F_2^{exp} obtained for the isotope ^{76}Se by using (■) the Saclay experimental data [21] along with (solid curves) the results of calculations for F_1^{theor} and F_2^{theor} [10, 11]. The dashed curves correspond to the results obtained without allowance for the contributions of the $(\gamma, 1n1p)$ reaction.

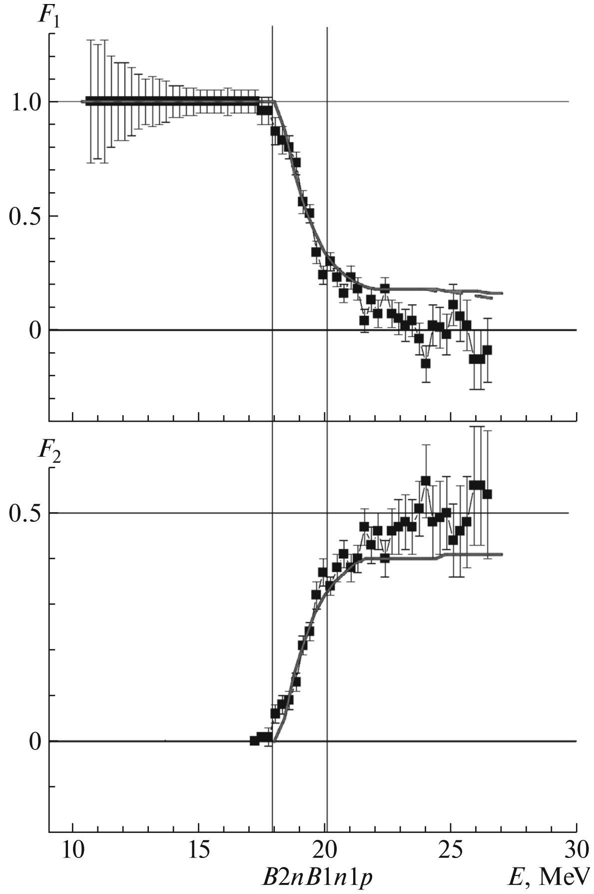

Fig. 2. As in Fig. 1, but for the isotope ^{78}Se.

of medium mass and heavy nuclei (including ^{63,65}Cu, ^{80}Se, ^{91,94}Zr, ^{115}In, $^{112-124}$Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, ^{181}Ta, $^{186-192}$Os, ^{197}Au, ^{208}Pb, and ^{209}Bi), the experimental cross sections obtained for partial photoneutron reactions by means of neutron multiplicity sorting are not reliable. In many regions of photon energies, one observes negative values of the ratios F_1^{exp} and/or negative values of F_2^{exp} as well or, on the contrary, F_2^{exp} values exceeding the physically admissible upper limit of 0.50 and/or negative values of the ratio F_3^{exp} or, on the contrary, its values exceeding the physically admissible upper limit of 0.33.

The case of data for the isotope ^{80}Se is quite typical. This case was studied earlier in [15], and it was found that, in the region of energies above the threshold $B2n = 16.9$ MeV for the reaction $^{80}\mathrm{Se}(\gamma, 2n)^{78}\mathrm{Se}$, the ratios F_1^{exp} are substantially smaller than the ratios F_1^{theor}, while the ratios F_2^{exp} are, on the contrary, substantially greater than the ratios F_2^{theor}. Moreover, a large number of negative values of the ratio F_1^{exp} and a large number of F_2^{exp} values exceeding the physically admissible upper limit of 0.50 appear in the energy range of ∼24–28 MeV.

Figures 1–3 illustrate a comparison of the ratios $F_{1,2}^{\mathrm{exp}}$ and $F_{1,2}^{\mathrm{theor}}$ obtained on the basis of experimental data from [21] for the isotopes ^{76,78,82}Se.

In these figures, the dashed curves represent the results of the calculations performed without taking into account the $(\gamma, 1n1p)$ contributions. It can be seen that these contributions are negligible. In view of this, the notation $(\gamma, 1n)$ will henceforth be used for reactions involving the emission of one neutron.

One can clearly see that there are solid grounds to question the reliability of experimental data for the isotopes ^{76,78,82}Se, as was done earlier [15] for the respective data on the isotope ^{80}Se. For all three isotopes ^{76,78,82}Se, there are noticeable discrepancies between the values of F_i^{exp} and F_i^{theor}—in relation to the isotope ^{80}Se, they are smaller in the case of the isotopes ^{76,82}Se but are greater in the case of the isotope ^{78}Se—and clear-cut correlations between the

