ISSN 0027-1349, Moscow University Physics Bulletin, 2018, Vol. 73, No. 1, pp. 68–74. © Allerton Press, Inc., 2018.
Original Russian Text © V.V. Varlamov, V.D. Kaidarova, M.E. Stepanov, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2018, No. 1, pp. 68–75.

The Reliability of Cross Sections of Partial Photoneutron Reactions for ^{98}Mo

V. V. Varlamov[a, *], **V. D. Kaidarova**[b, **], **and M. E. Stepanov**[b]
[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Department of Physics, Moscow State University, Moscow, 119991 Russia*
**e-mail: varlamov@depni.sinp.msu.ru*
***e-mail: vd.kaydarova@physics.msu.ru*

Received January 16, 2017; in final form, February 17, 2017

Abstract—The cross sections of partial photoneutron reactions for ^{98}Mo were evaluated. These cross sections are free from the shortcomings of various methods for neutron multiplicity determination used at the beams of quasimonoenergetic annihilation photons and bremsstrahlung radiation. New data on the cross sections of reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) were obtained using the experimental–theoretical method for evaluation of cross sections of partial reactions satisfying the introduced physical reliability criteria. It is demonstrated that considerable deviations of the experimental cross sections from the evaluated ones result from an inaccurate sorting of neutrons between channels with a multiplicity of 1, 2, and 3.

Keywords: giant dipole resonance, cross sections of partial photoneutron reactions, neutron multiplicity, data reliability, experimental–theoretical method for evaluation of reaction cross sections.

DOI: 10.3103/S0027134918010149

INTRODUCTION

It is well known that data on the cross sections of partial photonuclear (primarily photoneutron) reactions such as (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) are highly relevant for research into the giant dipole resonance (GDR) of atomic nuclei. These data are used widely in various fields of science and engineering (nuclear physics; atomic power engineering; and radiation chemistry, geology, medicine, etc.).

The data on the cross sections of partial photoneutron reactions were largely obtained in experiments with quasimonoenergetic annihilation photons at the Lawrence Livermore National Laboratory (Livermore, United States) and the Saclay Nuclear Research Center (Saclay, France).

While the energy spectra of photons interacting with the target nucleus were almost the same, the methods for neutron multiplicity determination based on the measured kinetic energy of these neutrons differed significantly. Thus, the experimental conditions were substantially different. This resulted in well-known systematic discrepancies between the obtained reaction cross sections [1, 2]. Such discrepancies (relatively small: ~10%) were revealed even in the comparative analysis of data on the cross section of the neutron yield reaction [1, 2]:

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

The discrepancies between the cross sections of partial reactions (σ(γ, 1*n*), σ(γ, 2*n*), σ(γ, 3*n*), etc.) are more significant and may be as large as ~100%. In addition, they are definitely of a systematic nature: the cross sections of reaction (γ, 1*n*) determined at Saclay are typically larger than the same cross sections measured at Livermore, while the reverse is true for (γ, 2*n*).

The energy thresholds of partial reactions are low and relatively close to each other. As a result, it becomes necessary for the experimenters working, for example, in the energy region above the (γ, 2*n*) reaction energy threshold *B*2*n* to reliably identify the actual reaction ((γ, 1*n*) or (γ, 2*n*)) in which the detected neutron was produced. The same problem arises in experiments that probe the energy region above the (γ, 3*n*) reaction energy threshold *B*3*n*, where reactions that produce two and three neutrons are competing.

Special techniques for neutron sorting according to multiplicity are used to solve the problem of distinguishing between competing reactions. Detectors suitable for neutron multiplicity sorting based on the measurement of neutron energies were used in experiments with quasimonoenergetic photons (it was assumed that the energy of neutrons from the (γ, 1*n*) reaction is higher than that of neutrons from (γ, 2*n*)). As an example, the Livermore research team used the "ring ratio" method: neutron detectors were arranged in concentric rings in the moderator around the target, and the ring with a smaller (larger) diameter detected neutrons with lower (higher) kinetic energies. It was assumed that higher-energy neutrons were produced in the (γ, 1*n*) reaction, while lower-energy particles were tentatively associated with the (γ, 2*n*) reaction. The researchers in Saclay used a large scintillation detector that underwent special calibration with neutron sources.

