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Photoneutron Reactions on ^{51}V Nucleus: Systematic Uncertainties in Experiments and New Evaluated Data

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Abstract—On the basis of objective physics criteria, it is shown that the cross sections determined for partial photoneutron reactions on ^{51}V nucleus by the method of photoneutron multiplicity sorting, primarily at Livermore (USA) and Saclay (France), are not reliable because of large systematic uncertainties in them. New cross sections evaluated for such reactions by the experimental–theoretical method are found to satisfy the data reliability criteria. The discrepancies between the evaluated and experimental reaction cross sections are analyzed in detail. It is found that, in the case of the ^{51}V nucleus, which is relatively light, the disregard of the contribution from the $(\gamma,\ 1n1p)$ reaction is the main reason of sizable systematic uncertainties in the procedure used at Livermore to identify neutrons from the $(\gamma,\ 1n)$, $(\gamma,\ 1n1p)$, and $(\gamma,\ 2n)$ reactions.

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1. INTRODUCTION

The reason for substantial systematic uncertainties between the experimental cross sections obtained at Livermore (USA) and Saclay (France) for partial $(\gamma,\ 1n)$, $(\gamma,\ 2n)$, and $(\gamma,\ 3n)$ photoneutron reactions by the method of photoneutron multiplicity sorting [1–3] is one of the long-standing problems encountered in experimentally studying the photodisintegration of atomic nuclei and known to specialists. For 19 nuclei (^{51}V, ^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, ^{116,117,118,120,124}Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, and ^{238}U) studied at these both laboratories, it was found [4–6] that, despite a large scatter of data, the $(\gamma,\ 1n)$ cross section had as a rule substantially greater (by up to 100%) values at Saclay, while the $(\gamma,\ 2n)$ cross section had, on the contrary, greater values at Livermore. The average values of the ratios of integrated cross sections for the reactions being considered are substantially different; that is, $\langle R(n)\rangle = \langle\sigma^{\rm int}_{\rm Saclay}(\gamma,1n)/\sigma^{\rm int}_{\rm Livermore}(\gamma,1n)\rangle = 1.08$ and $\langle R(2n)\rangle = \langle\sigma^{\rm int}_{\rm Saclay}(\gamma,2n)/\sigma^{\rm int}_{\rm Livermore}(\gamma,2n)\rangle = 0.83$. Since, in the presence of such large systematic uncertainties, which are substantially greater than the reached statistical accuracy of about 5% to 10%, it is not clear which cross sections are reliable and are therefore appropriate for use in investigations and applications, the experimental partial reaction cross sections for a large number of nuclei (including ^{59}Co, ^{63,65}Cu, ^{75}As, ^{80}Se, $^{90-94}$Zr, ^{115}In, $^{112-124}$Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, ^{181}Ta, $^{186-192}$Os, ^{197}Au, ^{208}Pb, and ^{209}Bi) were analyzed by employing objective physical criteria of reliability of data on cross sections for partial photoneutron reactions. For such criteria, use was made of the following ones proposed in [7–9]:

(i) By definition, the values $F_i^{\rm exp}$ obtained from experimental data for the ratios of the cross sections for specific partial reactions, $\sigma(\gamma,in)$, to the neutron yield cross section, $\sigma(\gamma,xn)$,

$$\begin{aligned} F_i &= \sigma(\gamma,in)/\sigma(\gamma,xn) \\ &= \sigma(\gamma,in)/[\sigma(\gamma,1n)+2\sigma(\gamma,2n) \\ &\quad + 3\sigma(\gamma,3n)+\ldots], \end{aligned} \tag{1}$$

should not exceed 1.00, 0.50, and 0.33 for $i = 1$, 2, and 3, respectively.

(ii) The ratios $F_i^{\rm exp}$ (and partial reaction cross sections corresponding to them) should be positive.

(iii) The ratios $F_i^{\rm exp}$ should not differ substantially from $F_i^{\rm theor}$ values calculated on the basis of the combined photonuclear-reaction (CPNRM) model proposed in [10, 11].

The values of $F_i^{\rm exp}$ that do not meet al least one the proposed criteria indicate that the cross sections for partial reactions were obtained with substantial systematic uncertainties and, hence, cannot be thought to be reliable.

An analysis of $F_i^{\rm exp}$ values for a large number of the aforementioned nuclei revealed that, in many cases,

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the experimental partial reaction cross sections obtained both at Livermore and Saclay were not reliable. Many cross sections have physically forbidden negative values, or $F_i^{\rm exp}$ values either exceed substantially the above physics evaluate limits or deviate strongly from the $F_i^{\rm theor}$ values [5–9, 12–21].

In order to evaluate how the partial reaction cross sections may look, provided that the neutron yield cross sections $\sigma(\gamma, xn)$ are quite reliable [2], an experimental–theoretical method was proposed in [7]. Within this method, the partial reaction cross sections satisfying the physics criteria of reliability are defined as

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

This means that they are virtually independent of problems of experimental neutron multiplicity sorting. The point is that the yield cross sections $\sigma^{\rm exp}(\gamma, xn)$ depend only slightly on multiplicity problems, since they include neutrons produced in all partial reactions and the ratios $F_i^{\rm theor}$ do not have any dependence on these problems [4–6].

It was found [5–9, 12–21] that, in the majority of cases, the experimental cross sections obtained either at Livermore or at Saclay differed substantially from the evaluated cross section. It was shown that these discrepancies were due to systematic uncertainties in the procedure of experimentally attributing the detected neutrons to $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions within the method used, which relies on neutron multiplicity sorting and involves determining the multiplicity of the detected neutron from its measured kinetic energy. It turned out that these systematic uncertainties owe their existence to a number of reasons associated with special features of the spectra of neutrons produced in different reactions and with properties of the neutron detectors used [8, 22], as well as with some technical problems in the Livermore experiments.

Moreover, it was established that, for some nuclei—first all, ^{75}As [9], ^{127}I, ^{181}Ta [13], and ^{208}Pb—there are additional systematic discrepancies of a totally different origin between the results of the Livermore and Saclay experiments. Specifically, substantial discrepancies between the Livermore and Saclay data (as well as the data evaluated by means of the experimental–theoretical method) were observed for these nuclei not only for the partial reaction cross sections but also for the neutron yield cross sections $\sigma^{\rm exp}(\gamma, xn)$ and the cross sections for the total photoneutron reaction,

$$\sigma^{\rm exp}(\gamma, Sn) = \sigma^{\rm exp}(\gamma, 1n) \quad (3)$$
$$+ \sigma^{\rm exp}(\gamma, 2n) + \sigma^{\rm exp}(\gamma, 3n),$$

even in the region of low energies [below the threshold $B2n$ for the $(\gamma, 2n)$ reaction, where there are only neutrons originating from the $(\gamma, 1n)$ reaction and where neutron multiplicity problems therefore do not arise, so that the cross sections $\sigma^{\rm exp}(\gamma, 1n)$, $\sigma^{\rm exp}(\gamma, xn)$, and $\sigma^{\rm exp}(\gamma, Sn)$ should be identical. It was shown that discrepancies reaching several tens of percent may be explained only by technical problems that arose in the Livermore experiments for these nuclei and which resulted in the loss of a significant part of neutrons from the $(\gamma, 1n)$ reaction.