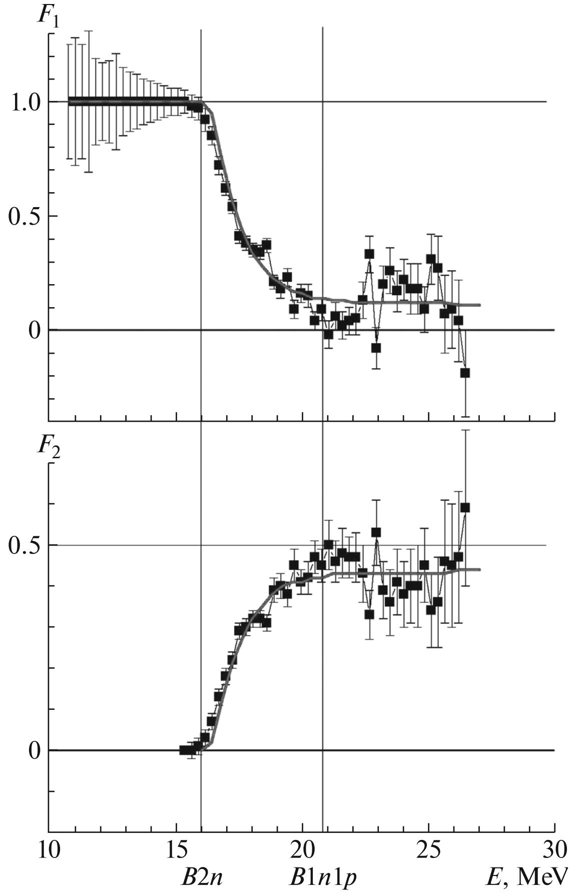

Fig. 3. As in Fig. 1 but for the isotope ^{82}Se. The dashed and solid curves virtually coincide.

underestimated data for $(\gamma, 1n)$ reactions and overestimated data for $(\gamma, 2n)$ reactions.

Additionally, we would like to highlight a rather strange behavior of the energy dependences of $F_1^{\rm exp}$ and $F_2^{\rm exp}$ for the ^{82}Se nucleus in the region of energies above some 21 MeV: the ratios $F_1^{\rm exp}$ are substantially smaller than $F_1^{\rm theor}$, while the ratios $F_2^{\rm exp}$ are on the contrary substantially greater than $F_2^{\rm theor}$.

Thus, the data in Figs. 1–3 suggest that the reliability of the cross sections obtained in [21] for $(\gamma, 1n)$ and $(\gamma, 2n)$ partial reactions is questionable for all of the isotopes ^{76,78,80,82}Se. The doubts as to whether those data are reliable are associated with shortcomings of the experimental method [21] of neutron multiplicity sorting on the basis of measurements of the neutron energy. In [17, 22–24], the energy spectra of photoneutrons from ^{116}Sn, ^{141}Pr, ^{181}Ta, ^{186}W, ^{208}Pb, and ^{209}Bi nuclei were calculated within the CPNRM approach, and it was shown there that the proximity of the energies of neutrons from reactions characterized by different neutron multiplicities complicates substantially the determination of the neutron multiplicity from the neutron energy to such an extent that the results become ambiguous.

It is noteworthy that the energy dependences of the ratios $F_{1,2}^{\rm exp}$ obtained for the isotopes ^{76,78,80,82}Se on the basis of experimental data from [21] differ substantially from the analogous dependences deduced for many other nuclei from Saclay data. Earlier, it was found [6–8, 11–16] that, as a rule, the $(\gamma, 1n)$ cross sections obtained in Livermore proved to be unjustifiably underestimated (down to the appearance in them—as well as in the ratios $F_1^{\rm exp}$—physically forbidden negative values in many cases). At the same time, the $(\gamma, 1n)$ cross sections obtained in Saclay proved to be unjustifiably overestimated in many cases studied there, with the result that negative values did not appear in them. In those cases where the Livermore ratios $F_1^{\rm exp}$ turned out to be in the region of negative values, the Saclay ratios $F_1^{\rm exp}$ remained in the region of positive values. Before addressing the case of the isotopes ^{76,78,80,82}Se, negative values were not observed for the Saclay ratios $F_1^{\rm exp}$, even though such values were typical of the Livermore ratios $F_1^{\rm exp}$.

3. NEW RELIABLE REACTION CROSS SECTIONS EVALUATED WITH THE AID OF THE EXPERIMENTAL–THEORETICAL METHOD

With the aim of overcoming problems associated with unreliability of experimental cross sections for partial reactions and obtaining reliable data for many nuclei mentioned above, the experimental–theoretical method for evaluating such cross sections was used to obtain results that are independent of systematic uncertainties inherent in the experimental method of photoneutron multiplicity sorting [6–8, 11–17, 22–24]. Earlier, this evaluation method was employed in [15] to obtain new data on cross sections for photoneutron reactions on ^{80}Se nuclei [21]. It was found that the reliability of experimental data obtained for this nucleus raises serious doubts.