An approach utilizing special multiplicity transition functions was proposed in [1, 2] for the analysis of the reliability of data on photoneutron multiplicity sorting. These functions are the ratios of cross sections of specific partial reactions to the cross section of the neutron yield reaction:

$$F_i = \sigma(\gamma, in)/\sigma(\gamma, xn) = \sigma(\gamma, in)/[\sigma(\gamma, 1n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + \ldots]. \tag{2}$$

By definition, the values of such ratios do not exceed 1.00, 0.50, and 0.33, ... for $i = 1, 2$, and 3, ... If the ratios F_i^{exp} turn out to be higher than these limiting values, the sorting of neutrons between reactions (γ, 1*n*) and (γ, 2*n*), (γ, 2*n*) and (γ, 3*n*), etc., is physically inaccurate. The function F_2 is of special interest, since it is rather efficient for analyzing the ratios of cross sections of three partial reactions discussed in the present study: (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*).

Function F_2 is formed by dividing cross section σ(γ, 2*n*) by the same cross section multiplied by a factor of 2 (with added contributions from cross sections σ(γ, 1*n*) and σ(γ, 3*n*); see the denominator in (2)). Therefore, it does not exceed 0.50 at any photon energy. Since the cross section σ(γ, 2*n*) is located in the region of the decreasing high-energy part of cross section σ(γ, 1*n*), the deviation from 0.50 in the low-energy region is induced by σ(γ, 1*n*); when the photon energy increases, the value of F_2 should tend to 0.50 (but should not reach this limit). Deviations of the value of function F_2 from 0.50 at energies higher than *B*3*n* are associated with the contribution of the (γ, 3*n*) reaction cross section.

In accordance with the above, an experimental—theoretical method for evaluation of the cross sections of partial photoneutron reactions was proposed in [1, 2]. This method is free from the shortcomings of experimental neutron multiplicity sorting and is based on the simultaneous use of experimental data on just the cross section of neutron yield reaction (1), which is unaffected by the discussed multiplicity issues, and calculated data obtained using the combined model of photonuclear reactions [3, 4], which provides a satisfactory description of the cross section of reaction (1). In the present study, the reliability of experimental data was investigated and partial and total photoneutron reaction cross sections were evaluated for ^{98}Mo.

1. PHOTONEUTRON MULTIPLICITY TRANSITION FUNCTIONS F_i FOR ^{98}Mo

The experiments on photodisintegration of ^{98}Mo were carried out using quasimonoenergetic annihilation photon beams and bremsstrahlung radiation at the Saclay Nuclear Research Center [5] and the Skobeltsyn Institute of Nuclear Physics [6], respectively. It should be noted that the cross sections of partial reactions in [5] were measured directly using the neutron multiplicity sorting method, while the total photoneutron reaction cross section

$$\sigma(\gamma, sn) = \sigma(\gamma, 1n) + \sigma(\gamma, 2n) + \sigma(\gamma, 3n) + \ldots \tag{3}$$

and the cross section of neutron yield reaction (1) were determined based on these partial cross sections. The cross section of neutron yield reaction (1) was measured directly in [6], and cross section (3) was determined using the statistical theory of nuclear reactions. The cross sections of partial reactions were determined based on cross sections (1) and (3) by performing the corresponding subtraction operations. As an example, at energies below the *B*3*n* threshold,

$$\sigma(\gamma, 2n) = \sigma(\gamma, xn) - \sigma(\gamma, sn). \tag{4}$$

Figure 1 shows the energy dependences of neutron multiplicity transition functions (F_i^{exp} ratios (2)) determined for ^{98}Mo based on the data from [5, 6]. These functions are compared with F_i^{theor} [3, 4]. It is evident that ratios F_i^{exp} differ considerably from F_i^{theor}.

It should be noted that the energy dependences of functions $F_{1,2,3}^{\text{theor}}$ [3, 4] are physically credible and fit definition (2):

(i) $F_1^{\text{theor}} = 1$ up to threshold $B2n = 15.47$ MeV of reaction (γ, 2*n*); when the 2*n* channel opens, F_1^{theor} decreases as expected in the context of competition between the increasing cross section (γ, 2*n*) and the decreasing cross section (γ, 1*n*) and smoothly approaches zero;

(ii) $F_1^{\text{theor}} = 0$ in the same energy region; when the 2*n* channel opens, F_2^{theor} increases as expected in the context of competition between the increasing cross section (γ, 2*n*) and the decreasing cross section (γ, 1*n*) and approaches 0.50 from below, but never reaches this limit; when the 3*n* channel opens, F_2^{theor} decreases as the contribution of (γ, 3*n*) in the denominator of (2) becomes more and more significant;

(iii) $F_3^{\text{theor}} = 0$ up to threshold $B3n = 24.62$ MeV of reaction (γ, 3*n*); at higher energies, it increases as expected in the context of competition between the increasing cross section (γ, 3*n*) and the decreasing cross section (γ, 2*n*).