Yet another kind of reasons behind the systematic discrepancies under discussion between the results of the different experiments was found in [21] for the ^{59}Co nucleus, which is relatively light and for which two experiments were performed at Livermore—an earlier [23] and a later [24] one, where the method of neutron multiplicity sorting was implemented quite differently. In the experiment reported in [23], the identification of the multiplicity of a neutron depended substantially on the place of its detection in the detector volume. In the experiment reported in [24], this dependence was substantially weakened. On the basis of a detailed analysis of discrepancies between the experimentally measured and evaluated reaction cross sections, it was shown in [21] that, in the case of the ^{59}Co nucleus, the loss of the contribution from the $(\gamma, 1n1p)$ reaction played a dominant role in the earlier experiment reported in [23]. The results of the calculations performed within the CPNRM model reveal that, in the case of relatively light nuclei, the cross section for this photoproton reaction is rather close to the $(\gamma, 2n)$ cross section both in magnitude and in position on the energy scale. This circumstance is of paramount importance since, owing to a direct neutron detection in all of the experiments performed at Livermore and Saclay, they actually study the sum of the $(\gamma, 1n)$ and $(\gamma, 1n1p)$ reactions. The distribution of the excitation energy of the nucleus under study between the neutron and the proton in the $(\gamma, 1n1p)$ two-nucleon reaction occurs approximately in the same way as between the two neutrons in the $(\gamma, 2n)$ two-neutron reaction, but, in the former, the neutron multiplicity is equal to unity, while, in the latter, it is equal to two. In the case of relatively light nuclei, the appearance in photoneutron reactions of a significant number of low-energy neutrons whose multiplicity was equal to unity introduced an additional uncertainty in identifying the multiplicity of a neutron on the basis of its energy.

For this reason, the problem of systematic uncertainties in the cross sections for partial photoneutron reactions on the ^{51}V nucleus, which is relatively light, is of great interest, especially from the point of view of a comparison with the results of the investigation of

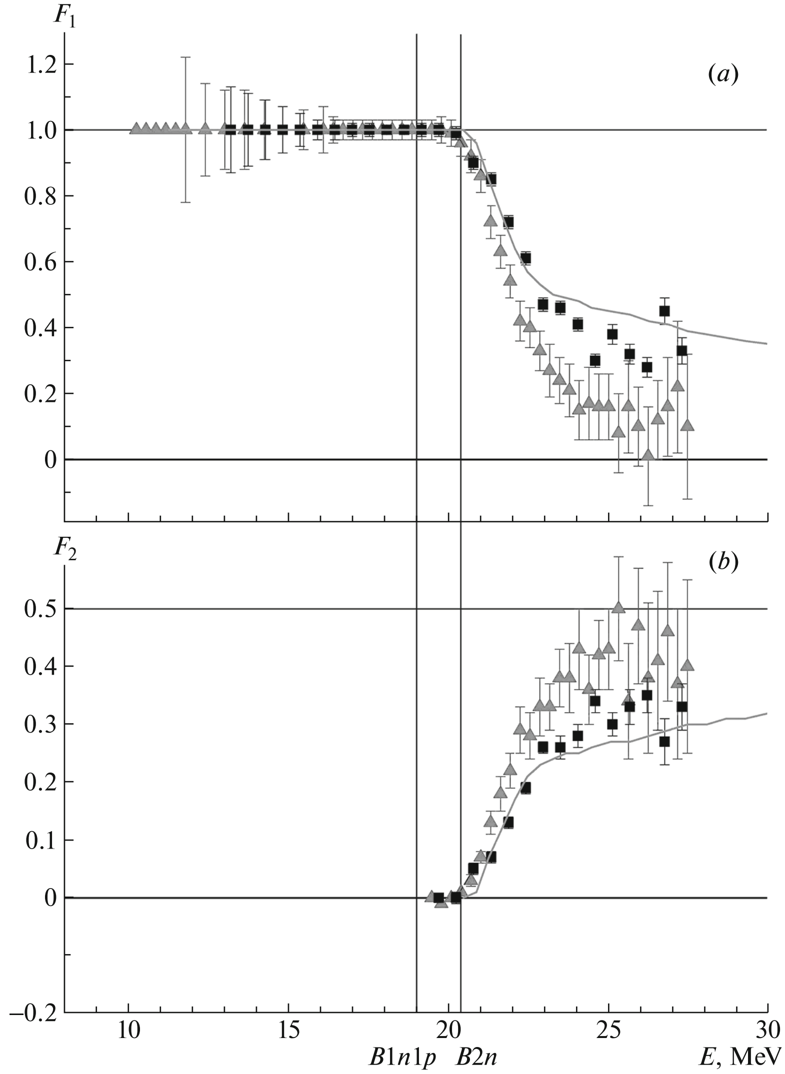

Fig. 1. Ratios $F_1^{\rm exp}$ and $F_2^{\rm exp}$ obtained for the ^{51}V nucleus by employing (triangles) Livermore [23] and (squares) Saclay [25] experimental data along with the results obtained by calculating $F_{1,2}^{\rm theor}$ (curves) on the basis of the combined photonuclear-reaction model CPNRM [10, 11].

these reactions on ^{59}Co nuclei [23]. Yet another point in favor of studying ^{51}V is that, for it—in contrast to the ^{59}Co nucleus, for which only the result of two Livermore experiments are available—there are also the result of a Saclay experiment [25] and the neutron yield cross section obtained in a beam of bremsstrahlung photons [26]. The present study is devoted to deriving, by means of the experimental–theoretical method based on the use of the objective physics criteria of data reliability, new cross sections for partial photoneutron reactions on the ^{51}V nucleus, which is the lightest among the aforementioned 19 nuclei, and to discussing in detail the reasons of the discrepancies between the evaluated reaction cross sections and their counterparts measured in different experiments.

