ISSN 1063-7788, Physics of Atomic Nuclei, 2024, Vol. 87, Suppl. 2, pp. S264–S273. © Pleiades Publishing, Ltd., 2024.

NUCLEI
Experiment

New Data on Photoneutron Reaction Cross Sections for ^{68}Zn

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Received September 28, 2024; revised September 28, 2024; accepted September 28, 2024

Abstract—New data on cross sections of the $(\gamma,1n)$ and $(\gamma,2n)$ reactions on the ^{68}Zn nucleus, for which the neutron yield cross sections of $\sigma^{\rm exp}(\gamma,xn)=\sigma(\gamma,1n)+2\sigma(\gamma,2n)$ and the total photoneutron reaction $\sigma^{\rm exp}(\gamma,sn)=\sigma(\gamma,1n)+\sigma(\gamma,2n)$ have been obtained in two experiments on the beams of bremsstrahlung, were determined using the possibilities of the experimental—theoretical method for the evaluation of cross sections of partial photoneutron reactions based on objective physical criteria. The contributions of partial reaction cross sections $\sigma^{\rm eval}(\gamma,in)=F_i^{\rm theor}\times\sigma^{\rm exp}(\gamma,xn)$ for $i=1$ and 2 to the neutron yield cross section were evaluated using the ratios $F_i^{\rm theor}=\sigma^{\rm theor}(\gamma,in)/\sigma^{\rm theor}(\gamma,xn)$ calculated within the combined photonuclear reaction model (CPNRM).

DOI: 10.1134/S106377882470090X

Devoted to the 270th Anniversary of Moscow University

1. INTRODUCTION

The vast majority of data on cross sections of $(\gamma,1n)$, $(\gamma,2n)$, and $(\gamma,3n)$ partial photoneutron reactions, widely used in fundamental nuclear physics research and neutron yield various applications, were obtained in experiments on the beams of quasi-monoenergetic photon formed during the annihilation of accelerated positrons in flight [1–3], and some data were obtained in experiments on bremsstrahlung radiation [2, 3]. To date, there are no sufficiently intense sources of monoenergetic γ photons. To obtain information on the cross sections of partial reactions, as well as the cross sections of the total photoneutron reaction

$$\sigma(\gamma,sn)=\sigma(\gamma,1n)+\sigma(\gamma,2n)+\sigma(\gamma,3n) \quad (1)$$

and neutron yield

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

special methods are used to create conditions in which the photons causing the reaction under study could be interpreted as quasi-monoenergetic ones.

These methods differ significantly. In experiments on annihilation photon beams, first, the cross sections of the $(\gamma,1n)$, $(\gamma,2n)$, and $(\gamma,3n)$ partial reactions are determined, using which one obtains the total cross sections (1) and (2) by simple summation. In experiments on bremsstrahlung γ radiation beams, on the contrary, the cross section of the yield (2) is determined first, from which, using corrections calculated according to the statistical theory and the corresponding difference procedures, one obtains the cross sections of partial reactions. The specific implementations of such methods in different experiments also differ significantly. All these differences are the reason of significant systematic disagreements in the form and the absolute value of the results of experiments performed on photon beams not only of different types but also of the same type [4–8]. It has been found that the cross sections of $(\gamma,1n)$ and $(\gamma,2n)$ reactions determined 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, ^{238}U) on quasi-monoenergetic annihilation photon beams using the method of photoneutron multiplicity sorting in two laboratories (Lawrence Livermore National Laboratory (USA) and Nuclear Research Centre in Saclay (France)) differ significantly (up to 100% of the magnitude) systematically and in different directions. The cross sections of the $(\gamma,1n)$ reaction have large absolute values in one laboratory, while those of the $(\gamma,2n)$ reaction have large values in the other [4, 9]. Moreover, almost all reaction cross sections obtained on annihilation photon beams have a shape (strongly

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smoothed) that differs significantly from the shape of the cross sections obtained on bremsstrahlung beams [7, 8, 10].

For many years, the observed disagreements have raised questions about which of the significantly different cross sections of different reactions are reliable and whether the data obtained by such methods are reliable as a whole. A method for analyzing the reliability of data on the partial photoneutron reaction cross sections that is independent of the way of their obtaining and a method for evaluating cross sections of such reactions that satisfy objective physical reliability criteria have been proposed [11, 12]. It has been established that, in cases of a large number ($\sim$50) of nuclei studied in annihilation photon beams, the experimental cross sections are not reliable, since they contain significant systematic uncertainties of various types caused by shortcomings of the indirect method used in both laboratories for determining the neutron multiplicity based on their energy data [11–32].