The cross sections for reactions proceeding on nuclei of the isotopes ^{76,78,82}Se and producing neutrons of different multiplicity ($i = 1, 2, 3, \ldots$) were evaluated according to relations (2), in which use was made of the experimental [21] neutron yield cross sections $\sigma^{\rm exp}(\gamma, xn)$ and the ratios $F_i^{\rm theor}$ calculated within the CPNRM approach [10, 11]. This evaluation method means that the competition between the cross sections for partial reactions are taken in accordance with the equations of the model, while the respective sum of these cross sections,

$$\sigma^{\rm eval}(\gamma, xn) = \sigma^{\rm eval}(\gamma, 1n) \qquad (5)$$

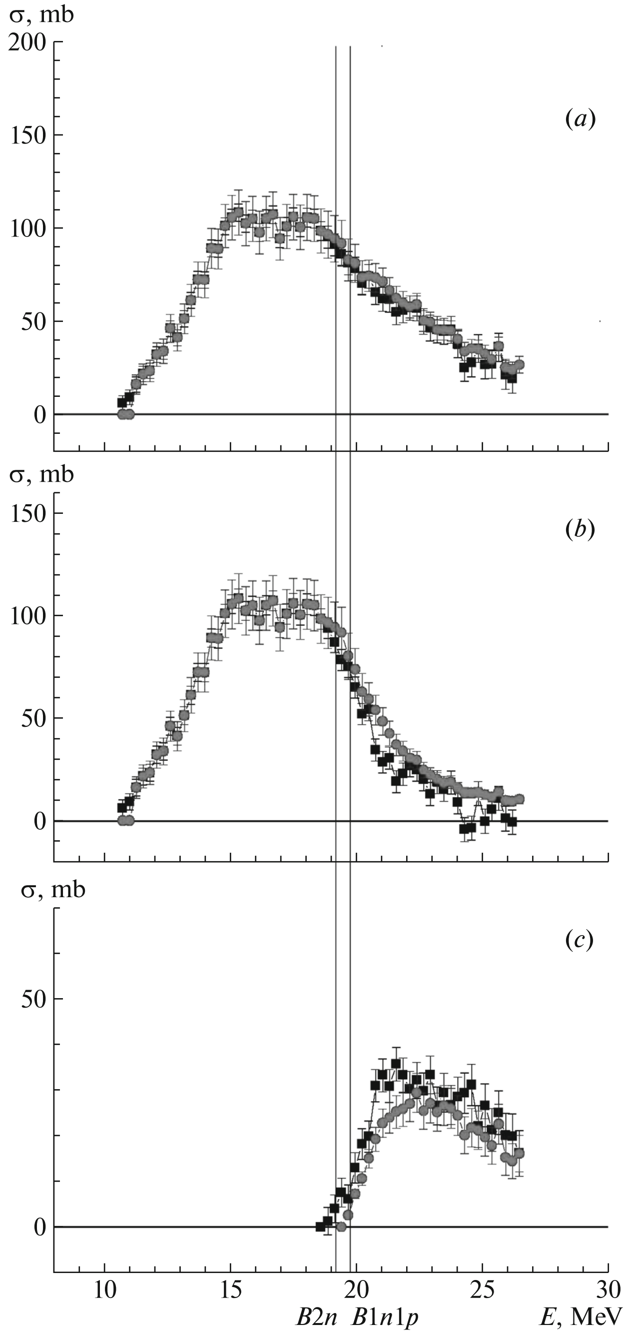

Fig. 4. Comparison of (closed circles) evaluated and (closed boxes) experimental [21] data on the reaction cross sections for the isotope ^{76}Se: (*a*) $\sigma(\gamma, Sn)$, (*b*) $\sigma(\gamma, 1n)$, and (*c*) $\sigma(\gamma, 2n)$.