2. EXPERIMENTAL CROSS SECTIONS FOR PARTIAL PHOTONEUTRON REACTIONS ON ^{51}V NUCLEUS AND OBJECTIVE PHYSICAL CRITERIA OF DATA RELIABILITY

As was indicated in the Introduction, it was proposed in [7] to formulate objective physical criteria of reliability of data on the cross sections for partial photoneutron reactions in terms of the ratios F_i (1) of the cross sections for specific partial reactions, $\sigma(\gamma, in)$, to the neutron yield cross section $\sigma(\gamma, xn)$. Since the energy thresholds $B1n1p$ and $B2n$ for the reactions $^{51}{\rm V}(\gamma, 1n1p)^{49}{\rm Ti}$ and $^{51}{\rm V}(\gamma, 2n)^{49}{\rm V}$ are very close

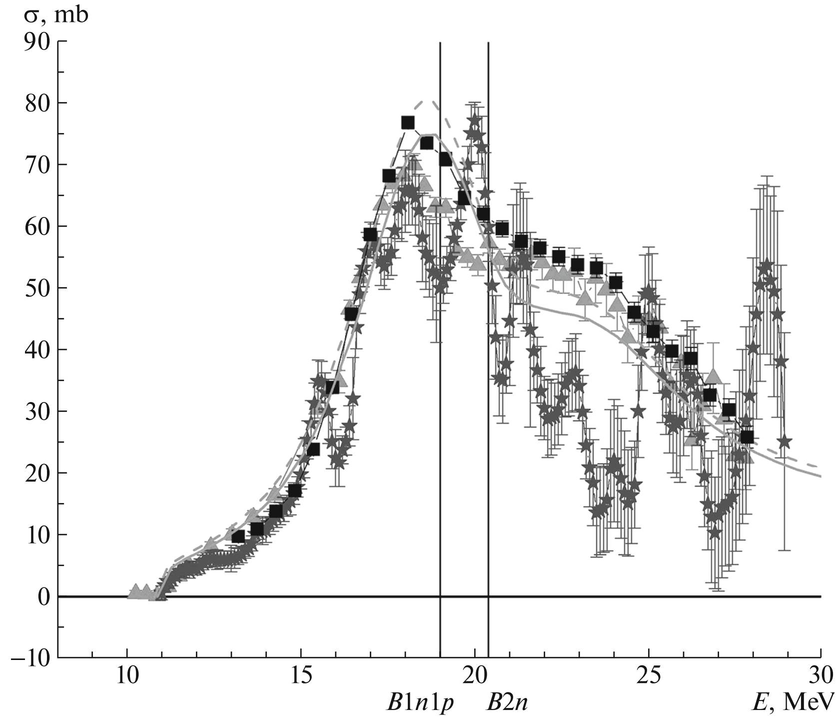

Fig. 2. Experimental neutron yield cross sections $\sigma^{\rm exp}(\gamma, xn)$ for the ^{51}V nucleus from (triangles) [23], (squares) [25], and (stars) [26] along with the cross section $\sigma^{\rm theor}(\gamma, xn)$ (curves) calculated on the basis of the combined photonuclear reaction model CPNRM [10, 11]. The dashed and solid curves represent results, respectively, prior to and after an additional correction (see below).

and are equal to 19.0 and 20.4 MeV, respectively, it is necessary to take into account the competition of these two reactions in the region of incident photon energies under discussion, which extends up to about 30.0 MeV. Since the threshold $B1n1p$ is relatively low, the notation $(\gamma, 1n) + (\gamma, 1n1p)$ is used for the first of them over the whole range of a comparison of data for the reaction involving the emission of one and two neutrons.

A comparison of the ratios $F_1^{\rm exp}$ and $F_2^{\rm exp}$ obtained for, respectively, the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions on ^{51}V nucleus with the aid of data from the Livermore [22] and Saclay [25] experiments with the calculated ratios $F_{1,2}^{\rm theor}$ [10, 11] is illustrated in Fig. 1. One can see that, although the ratios $F_{1,2}^{\rm exp}$ do not take physically forbidden negative values or values that exceed the corresponding physically motivated upper limits (1.00 and 0.50, respectively), the ratios $F_{1,2}^{\rm exp}$ obtained on the basis of either the Livermore data or the Saclay data differ substantially from the ratios $F_{1,2}^{\rm theor}$ calculated within the CPNRM model [10, 11], the deviations of $F_{1,2}^{\rm exp}$ from $F_{1,2}^{\rm theor}$ being quite large for the Livermore data. As was indicated earlier, the discrepancies between the theoretical and experimental data for the ratios F indicate that the reliability of the experimental data is questionable, especially for the Livermore data in the present case [23].

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

With the aim of overcoming the problem of systematic discrepancies between data obtained for the partial reaction cross section in the different experiment, we use the experimental–theoretical method proposed in [7] for evaluating cross sections for such reactions according to Eq. (2). This method is free from the uncertainties that plague the experimental method of neutron multiplicity sorting. New reliable evaluated cross sections are obtained by employing the experimental neutron yield cross sections $\sigma^{\rm exp}(\gamma, xn)$ and the ratios $F_i^{\rm theor}$ calculated within the CPNRM [10, 11] for a large number of nuclei [5–9, 12–21].

As was indicated above, data on the neutron yield cross section $\sigma^{\rm exp}(\gamma, xn)$ for the ^{51}V nucleus were obtained in three experiments [23, 25, 26]. In order to choose the most appropriate among them for use in the evaluation according to Eq. (2) within the experimental–theoretical method, all three experimental cross sections were compared (see Fig. 2)

Table 1. Experimental [23, 25, 26] and theoretical [10, 11] integrated cross sections σ^{int} (in MeV mb units) and centers of gravity $E^{\text{c.g.}}$ (in MeV units) of the neutron yield cross section $\sigma(\gamma, xn)$ for the ^{51}V nucleus (according to calculation performed up to the energy of $E^{\text{int}} = B2n = 20.39$ MeV)

	σ^{int}	$E^{\text{c.g.}}$
SINP MSU experiment, Moscow [26]	293.80 ± 2.43	17.84 ± 0.61
Livermore experiment [23]	316.67 ± 1.92	17.62 ± 0.41
Saclay experiment [25]	330.43 ± 1.37	17.80 ± 0.29
Calculations based on CPNRM model [11, 12] before correction	354.34 ± 6.58	17.72 ± 1.39
Calculations based on CPNRM model after correction	327.34 ± 6.08	17.75 ± 1.39

Table 2. Integrated values σ^{int} (in MeV mb) of the evaluated cross sections for the total and partial photoneutron reactions on ^{51}V nucleus and experimental cross sections [23, 25] (the respective integrals are taken up to the energy value of $E^{\text{int}} = 27.30$ MeV)