The proposed methods for the analysis of the reliability of experimental data and the evaluation of reaction cross sections satisfying the physical reliability criteria [11, 12] are universal and applicable to cross sections of reactions with any neutron multiplicity obtained on incident photon beams of any type. They were used to analyze the reliability of experimental cross sections of partial photoneutron reactions obtained for several nuclei (^{51}V, ^{52}Cr, ^{59}Co, ^{58,60}Ni) on bremsstrahlung beams by methods alternative to the method of photoneutron multiplicity sorting [33–36] and based on the introduction of corrections calculated according to the statistical theory to the neutron yield cross sections Eq. (2), and to evaluate new reaction cross sections satisfying physical reliability criteria. It was established that there are certain claims to the reliability of the data obtained in experiments of this type because of certain limitations in the applicability of the corrections used. It was shown that the shortcomings of the reaction cross sections determined in experiments of both types are due, first of all, to the fact that the partial reactions in them were sorted by indirect and unreliable (because of the significant systematic uncertainties) methods.

At the same time, on the basis of a detailed comparison of the data obtained for the ^{181}Ta [14], ^{197}Au [37], and ^{209}Bi [19] nuclei by the activation method, in which direct sorting of partial reactions is carried out not by the spectra of emitted neutrons, but by the characteristics of the final nuclei, it was shown that the new partial reaction cross sections evaluated using the experimental–theoretical method are consistent with the results of such experiments.

In connection with the above, in this work, the experimental–theoretical method is used to evaluate the cross sections of the ^{68}Zn$(\gamma, 1n)^{67}$Zn and ^{68}Zn$(\gamma, 2n)^{66}$Zn reactions that satisfy physical reliability criteria, for which experimental data are up to now unavailable.

2. EXPERIMENTAL–THEORETICAL METHOD FOR EVALUATION OF PARTIAL PHOTONEUTRON REACTION CROSS SECTIONS

As noted above, the experimental cross sections of the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions for a large number of nuclei differ significantly (up to 100% of the magnitude), which is due to systematic uncertainties of in the indirect methods of their sorting. At the same time, the neutron yield cross sections $\sigma(\gamma, xn)$ (2) differ insignificantly ($\sim$10% of the magnitude) [4], since all possible energetically partial reactions contribute to such a cross section (with the corresponding multiplicity coefficients). In this regard, it was proposed [11, 12] to evaluate the cross sections of the partial reactions

$$\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}} \times \sigma^{\text{exp}}(\gamma, xn), \tag{3}$$

which are free from the aforementioned shortcomings, using only the experimental neutron yield cross section $\sigma^{\text{exp}}(\gamma, xn)$ (2), and to determine the contributions of the cross sections of $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions, as well as that of the $(\gamma, 3n)$ reaction in the energy-accessible region using the corresponding ratios of the cross sections of a certain partial reaction $\sigma^{\text{theor}}(\gamma, in)$ to the neutron yield cross section $\sigma^{\text{theor}}(\gamma, xn)$:

$$\begin{aligned} F_i^{\text{theor}} &= \sigma^{\text{theor}}(\gamma, in)/\sigma^{\text{theor}}(\gamma, xn) \\ &= \sigma^{\text{theor}}(\gamma, in)/[\sigma^{\text{theor}}(\gamma, 1n) + 2\sigma^{\text{theor}}(\gamma, 2n) \\ &\quad + 3^{\text{theor}}\sigma(\gamma, 3n), \end{aligned} \tag{4}$$

calculated within the combined photonuclear reaction model (CPNRM) [38, 39], a pre-equilibrium model based on the nuclear level densities calculated in the Fermi gas model and taking into account the effects of nuclear deformation and isospin splitting of the giant dipole resonance of the nucleus under study. Thus, the essence of the experimental–theoretical method is that the experimental neutron yield cross section $\sigma^{\text{exp}}(\gamma, xn)$ (2), almost independent of the problems of experimental determination of neutron multiplicity, is divided into contributions of the partial reaction cross sections using ratios F_i^{theor} (4), absolutely independent of these problems, and at the same time $\sigma^{\text{eval}}(\gamma, xn) = \sigma^{\text{exp}}(\gamma, xn)$.

The ratios F_i (4), calculated from the experimental cross section data, make it possible to formulate two strict absolute physical criteria for the reliability of these data [11, 12]:

1) The ratios $F_i^{\rm exp}$ should not exceed the absolute physical upper limits (1.00, 0.50, 0.33, ..., respectively, for $i = 1, 2, 3, \ldots$).

2) The ratios $F_i^{\rm exp}$ should be definitely positive, since all terms of ratios (4) represent cross sections with the dimension of area and/or their sums.

Additionally, on the basis of a detailed comparison of the data evaluated for the ^{181}Ta [14], ^{197}Au [37], and ^{209}Bi [19] nuclei with the results of the corresponding activation experiments, the third (not strict) data physical reliability criterion was established: the proximity of the experimental ratios $F_i^{\rm exp}$ to ratios $F_i^{\rm theor}$ obtained from the results of calculations within CPNRM [38, 39].