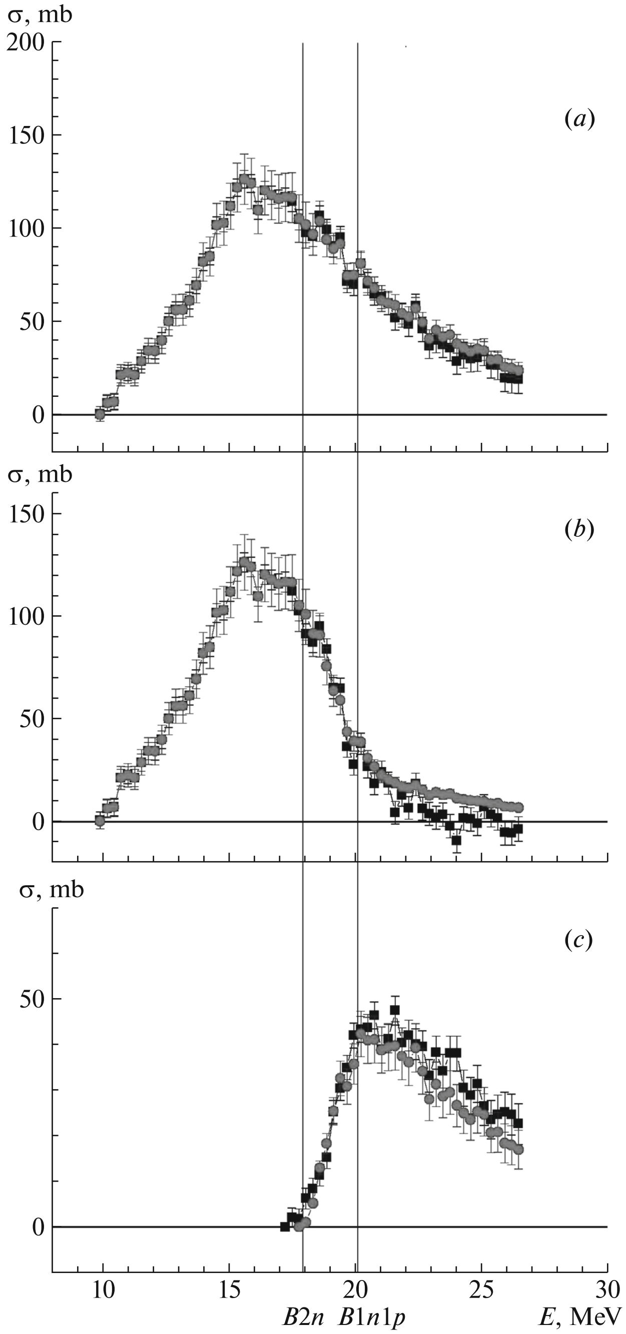

Fig. 5. As in Fig. 4, but for the isotope ^{78}Se.

$$+ 2\sigma^{\mathrm{eval}}(\gamma, 2n) + 3\sigma^{\mathrm{eval}}(\gamma, 3n),$$

coincides with the experimental neutron yield cross section $\sigma^{\exp}(\gamma, xn)$, which is independent of the problems arising in neutron multiplicity sorting, since this cross section includes the contributions from all of the partial reactions that proceed. The partial reaction cross sections $\sigma(\gamma, 1n)$ and $\sigma(\gamma, 2n)$ and the total photoneutron reaction cross section

$$\sigma(\gamma, Sn) = \sigma(\gamma, 1n) + \sigma(\gamma, 2n), \qquad (6)$$

evaluated for the isotopes ^{76,78,82}Se are presented in Figs. 4–6.

By analogy with what was done earlier in [15] for the isotope ^{80}Se, the cross sections for the neutron yield reaction, $\sigma^{\mathrm{theor}}(\gamma, xn)$, that were calculated for the isotopes ^{76,78,82}Se within the CPNRM approach were slightly corrected in order to attain

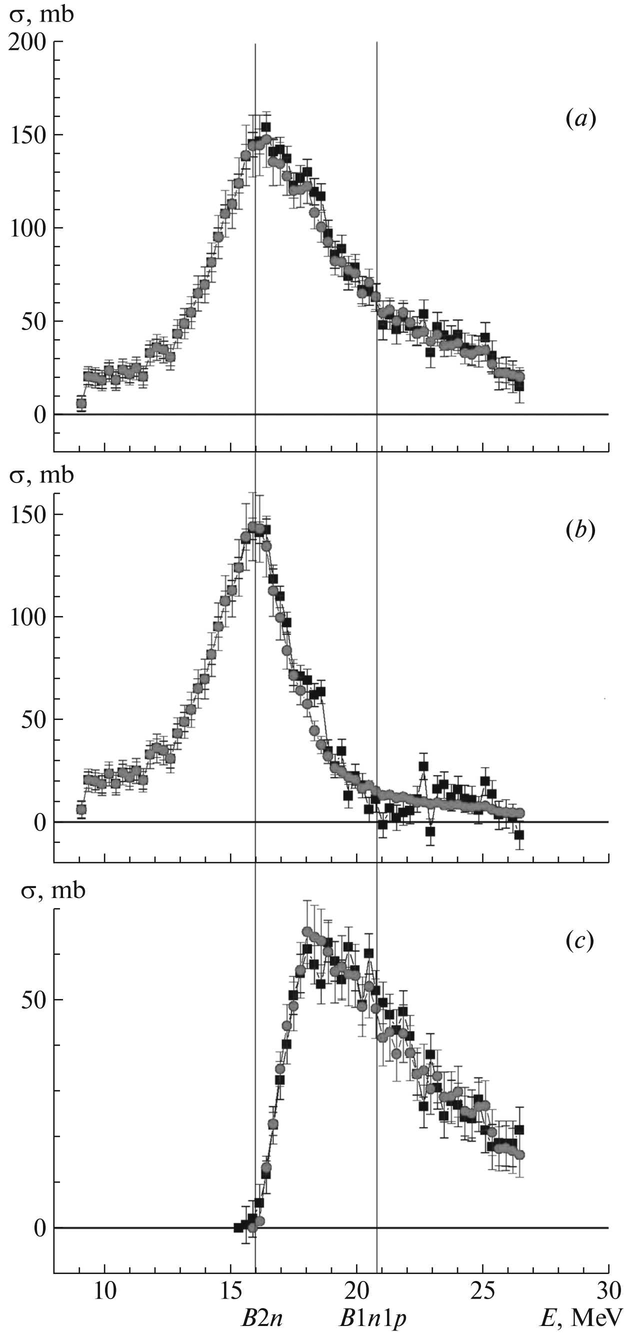

Fig. 6. As in Fig. 4, but for the isotope ^{82}Se.

the best agreement with the respective experimental cross sections $\sigma^{\text{exp}}(\gamma, xn)$ prior to employing the former in the evaluation procedure based on Eqs. (2). Use was made of data evaluated for integrated cross sections and energy centers of gravity of the cross sections under analysis in various regions of incident photon energies. The cross section $\sigma^{\text{theor}}(\gamma, xn)$ was multiplied by 1.090 for ^{76}Se, was multiplied by 1.069 and was shifted by 0.020 MeV toward higher energies for ^{78}Se, and was multiplied by 0.890 and was shifted by 0.080 MeV toward higher energies for ^{82}Se.