Reaction	Livermore [23]	Saclay [25]	Evaluation
$(\gamma, xn)^*$	629.36 ± 4.44	663.92 ± 2.59	651.62 ± 8.00
(γ, Sn)	532.67 ± 4.36	588.56 ± 2.58	587.17 ± 7.54
$(\gamma, 1n) + (\gamma, 1n1p)$	434.29 ± 4.50	513.26 ± 2.15	522.73 ± 7.40
$(\gamma, 2n)$	96.66 ± 2.59	75.30 ± 1.42	64.45 ± 1.47

* Experimental neutron yield cross section $\sigma(\gamma, xn)$ [25] used in the evaluation according to (2).

with the results of the calculations within the CPNRM [10, 11]. The respective data for the integrated cross sections and centers of gravity of the cross sections under comparison are quoted in Table 1. One can see that the cross section $\sigma^{\text{theor}}(\gamma, xn)$ calculated within the CPNRM differs substantially from the result of an experiment performed at Skobeltsyn Institute of Nuclear Physics at Moscow State University (SINP, MSU) in a beam of bremsstrahlung photons and agrees, by and large, with the results of the Livermore and Saclay experiments, turning out to be much closer to the result of the latter. This is the reason why the neutron yield cross section $\sigma^{\text{exp}}(\gamma, xn)$ obtained at Saclay [25] is used in the following to evaluate, according to Eq. (2), the cross sections by the experimental–theoretical method. Since the cross section from [26] differs substantially from the remaining experimental cross sections [23, 25] and the theoretical cross section, we do not use it below.

Although the experimental [25] and theoretical [10, 11] neutron yield cross sections $\sigma(\gamma, xn)$ are rather close to each other, the latter was slightly corrected in order to reach better agreement. By employing the data in Table 2, $\sigma^{\text{theor}}(\gamma, xn)$ was shifted toward lower energies by a value of 0.08 MeV (17.80 MeV−17.72 MeV) and was multiplied by a coefficient of 0.93 (330.43/354.34). The ratios F_i^{theor} corresponding to the changes associated with this correction were used in the evaluation procedure based on Eq. (2) to obtain new results for the partial reaction cross sections $\sigma^{\text{eval}}(\gamma, 1n) + \sigma^{\text{eval}}(\gamma, 1n1p)$ and $\sigma^{\text{eval}}(\gamma, 2n)$. Summing them in just the same way as in Eq. (3), we have also obtained the evaluated cross section for the total photoneutron reaction in (4) (see below).

All of the reaction cross sections evaluated for the ^{51}V nucleus are shown in Fig. 3 along with the data from the Saclay and Livermore experiments. The respective values of the integrated reaction cross sections are given in Table 2. The data in Fig. 3 and in Table 2 demonstrate the following:

(i) At Saclay [25], the integrated cross section σ^{int} calculated on the basis of the experimental data for the $(\gamma, 1n) + (\gamma, 1n1p)$ reaction has a value that is smaller by 1.8% (513.26 versus 522.73 MeV mb) than σ^{int} for the evaluated cross section, but, for the $(\gamma, 2n)$ reaction, the integrated experimental cross section is, on the contrary, larger by 16.8% (75.30 versus 64.45 MeV mb) than the value of σ^{int} for the evaluated cross section.

(ii) At Livermore [23], σ^{int} calculated for the $(\gamma, 1n) + (\gamma, 1n1p)$ reaction on the basis of the experimental data has a value that is smaller by 20.4%

(434.29 versus 522.73 MeV mb) than the value of σ^{int} for the evaluated cross section, but, for the $(\gamma, 2n)$ reaction, the integrated experimental cross section is, on the contrary, larger by 50.0% (96.66 versus 64.45 MeV mb) than the value of σ^{int} for the evaluated cross section.

The observed substantial discrepancies [underestimation of the experimental cross section for the $(\gamma, 1n)$ reaction and overestimation of the experimental cross section for the $(\gamma, 2n)$ reaction in relation to the respective evaluated cross sections] are typical [5–9, 12–21] for the Livermore data. These were the discrepancies that were observed for a large number of medium-heavy nuclei studied earlier. An unreliable attribution of some neutrons originating from the $(\gamma, 1n)$ reaction to the $(\gamma, 2n)$ cross section because of specific structural features of the neutron detector, which are described below, is the main reason behind these discrepancies.

We emphasize that the observed similar discrepancies [underestimated experimental cross section for the $(\gamma, 1n)$ reaction and overestimated experimental cross section for the $(\gamma, 2n)$ reaction in relation to the respective evaluated cross sections], albeit being insignificant, which are typical of the Livermore data, are not typical of the Saclay data. This suggests that, in the case of the ^{51}V nucleus, a traditional unreliable overestimation of the $(\gamma, 1n)$ cross section because of neutron detector features described below coexists with a nontraditional and stronger overestimation of the $(\gamma, 2n)$ cross section because of the appearance of an additional amount of low-energy neutrons, which were absent in the cases of medium-heavy nuclei. Taking into account the above data on all partial photoneutron reactions possible in the photon energy range under study, as well as on the neutron yield reaction, we can conclude that such neutrons may originate only from the $(\gamma, 1n1p)$ photoproton reaction, whose contribution was disregarded, as was indicated above, in the Livermore and Saclay experiments.

With the aim of studying in detail all reasons behind the observed discrepancies between the experimental and evaluated cross sections for partial reactions on ^{51}V nucleus, we determined the following differences for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions individually:

$$\Delta\sigma = \sigma^{\text{eval}} - \sigma^{\text{exp}}. \quad (4)$$

These differences are shown in Fig. 4 along with the cross section $\sigma(\gamma, 1n1p)$ calculated within the CPNRM [10, 11]. This comparison is performed in view of the fact that the results of such calculations indicate that the features of this cross section are rather close to the features of the cross section $\sigma(\gamma, 2n)$. For example, $\sigma(\gamma, 1n1p)$ reaches a maximum value of 12.03 mb at the photon energy of $E_\gamma =$