3. EXPERIMENTAL DATA ON PHOTONEUTRON REACTIONS FOR ^{68}Zn NUCLEUS

To date, only one photoneutron yield cross section $\sigma^{\rm exp}(\gamma, xn)$ (2) [40] and one cross section $\sigma^{\rm exp}(\gamma, sn)$ of the total photoneutron reaction (1) [41] for the ^{68}Zn nucleus were published. Both cross sections were obtained in similar experiments performed on bremsstrahlung beams. The energy dependences of the reaction yield

$$Y(E^{\rm M}) = \frac{N(E^{\rm M})}{\varepsilon D(E^{\rm M})} = \alpha \int_{E_{\rm thres}}^{E^{\rm M}} W(E^{\rm M}, E)\sigma(E)dE, \quad (5)$$

where $\sigma(E)$ is the desired cross section at the photon energy E, $E_{\rm thres}$ is the energy threshold of the reaction, $W(E^{\rm M},\ E)$ is the spectrum of the bremsstrahlung γ-radiation photons with an upper boundary $E^{\rm M}$, $N(E^{\rm M})$ is the number of reaction events, $D(E^{\rm M})$ is the γ-radiation dose, ϵ is the detector efficiency, and α is the normalization constant, were measured using $^{10}BF_3$ counters placed in a paraffin moderator (data on the radiative capture of neutrons moderated to thermal energies were used). The measurements were carried out in the energy ranges of incident photons from the threshold $B1n =$ 10.2 MeV of the $(\gamma, 1n)$ reaction to 27 MeV (with a step of 50 keV) [40] and 25 MeV (with a step of 143 keV) [41], respectively. In both experiments, the reaction cross section $\sigma(E)$ was determined by the traditional method [42] due to the fact that the spectrum $W(E^{\rm M},\ E)$ of the photons causing the reaction has a continuous form. To the solution of the inverse problem (5) of its unfolding from the yield $Y(E^{\rm M})$ by the Penfold–Leiss method was used. In the experiment [40], a variant with a variable processing step was used: 0.2 MeV in the photon energy range of 10.0–11.5 MeV, 0.5 MeV in the range of 11.5–16.5 MeV, and 1.0 MeV in the range of 16.5–27.0 MeV. A variant with a constant step of 1 MeV was used in the experiment [41].

Table 1. Thresholds B (MeV), energy position of the maximum $E^{\rm max}$ (MeV), and amplitude $\sigma^{\rm max}$ (mb) of the cross sections of photonuclear reactions on the ^{68}Zn nucleus

Reaction	B	$E^{\rm max}$	$\sigma^{\rm max}$
$(\gamma, 1n)$	10.20	17.6	137.7
$(\gamma, 2n)$	17.25	19.6	43.0
$(\gamma, 1n1p)$	19.11	25.0	6.1
$(\gamma, 3n)$	28.32	34.0	6.0

The experimental cross section $\sigma(E)$ (5) is presented in the form [40]

$$\sigma^{\rm exp}(\gamma, xn) = \sigma^{\rm exp}(\gamma, 1n) + \sigma^{\rm exp}(\gamma, 1n1p) + 2\sigma^{\rm exp}(\gamma, 2n), \quad (6)$$

which somewhat differs from the general form (2). This is due to the fact that three reactions listed above are possible in the photon energy region up to $E_\gamma \sim$ 27 MeV: $(\gamma, 1n)$, $(\gamma, 1n1p)$, and $(\gamma, 2n)$. The data on the thresholds of these reactions together with the energy positions and amplitudes of the reaction cross sections calculated in CPNRM are given in Table 1, and the theoretically calculated reaction cross sections $\sigma^{\rm theor}(\gamma, 1n)$, $\sigma^{\rm theor}(\gamma, 2n)$, and $\sigma^{\rm theor}(\gamma, 1n1p)$ on the ^{68}Zn nucleus are given themselves in Fig. 1.

The importance of taking into account the contribution of the $(\gamma, 1n1p)$ reaction to photodisintegration of nuclei was noted in all previous studies of the reliability of data on the partial reaction cross sections [11–36]. This is due to the fact that such a two-nucleon reaction with the neutron multiplicity 1 does not compete in neutron energies with a one-nucleon $(\gamma, 1n)$ reaction with the same multiplicity. It competes with a two-nucleon $(\gamma, 2n)$ reaction, the neutron multiplicity of which is 2. In the method of photoneutron multiplicity sorting on the basis of their energy data used on annihilation photon beams, this circumstance is a source of additional systematic uncertainties that distort the identification of neutrons with relatively small and close energies of $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions. When the corrections calculated from the statistical theory are introduced into the neutron yield cross section, the nonnegligible contribution of the $(\gamma, 1n1p)$ reaction distorts the accuracy of such corrections.