It is noteworthy that, in just the same way as for the isotope ^{80}Se studied earlier in [15], the cross sections for the reactions in question on nuclei of the isotopes ^{76,78,82}Se, which are studied here, are close (nearly coincident) in the region of incident photon energies below the respective $(\gamma, 2n)$ thresholds $B2n$. At higher energies, however, there arise substantial discrepancies directed oppositely for $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions (the respective integrated cross sections are presented in Table 1). In the case of the ^{76}Se nucleus, the relative discrepancy between the experimental and evaluated cross sections for the $(\gamma, 1n)$ reaction, $\Delta\sigma_1/\sigma^{\text{int-eval}}(\gamma, 1n)$, where

$$\Delta\sigma_1 = \sigma^{\text{int-eval}}(\gamma, 1n) - \sigma^{\text{int-exp}}(\gamma, 1n), \quad (7)$$

is 36% (247.9 and 182.0 MeV mb, respectively); for the $(\gamma,\ 2n)$ reaction, the relative discrepancy $\Delta\sigma_2/\sigma^{\text{int-eval}}(\gamma, 2n)$, where

$$\Delta\sigma_2 = \sigma^{\text{int-exp}}(\gamma, 2n) - \sigma^{\text{int-eval}}(\gamma, 2n), \quad (8)$$

is 28% (183.1 and 142.5 MeV mb, respectively). In the case of the isotope ^{78}Se, the respective values are 28% (251.4 and 195.9 MeV mb) and 15% (273.8 and 238.8 MeV mb), while, in the case of the isotope ^{80}Se, they are 45% (360.1 and 246.9 MeV mb) and 20% (389.5 and 328.5 MeV mb) [15].

We note that the above relative discrepancies for the isotope ^{82}Se, −1.5% (360.5 and 366.3 MeV mb) and 3% (397.8 and 385.4 MeV mb), differ substantially from their counterparts for the isotopes ^{76,78,80}Se (see above). This may be due to noticeable systematic measurement uncertainties reflected in the energy dependences of the ratios F_1^{exp} and F_2^{exp} at energies above about 21 MeV (see Fig. 3)—in particular, we can observe an unreliable increase in F_1^{exp}, and this increase correlates with a decrease in F_2^{exp}.

All of the foregoing is obviously confirmed by the energy dependences of the differences $\Delta\sigma_1$ (7) and $\Delta\sigma_2$ (8) of the evaluated and experimental reaction cross sections for the isotopes ^{76,78,82}Se in Figs. 7–9 and by the analogous data obtained earlier for the isotope ^{80}Se [15].

As was indicated in the Introduction, the dedicated investigations reported in [12, 16–19] led to the conclusion that the cross sections evaluated for partial photoneutron reactions on the basis of the experimental–theoretical method outlined above are reliable. The underlying arguments are the following. First, the evaluated cross sections satisfy the objective physical criteria of reliability. Second, they comply with the results obtained by the activation method.

Table 1. Integrated cross sections $\sigma^{\rm int}$ (in MeV mb units) based evaluated cross sections for total and partial photoneutron reactions on the isotopes ^{76,78,80,82}Se along with experimental data from [21]