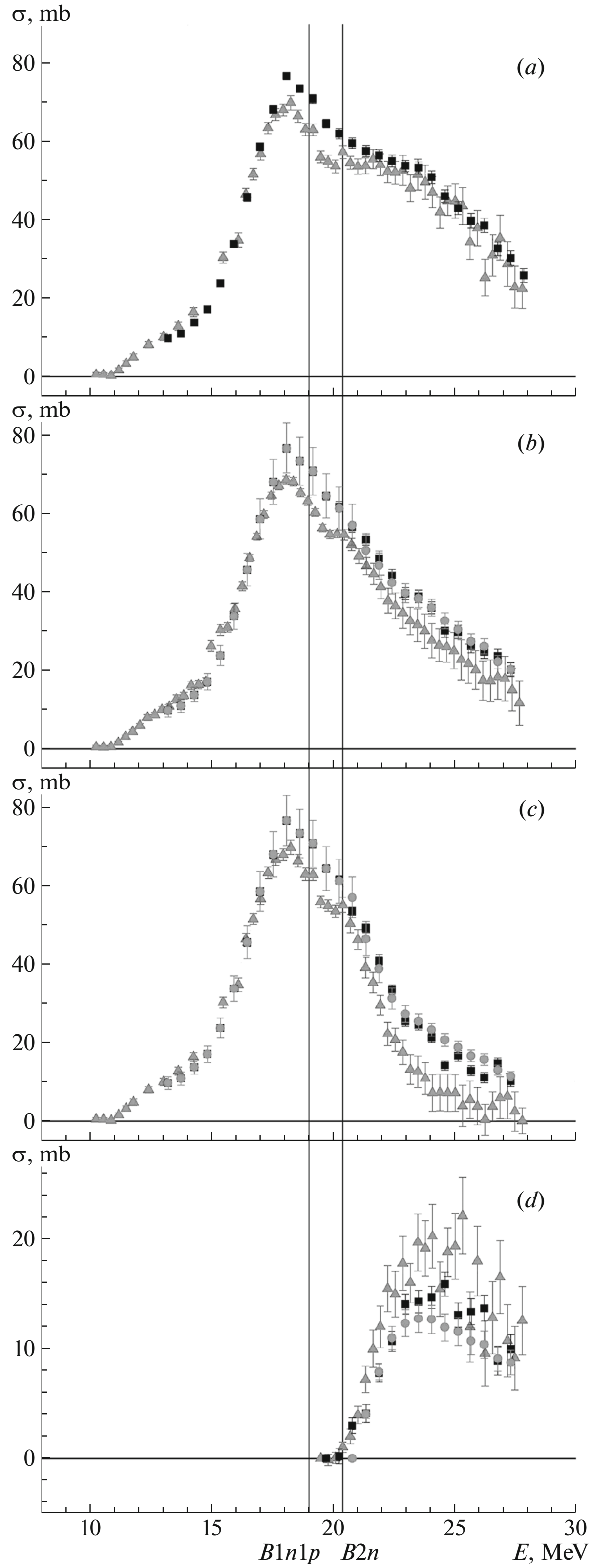

Fig. 3. Comparison of (circles) evaluated cross sections for reactions on ^{51}V nucleus with their experimental counterparts from (triangles) [23] and (squares) [25]: (*a*) $\sigma(\gamma, xn)$, (*b*) $\sigma(\gamma, Sn)$, (*c*) $\sigma(\gamma, 1n) + \sigma(\gamma, 1n1p)$, and (*d*) $\sigma(\gamma, 2n)$.

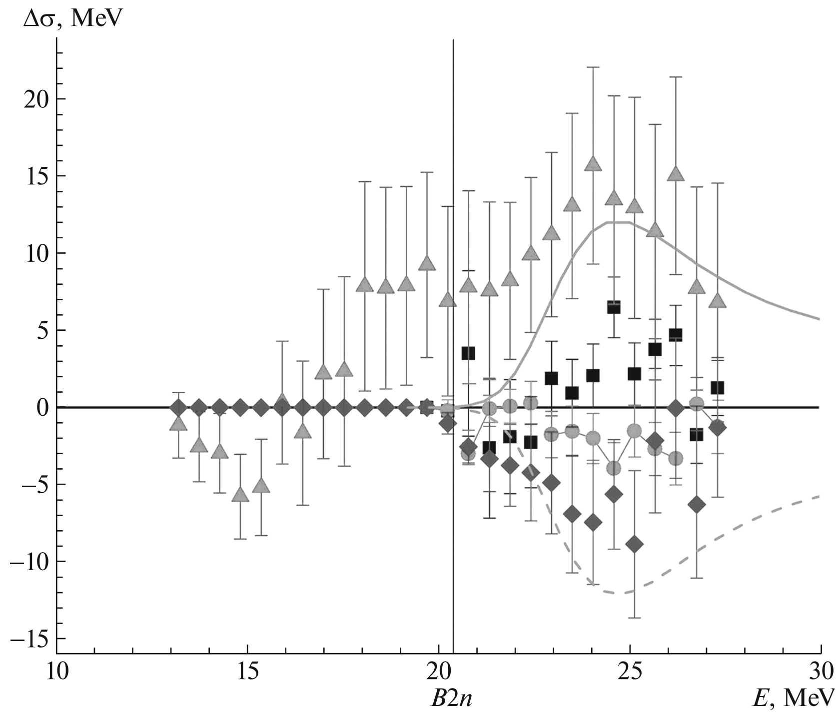

Fig. 4. Comparison of the differences $\Delta\sigma$ (4) of the evaluated and experimental cross sections for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions on ^{51}V. The triangles and diamonds represent the results for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions, respectively, according to the Livermore data from [23], while the squares and circles correspond to the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions for the case of the Saclay data from [25]. Both curves were calculated for the $(\gamma, 1n1p)$ reaction within the model CPNRM [11, 12].

24.4 MeV, while $\sigma(\gamma, 2n)$ reaches a maximum value of 11.93 mb at $E_\gamma = 23.6$ MeV.

From the data in Fig. 4, one can see that the differences $\Delta\sigma$ in (4) that were obtained on the basis of the Saclay and Livermore data differ substantially. In the Saclay data for energies in the region above $B2n$, the cross section for the reaction leading to the emission of one neutron is smaller than its evaluated counterpart by about 4 to 6 mb, while the cross section for the reaction leading to the emission of two neutrons is larger that the respective evaluated cross section by about 2 to 3 mb. Thus, the differences $\Delta\sigma[(\gamma, 1n) + (\gamma, 1n1p)]$ and $\Delta\sigma(\gamma, 2n)$ do not look like "mirror reflections" of each other, in contrast to what was observed in those cases of medium-heavy nuclei [5–9, 12–21] where the discrepancies between the cross sections for reactions leading to the emission of one and two neutrons were interpreted as the result of unjustifiably removing part of the neutrons from the $(\gamma, 2n)$ reaction and associating them with the reaction $(\gamma, 1n)$. The above values of the differences in question for the ^{51}V nucleus, which is relatively light, suggest that, along with the traditional unreliable overestimation of the number of neutrons in the $1n$ channel, there is a more sizable unreliable overestimation of the number of neutrons in the $2n$ channel. It was indicated above that, in the photon energy region being studied, additional neutrons of low energy close to the energy of neutrons from the $(\gamma, 2n)$ reaction can be produced only in the $(\gamma, 1n1p)$ reaction. Since their multiplicity is one rather than two, this may lead to the growth of systematic uncertainties in the statistical analysis of events featuring one and two neutrons, which was used to separate the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions.