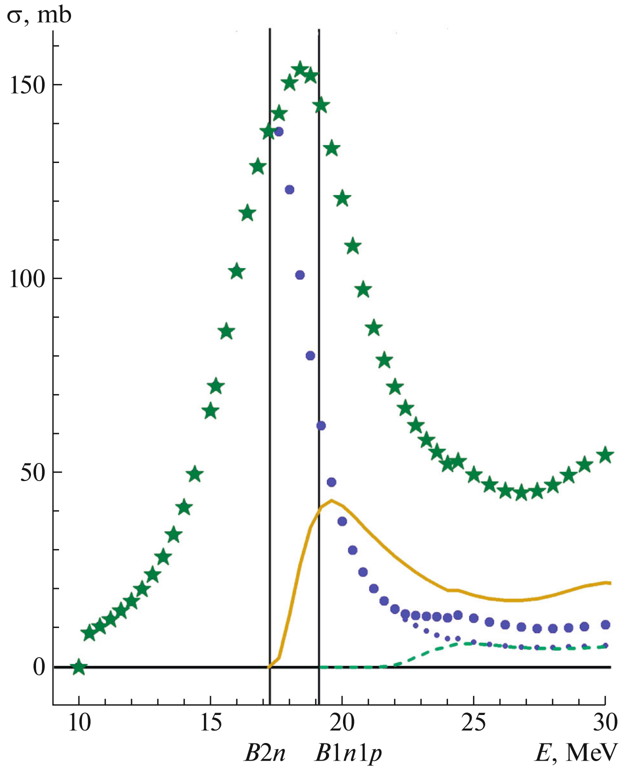

Fig. 1. Cross sections of different reactions on the ^{68}Zn nucleus theoretically calculated within CPNRM [38, 39]: neutron yield cross section $\sigma^{\rm theor}(\gamma, xn)$ (asterisks), $\sigma(\gamma, 1n) + \sigma(\gamma, 1n1p)$ (circles), $\sigma(\gamma, 2n)$ (solid curve), $\sigma(\gamma, 1n1p)$ (dashed curve), and $\sigma(\gamma, 1n)$ (points).

The data presented in Fig. 1 and Table 1 indicate that the contribution of the $(\gamma, 1n1p)$ reaction to the photodisintegration processes of the ^{68}Zn nucleus is not negligibly small compared to the contributions of the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions but has no noticeable effect on these processes.

The data on the neutron yield cross section $\sigma^{\rm exp}(\gamma, xn)$ were not published in experiment [41]. This cross section was used to obtain the total photoneutron reaction cross section $\sigma^{\rm exp}(\gamma, sn)$ by applying the traditional method [42] of introducing corrections to the yield cross section, which were calculated according to the statistical theory [43].

4. EVALUATION OF PARTIAL REACTION CROSS SECTIONS FOR ^{68}Zn NUCLEUS USING EXPERIMENTAL–THEORETICAL METHOD

The data in Table 1 and Fig. 1 indicate that the $(\gamma, 1n1\mathrm{p})$ reaction plays a certain role in the photodisintegration processes of the ^{68}Zn nucleus; therefore, the partial reaction cross sections for this nucleus (3) were evaluated taking into account the cross sections $\sigma^{\rm theor}(\gamma, 1n)$, $\sigma^{\rm theor}(\gamma, 2n)$, and $\sigma^{\rm theor}(\gamma, 1n1p)$ theoretically calculated within CPNRM [38, 39] and also cross sections $\sigma^{\rm theor}(\gamma, 1n) + \sigma^{\rm theor}(\gamma, 1n1p)$ and $\sigma^{\rm theor}(\gamma, xn)$ obtained using them.

The corresponding ratios $F_i^{\rm theor}$ (4) shown in Fig. 2 were obtained using theoretically calculated cross sections. These ratios were used to evaluate the partial reaction cross sections (3) on the basis of the experimental neutron yield cross section $\sigma^{\rm exp}(\gamma, xn)$ [40] for the ^{68}Zn nucleus, which is shown in Fig. 3 in comparison with the theoretical cross section $\sigma^{\rm theor}(\gamma, xn)$ [38, 39] calculated within CPNRM. In order to bring the experimental [40] and theoretical [38, 39] neutron yield cross sections as close as possible, the latter (dashed curve in Fig. 3) was slightly corrected (solid curve in Fig. 3) on the basis of the data on the integrated cross sections and energy centers of gravity of both cross sections given in Table 2. The correction consisted in shifting the theoretical cross section $\sigma^{\rm theor}(\gamma, xn)$ towards lower energies by $\Delta E^{\rm c.g} = E^{\rm c.g-theor} - E^{\rm c.g-exp} = 19.2 - 18.5 = 0.7$ MeV and multiplying it by the coefficient $\sigma^{\rm int-exp}/\sigma^{\rm int-theor} = 1610/1203 = 1.33$ (relevant data calculated up to the incident photon energy of 26.85 MeV were used). The ratios $F_i^{\rm theor-corr}$ (4) refined according to the parameters of the corrected cross section $\sigma^{\rm theor-corr}(\gamma, xn)$ were used in the procedure (3) of the evaluation of partial reaction cross sections.