Reaction	Experiment	Evaluation	Experiment	Evaluation
		^{76}Se		
	$E^{\rm int} = B2n = 19.18$ MeV		$E^{\rm int} = 26.46$ MeV	
$(\gamma, xn)^*$	636.0 ± 4.9	632.5 ± 10.9	1183.9 ± 8.4	1165.5 ± 14.3
(γ, Sn)	635.1 ± 4.9	632.5 ± 10.9	994.2 ± 8.3	1022.92 ± 12.8
$(\gamma, 1n)$	634.2 ± 4.9	632.5 ± 10.9	816.2 ± 7.3	880.4 ± 12.3
$(\gamma, 2n)$	0.9 ± 0.7		183.1 ± 4.1	142.5 ± 3.6
		^{78}Se		
	$E^{\rm int} = B2n = 17.92$ MeV		$E^{\rm int} = 26.46$ MeV	
$(\gamma, xn)^*$	587.1 ± 4.7	586.7 ± 10.5	1328.2 ± 7.5	1315.5 ± 15.1
(γ, Sn)	585.8 ± 4.7	586.3 ± 10.5	1054.3 ± 8.4	1076.7 ± 12.7
$(\gamma, 1n)$	584.6 ± 4.7	586.6 ± 10.5	780.5 ± 7.5	838.0 ± 11.8
$(\gamma, 2n)$	1.3 ± 0.5		273.8 ± 3.7	238.8 ± 4.7
		^{80}Se [15]		
	$E^{\rm int} = B2n = 16.88$ MeV		$E^{\rm int} = 28.00$ MeV	
$(\gamma, xn)^*$	453.2 ± 6.1	453.2 ± 6.1	1527.2 ± 16.2	1527.2 ± 16.2
(γ, Sn)	501.9 ± 7.3	502.5 ± 6.8	1137.7 ± 21.5	1191.1 ± 16.0
$(\gamma, 1n)$	501.4 ± 6.6	502.5 ± 6.6	748.3 ± 13.6	862.6 ± 13.6
$(\gamma, 2n)$			389.5 ± 8.5	328.5 ± 8.4
		^{82}Se		
	$E^{\rm int} = B2n = 15.98$ MeV		$E^{\rm int} = 26.46$ MeV	
$(\gamma, xn)^*$	363.4 ± 4.5	363.2 ± 8.7	1524.4 ± 10.2	1494.2 ± 17.6
(γ, Sn)	362.9 ± 4.5	363.2 ± 8.7	1126.5 ± 10.15	1190.1 ± 13.1
$(\gamma, 1n)$	362.4 ± 4.4	363.2 ± 8.7	728.7 ± 8.5	723.7 ± 11.3
$(\gamma, 2n)$	0.6 ± 0.9		397.8 ± 5.5	385.4 ± 6.7

* The experimental cross section for neutron yield reaction, $\sigma^{\rm exp}(\gamma, xn)$ [21], was used as an input for evaluations on the basis of Eqs. (2).

This means that the experimental data that the authors of [21] obtained for the isotopes ^{76,78,80,82}Se and which exhibit substantial deviations from the evaluated data are unreliable. The differences $\Delta\sigma_1$ and $\Delta\sigma_2$ obtained in the present study and in [15] clarify the reason behind this: it is the erroneous attribution of a noticeable number of neutrons from $(\gamma, 1n)$ to $(\gamma, 2n)$ reactions because of an compliceted and indirect relation between the multiplicity of neutrons that was determined in the experiment reported in [21] and their measured kinetic energy. It was shown in [7, 17, 23] that such uncertainties arise because of a substantial overlap of the energy spectra of neutrons from different decay channels.

We indicated above that an unreliable transfer of neutrons from $(\gamma, 1n)$ to $(\gamma, 2n)$ reactions is charac-

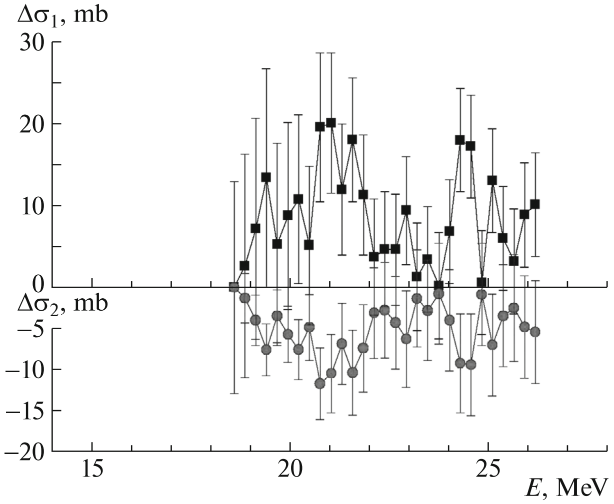

Fig. 7. Comparison of the differences of the evaluated and experimental reaction cross sections (closed boxes and circles for $\Delta\sigma_1$ and $\Delta\sigma_2$, respectively) for the isotope ^{76}Se.

teristic of the experiments performed in Livermore. As a rule, an inverse redistribution of neutrons occurred in the experiments performed in Saclay. An analysis of special features of the Saclay data from [21] for the isotopes ^{76,78,80,82}Se is likely to suggest that the relation between the multiplicity of neutrons and their measured kinetic energy is indirect and quite complicated.

4. COMPARISON OF EVALUATED AND EXPERIMENTAL DATA ON CROSS SECTIONS FOR THE TOTAL PHOTONEUTRON REACTION

In [21], experimental data on the total photoneutron reaction are compared with the predictions of the Thomas–Reiche–Kuhn (TRK) classical dipole sum rule

$$\sigma^{\text{int}}(\gamma, Sn) \approx \sigma^{\text{int}}(\gamma, \text{abs}) = \int\limits_0^{E^{\infty}} \sigma(E)dE \quad (9)$$

$$= [2\pi^2 e^2 hNZ]/[McA] = 60NZ/A \text{ [MeV mb]},$$

where M is the nucleon mass; Z is the number of protons in the nucleus being considered; N is the number of neutrons; $A = Z + N$ is the mass number; $\sigma^{\text{int}}(\gamma, Sn)$ is the integrated cross section for the total photoneutron reaction; and $\sigma^{\text{int}}(\gamma, \text{abs})$ is the integrated photoabsorption cross section,

$$\sigma^{int}(\gamma, \text{abs}) = \int\limits_B^{E^{\text{int}}} \sigma(E)\, dE. \quad (10)$$

The respective integrated cross sections obtained in [2, 21] for the GDR energies in the isotopes ^{76,78,80,82}Se are given in Table 2 along with the predictions of the TRK sum rule and evaluated data.