In the case of the Livermore data from [23], the $(\gamma, 1n1p)$ reaction plays an even more important role. According to the data in Figs. 3 and 4 and in Table 2, the differences $\Delta\sigma$ in (4) for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions at energies in the region of $E_\gamma > B2n$ take values between about 10 and 15 mb; that is, they are greater than the respective differences in the Saclay data by a factor of 2.5 to 3.0. The differences for these two reactions are rather close in magnitude to the $(\gamma, 1n1p)$ cross section calculated within the CPNRM. This lends additional support to the statement that neutrons erroneously attributed to the $(\gamma, 2n)$ reaction belong to the $(\gamma, 1n1p)$ reaction rather than to the $(\gamma, 1n)$ reaction.

This role of the $(\gamma, 1n1p)$ reaction is obviously confirmed by the data in Fig. 5 for the additional differences

$$\Delta\sigma_{1n1p} = \sigma^{\text{evel}} - \sigma^{\text{exp}} - \sigma^{\text{theor}}_{1n1p}, \tag{5}$$

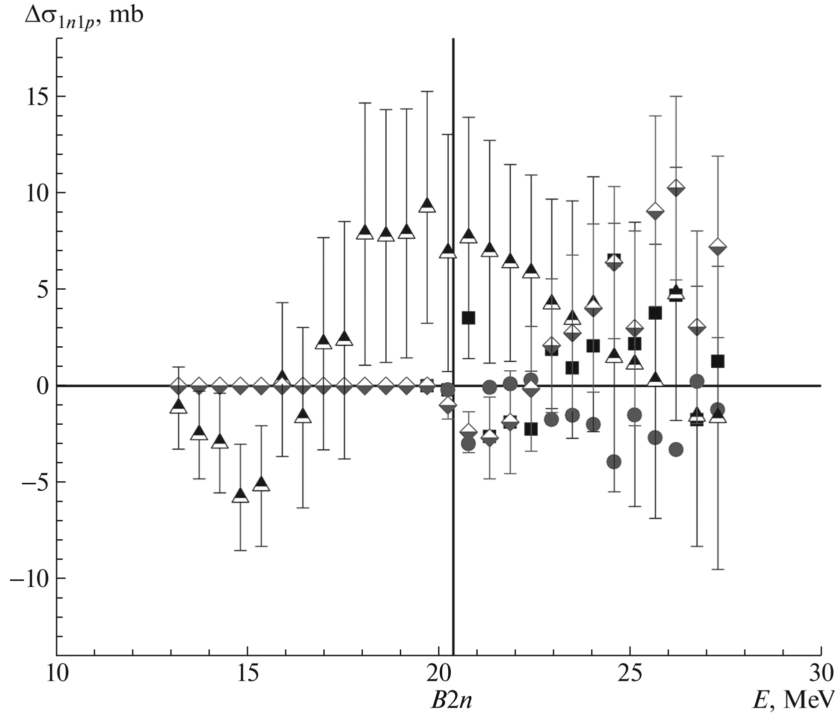

Fig. 5. Differences $\Delta\sigma_{1n1p}$ (5) of the evaluated and experimental cross sections for the $(\gamma,1n)+(\gamma,1n1p)$ and $(\gamma,2n)$ reactions on ^{51}V nucleus according to the Livermore data from [23] for (half-filled triangles) $(\gamma,1n)+(\gamma,1n1p)$ and (half-filled diamonds) $(\gamma,2n)$ and according to the Saclay data from [25] for (squares) $(\gamma,1n)+(\gamma,1n1p)$ and (circles) $(\gamma,2n)$.

which were obtained after the subtraction of the $(\gamma,1n1p)$ contributions calculated on the basis of the CPNRM. One can see that, in the energy region of $E>B2n$, the subtraction of the contribution of the $(\gamma,1n1p)$ reaction leads to a substantial decrease of about 15 mb to about 5 mb in the discrepancies between the evaluated data for the $(\gamma,1n)$ reaction and the respective experimental data obtained at Livermore. In the case of the $(\gamma,2n)$ reaction, the differences $\Delta\sigma_{1n1p}$ in (5) undergo a change both in magnitude and in sign (from about -6 mb to about $+6$ mb). Both differences $\Delta\sigma_{1n1p}$ in (5) that were obtained on the basis of the Livermore data become rather close to the respective differences $\Delta\sigma$ in (4) that were obtained on the basis of the Saclay data for the $(\gamma,1n)$ reaction, which, as was indicated above, are affected by the $(\gamma,1n1p)$ reaction to a substantially smaller extent.

This situation around the data for the ^{51}V nucleus is similar to the situation for the ^{59}Co nucleus, which was studied in the same Livermore experiment [23] (see above). on the basis of a detailed comparison of data obtained in the Livermore experiments [23, 24] for the ^{59}Co nucleus, it was shown in [21] that significant discrepancies between the experimental [23] and evaluated cross sections for partial reactions are due precisely to an unreliable overestimation of the cross section for the $(\gamma,2n)$ reaction because of the presence of a significant number of neutrons from the $(\gamma,1n1p)$ reaction.

Thus, we can conclude that, in the Livermore experiment reported in [23], the erroneous attribution of neutrons from the $(\gamma,2n)$ and $(\gamma,1n1p)$ reactions to the $(\gamma,1n)$ and $(\gamma,2n)$ reactions is the main reason, both for ^{51}V and for ^{59}Co, behind the unreliable distribution of neutrons between the $1n$ and $2n$ channels [5–9, 12–21].