5. EVALUATED PARTIAL REACTION CROSS SECTIONS FOR ^{68}Zn NUCLEUS

New evaluated ^{68}Zn$(\gamma, 1n)^{67}$Zn, ^{68}Zn$(\gamma, 2n)^{66}$Zn, and ^{68}Zn$(\gamma, 1n1p)^{66}$Cu partial reaction cross sections, experimental data for which have not been obtained to date, are shown in Fig. 4. The integrated cross sections of the (γ, sn), $(\gamma, 1n)$, and $(\gamma, 2n)$ reactions corresponding to the evaluated data are shown in Table 3 together with similar data on the experimental yield cross section $\sigma^{\rm exp}(\gamma, xn)$ [40] used for the evaluation, and also the only published total photoneutron reaction cross section $\sigma^{\rm exp}(\gamma, sn)$ obtained in another experiment on the bremsstrahlung beam [41].

The comparison of the evaluated total photoneutron reaction cross section $\sigma^{\rm eval}(\gamma, sn) = \sigma^{\rm eval}(\gamma, 1n) + \sigma^{\rm eval}(\gamma, 2n)$ with the experimental cross section $\sigma^{\rm exp}(\gamma, sn)$ [41] allows one to evaluate the reliability of data on this cross section obtained using the introduction of corrections calculated according to the statistical theory into the neutron yield cross section. This comparison indicates the following. Only the $(\gamma, 1n)$ reaction is possible in the energy range of incident photons up to the threshold $B2n = 17.25$ MeV,

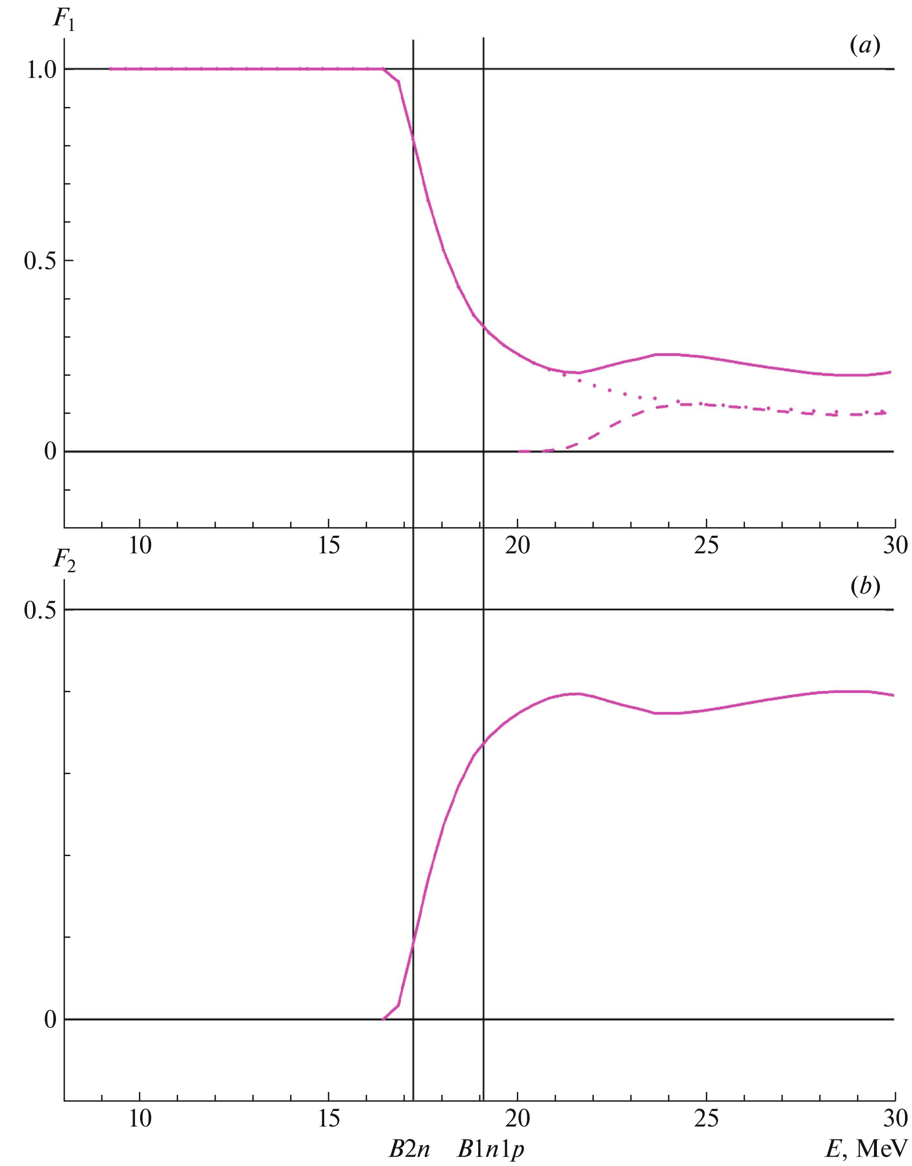

Fig. 2. Theoretical ratios $F_1^{\rm theor} = \sigma^{\rm theor}(\gamma, 1n) + \sigma^{\rm theor}(\gamma, 1n1p)/\sigma^{\rm theor}(\gamma, xn)$ (a) and $F_2^{\rm theor} = \sigma^{\rm theor}(\gamma, 2n)/\sigma^{\rm theor}(\gamma, xn)$ (b) for the ^{68}Zn nucleus determined from data on theoretical reaction cross sections calculated within CPNRM [38, 39]. At energies exceeding the threshold $B1n1p$ of the $(\gamma, 1n1p)$ reaction, the ratio $F_1^{\rm theor}$ is given disregarding (points) and taking into account (solid curve) the contribution of the cross section $\sigma^{\rm theor}(\gamma, 1n1p)$ (dashed curve).