In [21], it was supposed that the integration region is quite narrow and that the experimental values of the integrated cross sections for the total photoneutron reaction may differ substantially from the predictions of the TRK sum rule for the photoabsorption cross sections $\sigma^{\text{int}}(\gamma, \text{abs})$ because of the disregard of the possible contributions from reactions involving proton emission. Indeed, the inclusion of proton channels of GDR decay in the ^{76,78,80,82}Se nuclei could shift values of the integrated cross sections $\sigma^{\text{int}}(\gamma, \text{abs})$ toward the predictions of the TRK sum rule, and this may be the subject of subsequent investigations. However, preliminary evaluations based on the results of CPNRM calculations show that, for all

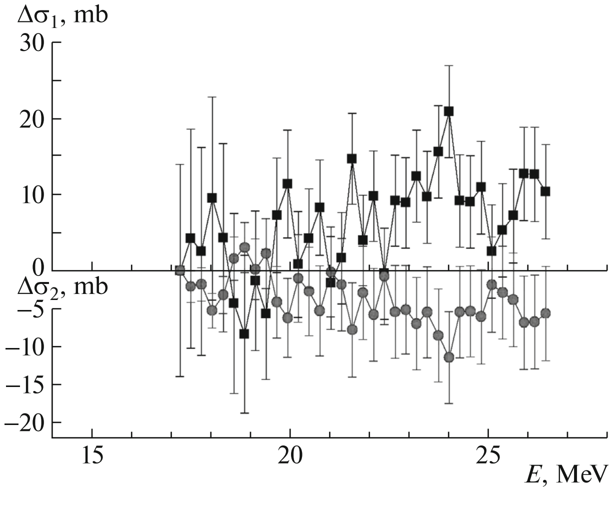

Fig. 8. As in Fig. 7, but for the isotope ^{78}Se.

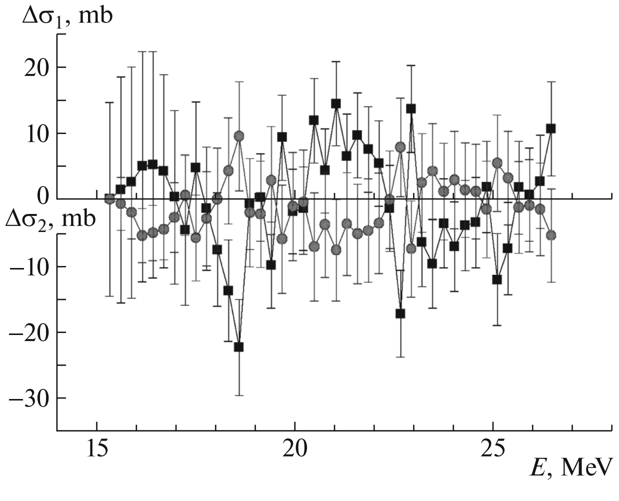

Fig. 9. As in Fig. 7, but for the isotope ^{82}Se.

Table 2. Evaluated and experimental (corresponding to data presented in [2, 21]) integrated cross sections σ^{int} (in MeV mb units) calculated over the region from $B1n$ to E^{int} along with the TRK predictions

	^{76}Se ($E^{\text{int}} = 26.5$ MeV)	^{78}Se ($E^{\text{int}} = 26.5$ MeV)	^{80}Se ($E^{\text{int}} = 28.0$ MeV)	^{82}Se ($E^{\text{int}} = 26.5$ MeV)
60 NZ/A	1127	1150	1173	1194
Evaluation	1023	1077	1191	1190
[21]*	1010	1060	1110	1130
[2]*	996	1050	1138	1124

* The integrated cross sections based on the data in [2, 21] are somewhat different.

of the four isotopes ^{76,78,80,82}Se, which are discussed in the present study, the $(\gamma, 1p)$ cross sections have small values of about a few millibarns even at the energies $E = E^{\text{int}}$ presented in Table 2 and decrease substantially as the photon energy increases.