In addition, it is worth noting that, in the case of the Livermore data for the ^{51}V nucleus, there are (see Fig. 3) relatively large (about 5 to 7 mb) differences in (4) at energies below the threshold of $B2n=20.39$ MeV for the $(\gamma,2n)$ reaction, where only neutrons from the $(\gamma,1n)$ reaction are present, so that the problems of neutron multiplicity sorting, which are being discussed, become nonexistent. As was indicated above, a detailed analysis of similar situations in the cases of ^{75}As [9], ^{127}I, ^{181}Ta [13], and ^{208}Pb nuclei revealed that this might be an experimental manifestation of systematic uncertainties other than those associated with an unreliable determination of the neutron multiplicity—namely, uncertainties stemming from the loss of some number of neutrons from the $(\gamma,1n)$ reaction. It is noteworthy that, in just the same way as in the cases of ^{75}As, ^{127}I, ^{181}Ta, and ^{208}Pb nuclei, the possible elimination of the discrepancies revealed in the range of energies below $B2n = 20.39$ MeV for data on the $(\gamma, 1n)$ reaction by means of a simple normalization naturally leads to the growth of the discrepancies between the $\sigma^{\rm int}$ values for the $(\gamma, 2n)$ reaction. According to the data in Table 2, this normalization in the case of the ^{51}V nucleus via the multiplication by a factor of 1.18 (522.73/439.29) renders closer the values of $\sigma^{\rm int}$ for the $(\gamma, 1n)$ reaction but naturally leads to the growth of the discrepancies between the values of $\sigma^{\rm int}$ for the $(\gamma, 2n)$ reaction—114.06 MeV mb instead of 96.6 MeV mb versus 64.45 MeV mb. All of the foregoing casts serious doubts on the reliability of the data obtained in the Livermore experiment reported in [23].

Yet, it remains unclear why the $(\gamma, 1n1p)$ reaction plays a prominent role in the Livermore experiments [23] for ^{51}V and ^{59}Co nuclei but exerts an effect of a relatively small magnitude in the Saclay experiment for the ^{51}V nucleus [25], even though both experiments employ the method of neutron multiplicity sorting to study partial reactions. It is likely that these discrepancies are associated with special features of the systems used to detect neutrons of different energy at Saclay and Livermore, where they are different, rather than with the method for determining the multiplicity of neutrons by their energy.

4. SPECIAL FEATURES OF NEUTRON DETECTION SYSTEMS AT SACLAY AND LIVERMORE

As was indicated above, the neutron detection systems used at Saclay and Livermore were based on neutron detectors of the "slowing-down"type, where special counters counted, between short pulses of an electron linac, neutrons produced in the reactions being studied and moderated to thermal energies. However, the neutron detection methods were different at those two laboratories.

At Saclay [23], the photoneutrons were detected by a large-volume (250 L) scintillator (N.E. 223) that has the shape of a sphere 1 m in diameter. The scintillator was enriched in gadolinium (^{160}Gd), which served simultaneously as a moderator for neutrons [27]. In order to record flares initiated by events of thermal neutron capture by gadolinium nuclei, the whole detector volume was scanned by eight photomultiplier tubes. A rather high detector efficiency (about 85%) depended quite weakly on the neutron energy and permitted reaching relatively high values of the detection efficiency for two neutrons from the $(\gamma, 2n)$ reaction and three neutrons from the $(\gamma, 3n)$ reaction—about 36.0% and about 21.6%, respectively. Thus, events of the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions were recorded with a rather high efficiency over the whole detector volume, irrespective of the place of neutron capture by gadolinium nuclei. At the same time, it was indicated in [22] that the detector at Saclay had a rather high level of background caused primarily by events featuring only one neutron. This led to large uncertainties in subtracting the background and in introducing corrections for miscounts (detector "... suffers from a much higher background rate, made up largely of single-neutron events, which introduces larger uncertainties in the background subtractions and pile-up corrections ..."). Thus, the detector used at Saclay had a trend to overestimate somewhat the contribution of neutrons from the $(\gamma, 1n)$ reaction in relation to the contribution of neutrons from the $(\gamma, 2n)$ reaction. As a matter of fact, this is an unreliable (erroneous) redistribution of some number of neutrons from the $(\gamma, 2n)$ reaction to the $(\gamma, 1n)$ reaction.

At Livermore, the situation was substantially different. Thermal neutrons were detected by 24 (in earlier experiments) and 48 (in more recent experiments) proportional $^{10}BF_3$ counters immersed in a large (18-inch) cube from a paraffin moderator and combined into concentric rings of various diameters. The minimum diameter of the first ring of counters was chosen in such a way that the respective amount of paraffin was sufficient for ensuring a high sensitivity of counters to neutrons of energy 25 keV, 1.2 MeV, and 2 MeV [27]. In the early experiments reported in [23], events of the following types were recorded by means of this system between the accelerator pulses: (i) all cases where the neutrons were identified as "single" ones; (ii) all cases where there appeared two or more neutrons identified as "double" ones; and (iii) all cases where there appeared three or more neutrons identified as "triple" ones. A statistical analysis of the data involving recorded neutron events and the numbers of neutrons emitted in the photodisintegration of the nucleus under study was used to determine the cross section for the $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions individually ("... the neutron counts were separated electronically as single, double, or triple counts during the gating interval. Statistical analysis was applied to the data, and the neutron counts recorded per beam pulse were correlated to the number of neutrons emitted per nuclear disintegration. The cross sections for the reactions $(\gamma, 1n)$ and $(\gamma, 2n)$ were then deduced"). In more recent experiments [22], the cross sections for partial reactions were deduced from neutrons multiplicities determined experimentally by the neutron energies. The neutron detector efficiencies were determined by means of the ring-ratio technique for each multiplicity and each data point ("... the partial photoneutron cross sections were determined by neutron multiplicity counting and the average neutron energies, and hence the neutron-detector efficiencies, were obtained for each multiplicity and for each data point by the ring-ratio technique"). In the case of employing a detector of this structure, there arises the possibility of unjustifiably overestimating the contribution of the $(\gamma, 2n)$ reaction in relation to the contribution of the $(\gamma, 1n)$ reaction. As a matter of fact, this is due to attributing some neutrons originating from the $(\gamma, 1n)$ reaction to the $(\gamma, 2n)$ reaction. The reason is that some number of neutrons characterized by rather high energies, produced predominantly in the $(\gamma, 1n)$ reaction, and not moderated to thermal energies on their path to inner counter rings are therefore expected to be captured by the counters of the outer rings, but their return to the inner rings of counters may be caused, with a nonnegligible probability, by multiple-scattering processes. After being reduced to the efficiency of a 4π detector, the detection efficiency for a "single"-neutron event was about 0.17, which is substantially lower than the efficiency of the detector at Saclay. Moreover, the detector efficiency was insufficient in many cases for recording "triple" events. This may be precisely the reason why, for some nuclei (^{115}In, ^{127}I, ^{159}Tb, ^{181}Ta, ^{197}Au, and ^{208}Pb, for example), the $(\gamma, 3n)$ cross sections were obtained at Saclay but were not determined at Livermore.