and there are no problems to determine the neutron multiplicity experimentally. The ratio of the evaluated integrated cross section of the (γ, sn) total photoneutron reaction to the experimental one [41] is $\sigma^{\rm int-eval}/\sigma^{\rm int-exp} = 1.90$ (640.58/337.29). Such a difference, remaining constant in the energy range up to 27 MeV, could be a consequence of a possible simple discrepancy in the normalization of the data on the neutron yield cross section from experiments [40] and [41]. However, these data indicate that such ratio decreases significantly with increasing photon energy. Thus, it is 1.76 (855.06/486.62) for energy ranges up to the threshold $B1n1p = 19.25$ MeV and 1.67 (1223.45/732.02) up to $E^{\rm int} = 24.40$ MeV. For the energy region exceeding $B2n = 17.25$ MeV, the ratio in question is even smaller: $\sigma^{\rm int-eval}/\sigma^{\rm int-exp} = 582.87/394.73 = 1.47$. This means that, in addition to possible disagreements associated with the normalization of data, which should not depend on the photon energy, the experimental total photoneutron reaction cross section [41] contains uncertainties of other origin, namely, certain shortcomings of the method for obtaining the cross section $\sigma^{\rm exp}(\gamma, sn)$ [41] using corrections calculated according to the statistical theory. The observed energy dependence

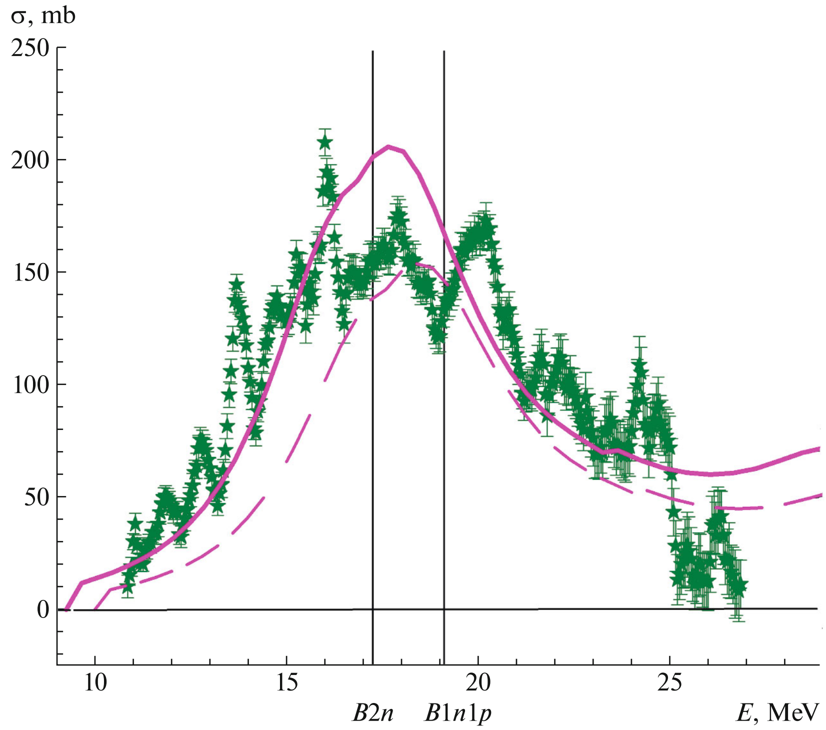

Fig. 3. Comparison of the experimental neutron yield cross section of the ^{68}Zn(γ, xn) ([40], asterisks) with the cross section theoretically calculated within CPNRM [38, 39] (before (dashed curve) and after (solid) correction).

of the ratio $\sigma^{\text{int-eval}}/\sigma^{\text{int-exp}}$ indicates that the cross section of the $(\gamma, 2n)$ reaction determined using such corrections and subtracted from the yield cross section $\sigma^{\text{exp}}(\gamma, xn)$ to obtain $\sigma^{\text{exp}}(\gamma, sn)$ [41] is unreliably (unreasonably) overestimated in comparison with the cross section of the $(\gamma, 2n)$ reaction evaluated using the experimental—theoretical method and satisfying the physical reliability criteria. In such a situation, the experimental cross section of the $(\gamma, 1n)$ reaction [41], accordingly, is unreliably underestimated in comparison with the evaluated cross section.