From the data in Table 2, one can see that, for the isotopes ^{76,78,80,82}Se, the integrated cross sections prove to be substantially larger than the respective experimental data from [2, 21] and are closer to the predictions of the TRK sum rule. According to the data in Figs. 1, 2 and 5, the erroneous redistribution of some neutrons from $(\gamma, 1n)$ to $(\gamma, 2n)$ reactions in the experiment reported in [21] obviously cannot be the reason for an overestimation of the sum of their cross sections—that is, the cross sections for the total photoneutron reaction. In all probability, this may stem from problems associated with the efficiency of the detector used in that experiment. For selenium isotopes, the data under discussion were obtained in Saclay [21] by employing a neutron detector in the form of a liquid scintillator enriched in gadolinium. The detector volume of 250 l was scanned by a large number of photomultiplier tubes. This highly efficient 4π “slowing-down” detector, in which neutrons produced during a short pulse of a linear electron accelerator were slowed down in the scintillator between the accelerator pulses, made it possible to measure separately and simultaneously cross sections for photoneutron reactions, including $(\gamma, 1n)$ and $(\gamma, 2n)$. As was indicated in [4], the efficiency estimated, by and large, at about 40% to 60% depends noticeably on the neutron energy. This means that a noticeable part of neutrons produced in the two partial reactions under study turn out to be lost. It follows that the neutron yield-reaction cross section $\sigma(\gamma, xn)$ in (5), which is used in the evaluation procedure based on Eq. (2) and which is independent of the problems of the neutron multiplicity, is more reliable than the total photoneutron reaction cross section $\sigma(\gamma, Sn)$ in (6), which depends on these problems to some extent. In the energy region extending to the threshold $B3n$, the cross section $\sigma(\gamma, Sn)$ differs from the cross section $\sigma(\gamma, xn)$ by the cross section $\sigma(\gamma, 2n)$, which obviously depends on the neutron multiplicity problems being discussed:

$$\sigma(\gamma, Sn) = \sigma(\gamma, xn) - \sigma(\gamma, 2n). \qquad (11)$$

5. CONCLUSIONS

In order to analyze systematic uncertainties that are present in the experimental cross sections for partial photoneutron reactions on nuclei of the isotopes ^{76,78,80,82}Se, we have applied objective physical criteria of reliability that employ the ratios $F_i = \sigma(\gamma, in)/\sigma(\gamma, xn)$ of cross sections for specific partial reactions to the cross section for the neutron yield reaction. Following the same line of reasoning as in the earlier studies reported in [6–8, 11–17, 22–24], we have shown that the experimental cross sections obtained for $(\gamma, 1n)$ and $(\gamma, 2n)$ partial reactions in a beam of quasimonoenergetic annihilation photons by means of photoneutron multiplicity sorting are unreliable. They contain a significant number of physically forbidden negative values and/or values that lead to the ratios F_i^{exp} in excess of the physically motivated upper limits, as well as to large discrepancies between F_i^{exp} and F_i^{theor}. This was due primarily to erroneously redistributing a noticeable number of neutrons between these two reactions because of substantial systematic uncertainties in the procedure for experimentally determining the multiplicity of neutrons on the basis of their measured kinetic energy.

It is noteworthy that the experimental data obtained in Saclay for selenium isotopes are substantially dissimilar to the Saclay data for a large number of other nuclei, where there were an unjustifiable overestimation of the $(\gamma, 1n)$ cross sections and an underestimation of the $(\gamma, 2n)$ cross sections. The Saclay data for the isotopes ^{76,78,80,82}Se are similar to Livermore data, which are characterized by an unreliable underestimation of the $(\gamma, 1n)$ cross sections and an overestimation of the $(\gamma, 2n)$ cross sections. This is a simple and direct corroboration of the conclusions drawn in the earlier investigations reported in [6–8, 11–16]: the relation between the neutron multiplicity, which is to be determined, and the kinetic energy of neutrons, which is measured, is indirect and quite complicated.

Earlier, it was shown in [12, 16–19] that the cross sections evaluated for partial photoneutron reactions by means of the experimental–theoretical method are reliable since they, on one hand, satisfy the aforementioned reliability criteria and, on the other hand, agree with data obtained on the basis of the alternative activation method, which permits a direct separation of reactions involving the emission of one and two neutrons. The experimental–theoretical evaluation method was used to find new reliable data on the cross sections for partial photoneutron reactions on nuclei of the isotopes ^{76,78,80,82}Se. With the aid of these cross sections, one obtains the cross sections for the total photoneutron reaction that are in substantially better agreement with the estimates based on the TRK sum rule than experimental data from [21].

Our present results confirm directly the conclusion that significant uncertainties in the method used to determine the neutron multiplicity are the main reason behind the well-known discrepancies between the cross sections obtained for partial photoneutron reactions in different experiments by means of photoneutron multiplicity sorting. Because of the presence of such uncertainties in the experimental data on the partial reaction cross sections, these cross sections are unreliable. In view of this, a large amount of data obtained by means of this method should be analyzed individually and evaluated. Since the evaluated reliable data differ substantially from unreliable experimental data, it is highly desirable to discuss the possible physical implications.

In view of the aforementioned difference of the Saclay data for the isotopes ^{76,78,80,82}Se from characteristic data obtained in Saclay for a large number of other nuclei and the similarity of the former to obviously unreliable Livermore data, it is of importance to compare the results of experiments performed with the aid of neutron multiplicity sorting with the results obtained by means of other methods for separating partial reactions. The latter may include experiments performed by the activation method in a beam of bremsstrahlung photons and experiments performed with the aid of a photoneutron detector, whose efficiency is virtually independent of the neutron energy, for example, in a beam of photons from the inverse Compton scattering of relativistic electrons on a powerful laser beam [25].

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