Thus, an unreliable overestimation of some number of neutrons from the $(\gamma, 1n)$ reaction at Saclay and, on the contrary, from the $(\gamma, 2n)$ reaction at Livermore is the main reason for the discovered systematic discrepancies between the results of the experiments performed at Livermore and Saclay. It is these special features of the neutron detection systems at Saclay and Livermore that are resposible for the observed typical discrepancies between the cross sections for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions.

The observed untypical discrepancies between the cross section for $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions on ^{51}V and ^{59}Co nuclei are obviously due to the presence of a significant number of neutrons having relatively low energies and which may originate only from the $(\gamma, 1n1p)$ reaction. It was indicated above that, at Saclay, events featuring different numbers of neutrons were recorded with a rather high efficiency over the whole detector volume, irrespective of the place of neutron capture by gadolinium nuclei. The presence of an extra number of neutrons having low energies and a multiplicity of unity introduced an additional uncertainty in the process of identifying the multiplicity of a neutron by its energy on the basis of a statistical analysis and led to the observed untypical discrepancies between the experimental and evaluated cross sections for partial reactions.

In the Livermore experiments, the $(\gamma, 1n1p)$ reaction played a more important role. The reason is that the neutron detector used at Livermore had a structural feature because of which the neutron multiplicity being determined depended not only on the neutron energy but also on the place of detection. Since the whole detector volume was divided by counter rings into several parts containing different amounts of the paraffin moderator, the neutron-detection process depended on the place of detection. Neutrons of higher energy, presumably from the $(\gamma, 1n)$ reaction, should be recorded predominantly by outer rings, while neutrons of lower energy from the $(\gamma, 2n)$ and $(\gamma, 1n1p)$ reactions should be recorded by inner rings.

Extra neutrons having relatively low energies, originating from the $(\gamma, 1n1p)$ reaction, and appearing near the inner rings of counters should lead to a substantial growth of systematic errors in the respective statistical analysis of detected events. Thus, the discrepancies between the experimental [23] and evaluated cross sections for partial reactions on ^{51}V nucleus might be due to the uncertainty not only in distributing the neutrons between the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions but also (even to a greater extent) in assessing their appurtenance to the $(\gamma, 2n)$ and $(\gamma, 1n1p)$ reactions.

To some extent, the ring-ratio method provided the possibility of analyzing the dependence of the energy of neutrons (and, hence, their multiplicity) on the the thickness of the paraffin moderator between the rings of the counters [27–29], thereby weakening the dependence of the neutron multiplicity being determined on the place of neutron detection. The average energies of neutrons from events featuring one, two, and three neutrons were determined for each data point, and the ratios of the number of neutrons recorded in outer rings to the number of neutrons recorded in inner rings were found to change with these energies. Although the efficiency of the detector at Livermore was not as high as the efficiency of the detector at Saclay, with the result that the determination of the neutron multiplicity was less reliable, the use of the ring-ratio method compensated for this drawback to some extent [22].

It is important to note that this feature of the detector at Livermore makes it possible to explain the discrepancies between the results of the earlier [23] and more recent [24] experiments at Livermore for the ^{59}Co nucleus. In the more recent experiment reported in [24], the use of the ring-ratio method described above permitted reducing the effect of the $(\gamma, 1n1p)$ reaction on the $(\gamma, 2n)$ cross section for the ^{59}Co nucleus. For example, the discrepancy between the cross section evaluated for the $(\gamma, 2n)$ reaction and the respective experimental cross section obtained with the aid of the ring-ratio method turned out to be about 5 mb [21], which is substantially smaller than the discrepancy of about 15 mb in the experiment not involving the ring-ratio method [23].

It is noteworthy that the discrepancies between the evaluated reaction cross sections and its experimental counterparts for the ^{59}Co nucleus in the case of employing the ring-ratio method [24] are rather close to similar discrepancies in the case of the ^{51}V nucleus for the cross sections obtained at Saclay [25].

5. BASIC CONCLUSIONS AND OUTLOOK

Relying on the objective physics criteria of data reliability, we have analyzed the experimental cross sections obtained at Livermore [23] and Saclay [25] for the $(\gamma, 1n) + (\gamma, 1n1p)$ and $(\gamma, 2n)$ reactions on ^{51}V nucleus by the method of neutron multiplicity sorting. We have shown that the data obtained at these two laboratories do not comply with such criteria formulated earlier in [7]: the ratios $F_{1,2}^{\mathrm{exp}}$ (1) obtained on the basis of the experimental data differ substantially from $F_{1,2}^{\mathrm{theor}}$ calculated within the CPNRM [10, 11].

By employing the experimental—theoretical method for evaluating partial reaction cross sections [7] that would comply with the physics reliability criteria, we have obtained new cross sections for the $(\gamma, 1n)$ and $(\gamma, 2n)$ partial reactions, as well as for the $(\gamma, Sn) = (\gamma, 1n) + (\gamma, 2n)$ total photoneutron reaction.

We have analyzed in detail the discrepancies between the evaluated and experimental cross sections for partial reactions, employing the results of the theoretical calculations from [10, 11] for the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions, as well as for the $(\gamma, 1n1p)$ reaction. The role of this reaction in processes leading to ^{51}V photodisintegration was neglected both in the Livermore [23] and in the Saclay [25] experiments. This was because the cross sections $\sigma(\gamma, 1n)$ obtained by means of direct neutron detection were in fact the summed cross section $\sigma[(\gamma, 1n) + (\gamma, 1n1p)]$.

On the basis of data on the discrepancies between the evaluated and experimental cross sections for partial reactions, we have shown the the observed substantial discrepancies between the data from the Livermore [23] and Saclay [25] experiments for the ^{51}V nucleus, which is relatively light, are due to systematic errors in assigning detected neutrons predominantly to the $(\gamma, 2n)$ and $(\gamma, 1n1p)$ reactions, rather than to the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions, as in studying the analogous reactions for medium-heavy nuclei.

In addition, we have found that, in the Livermore data obtained for the ^{51}V nucleus [23], there are also substantial systematic uncertainties of a different type, which are similar to those that were unearthed earlier in the cases of ^{75}As, ^{127}I, ^{181}Ta, and ^{208}Pb nuclei. These uncertainties manifest themselves in substantial discrepancies between the experimental and evaluated cross sections for the $(\gamma, 1n)$ reactions in the photon energy region below the threshold $B2n$ for the $(\gamma, 2n)$ reaction, where the photoneutron-multiplicity problems are nonexistent, and stem from the loss of a significant number of neutrons from the $(\gamma, 1n)$ reaction in the Livermore experiments [23].

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