The dependence of the competition of $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions on the energy of incident photons determined using the aforementioned corrections is generally consistent with the results obtained earlier during the evaluation of the partial photoneutron reaction cross sections on ^{51}V, ^{52}Cr, ^{59}Co, ^{58,60}Ni, and ^{90}Zr nuclei [33–36, 44] by the experimental—theoretical method using neutron yield cross sections $\sigma(\gamma, xn)$ (2) determined in experiments on bremsstrahlung beams. This is due to the fact that the corrections under discussion work well enough only in the region of relatively low ($\sim$10–15 MeV) energies of incident photons. In the region of higher energies, in which the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions compete, and in cases of relatively light nuclei the $(\gamma, 1n1p)$ reaction, competes also these corrections become less accurate because the pre-equilibrium decay of the composite system begins to play a role at such energies.

6. CONCLUSIONS

New cross sections of ^{68}Zn$(\gamma, 1n)^{67}$Zn and ^{68}Zn$(\gamma, 2n)^{66}$Zn partial reactions, which were not experimentally determined, have been obtained using the experimental—theoretical for evaluation of partial photoneutron reaction cross sections used previously to obtain data on such reactions that satisfy objective physical reliability criteria.

We have also evaluated the cross section of the ^{68}Zn(γ, sn) total photoneutron reaction (1), for which only one experimental result obtained using bremsstrahlung beam had previously been published.

To evaluate new cross sections of reactions on the ^{68}Zn nucleus, we used the only known neutron yield cross section $\sigma^{\text{exp}}(\gamma, xn)$ determined in an experiment on the bremsstrahlung beam [40] and the results of theoretical calculations within CPNRM [38, 39].

The comparison of the new evaluated cross section of the total photoneutron reaction $\sigma^{\text{eval}}(\gamma, sn)$ on the ^{68}Zn nucleus with the only experimental cross section of the total photoneutron reaction $\sigma^{\text{exp}}(\gamma, sn)$ [41] allows us to evaluate the reliability of data obtained using the corrections calculated according to the statistical theory. This comparison indicates that

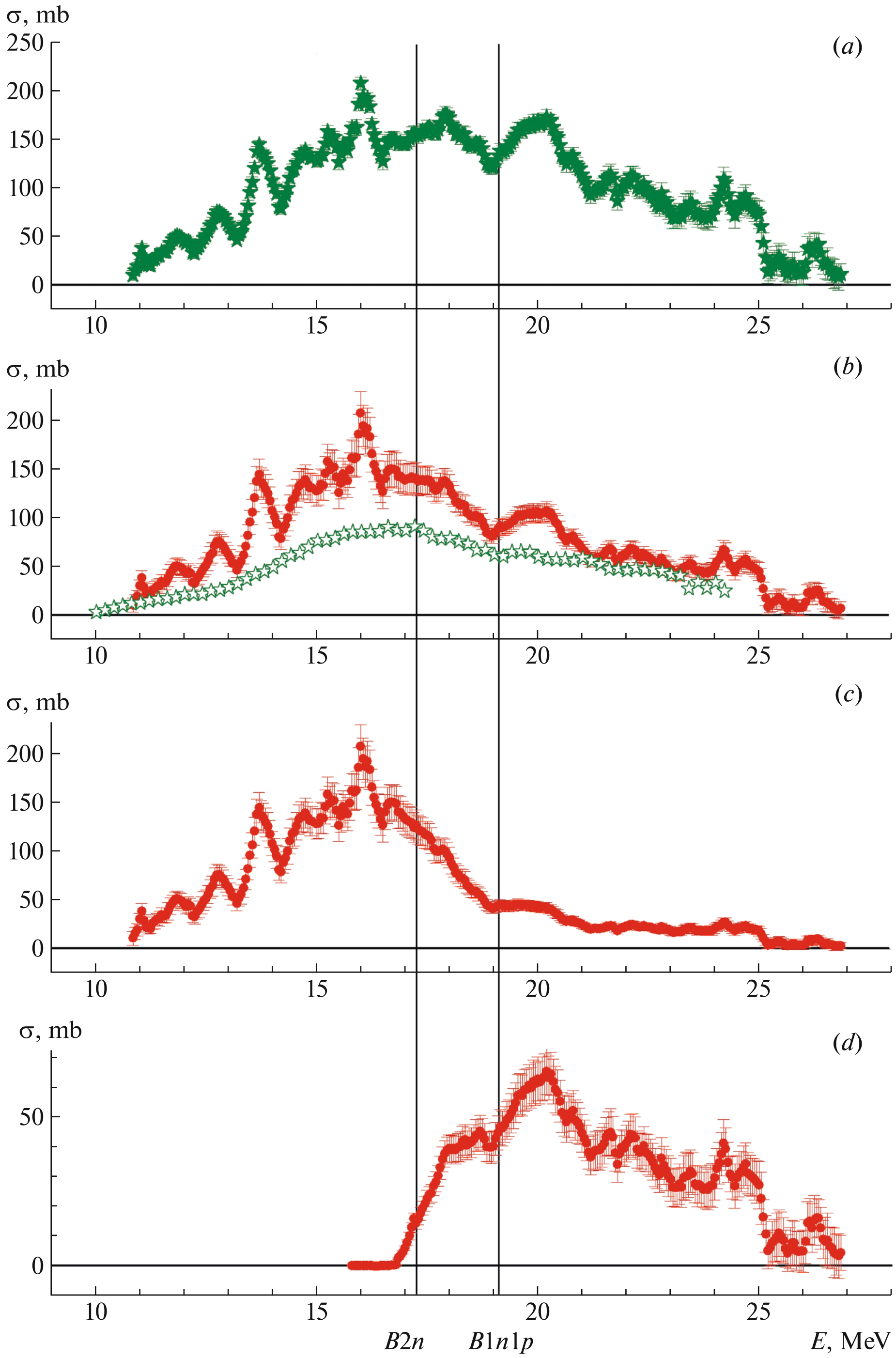

Fig. 4. Evaluated (circles) and experimental ([40], asterisks) reaction cross sections on the ^{68}Zn nucleus: (*a*) $\sigma^{\rm exp}(\gamma, xn)$; (*b*) $\sigma^{\rm eval}(\gamma, sn)$, unfilled asterisks—experimental cross section [41]; (*c*) $\sigma^{\rm eval}(\gamma, 1n)$; (*d*) $\sigma^{\rm eval}(\gamma, 2n)$.

the experimental total photoneutron reaction cross section [41] contains systematic uncertainties due to the shortcomings of the relevant method. The use of the discussed corrections led to an unreliable overestimation of the contribution of the cross section of the ^{68}Zn(γ, 2n)^{66}Zn reaction and, accordingly, to an underestimation of the contribution of the cross section of the ^{68}Zn$(\gamma, 1n)^{67}$Zn reaction relative to the evaluated cross sections satisfying the physical criteria of the reliability of data. This is due to the fact that, while working quite well in the region of relatively low photon energies, in which only the $(\gamma, 1n)$ reaction is possible, such corrections in the higher energy region, in which this reaction competes with

Table 2. Integrated cross sections σ^{int} and energy centers of gravity $E^{\text{c.g}}$ calculated from experimental [40] and theoretical [38, 39] (before and after correction) cross sections of the ^{68}Zn(γ, xn) reaction yield

Energy region	$E^{\text{int}} = B2n = 17.25$ MeV		$E^{\text{int}} = 26.85$ MeV	
	σ^{int}, MeV mb	$E^{\text{c.g}}$, MeV	σ^{int}, MeV mb	$E^{\text{c.g}}$, MeV
Experiment [40]	644.12 ± 2.29	14.91 ± 0.22	1610.9 ± 5.49	18.45 ± 0.31
Theory [38, 39]	359.47 ± 7.80	15.32 ± 1.43	1203.18 ± 12.18	19.20 ± 0.76
Theory—corr.	613.16 ± 12.67	15.20 ± 1.43	1643.86 ± 16.37	18.73 ± 0.72

Table 3. Integrated cross sections σ^{int} (in units of MeV mb) calculated for evaluated cross sections of the total and partial photoneutron reactions on the ^{68}Zn nucleus in comparison with the experimental data for the neutron yield cross section (γ, xn) [40] and cross section of the total photoneutron reaction (γ, sn) [41]

Reaction	Evaluated data	Experiment [40]	Experiment [41]
$E^{\text{int}} = B2n = 17.25$ MeV			
(γ, xn)		644.12 ± 2.29	
(γ, sn)	640.58 ± 5.52		337.29 ± 2.41
$(\gamma, 1n)$	637.03 ± 5.52		
$(\gamma, 2n)$	3.54 ± 0.12		
$E^{\text{int}} = B1n1p = 19.11$ MeV			
(γ, xn)		925.8 ± 2.77	
(γ, sn)	855.06 ± 6.01		486.62 ± 3.26
$(\gamma, 1n)$	785.67 ± 5.93		
$(\gamma, 2n)$	69.40 ± 0.97		
$E^{\text{int}} = 24.40$ MeV			
(γ, xn)		1517.47 ± 4.45	
(γ, sn)	1223.45 ± 6.68		732.02 ± 4.88
$(\gamma, 1n1p)$	20.79 ± 0.44		
$(\gamma, 1n)$*	929.40 ± 6.13		
$(\gamma, 2n)$	294.05 ± 2.65		
$E^{\text{int}} = 26.85$ MeV			
(γ, xn)		1610.89 ± 5.49	
(γ, sn)	1281.46 ± 7.00		
$(\gamma, 1n1p)$	31.95 ± 0.70		
$(\gamma, 1n)$*	952.01 ± 6.23		
$(\gamma, 2n)$	329.45 ± 3.20		

* The cross section of the $(\gamma, 1n)$ reaction with a small contribution of the $(\gamma, 1n1p)$ reaction.

$(\gamma, 2n)$ and $(\gamma, 1n1p)$ reactions, lose their accuracy owing to the fact that various nonstatistical processes begin to play a certain additional role.

FUNDING

This work was performed at the Department of Electromagnetic Processes and Interactions of

Atomic Nuclei (Center for Photonuclear Experiments Data), Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University. The study was conducted under the state assignment of Lomonosov Moscow State University

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by L. Mosina