It is worth noting that experimental ratios $F_{1,2}^{\text{exp}}$ differ considerably from the corresponding theoretical

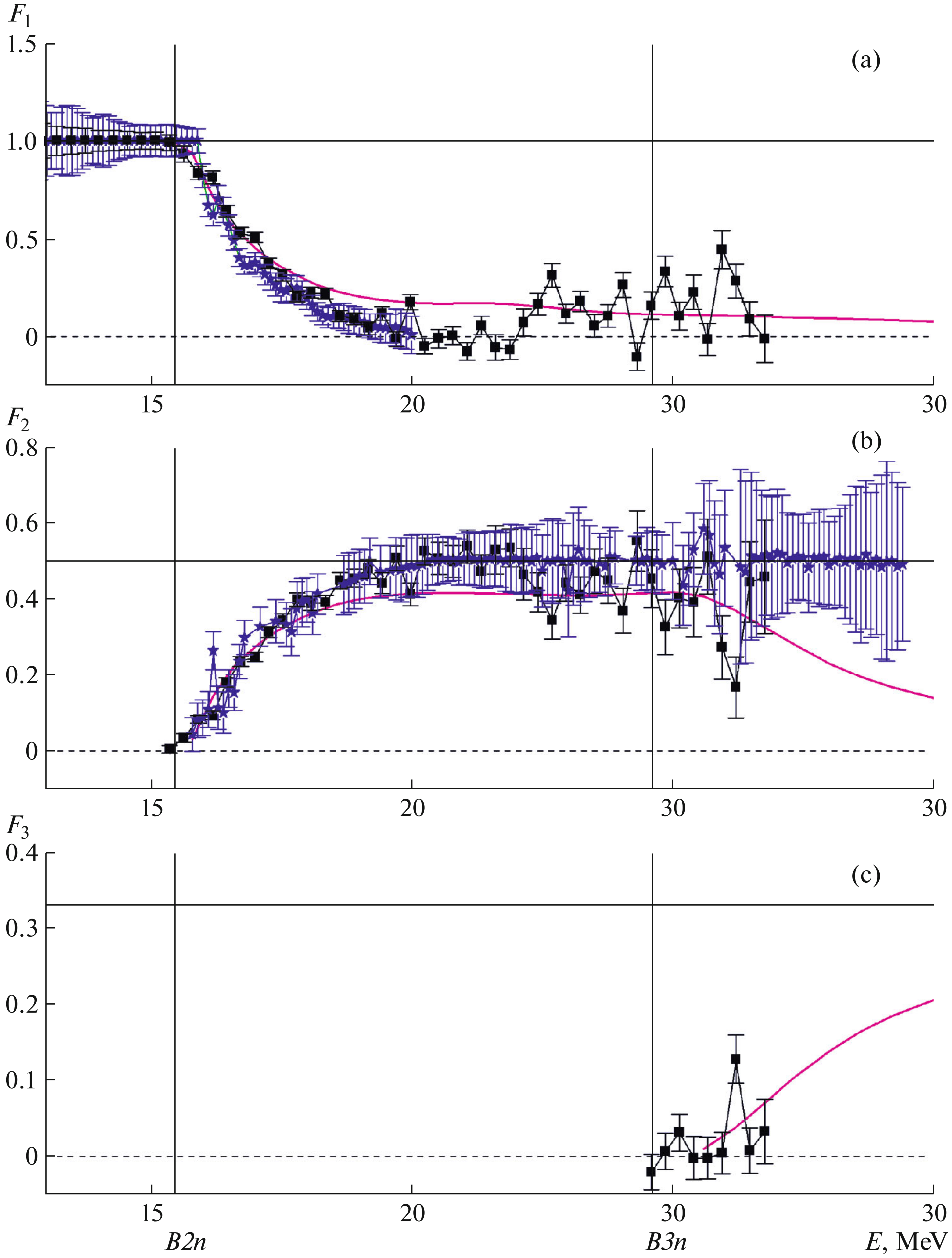

Fig. 1. Comparison of multiplicity transition functions F_i^{exp} (2) determined based on the experimental data from [5] (squares) and [6] (asterisks) with functions F_i^{theor} calculated theoretically [3, 4]: (a) functions F_1; (b) functions F_2; (c) functions F_3.

ratios $F_{1,2}^{\mathrm{theor}}$ almost at any energy above ~17 MeV. Physically forbidden negative ratios F_1^{exp}, which are correlated with unreliable values of $F_2^{\mathrm{exp}} > 0.50$, are observed in the energy interval of ~19.5–22.0 MeV and at ~24.2, ~25.7, and ~26.8 MeV. Such correlations suggest that neutrons were sorted inaccurately in experiments: some neutrons from the (γ, 1*n*) reaction were identified erroneously as particles from the (γ, 2*n*) reaction. As a result, the cross section of (γ, 1*n*) was underestimated to the point that forbidden negative values emerged, and the cross section of (γ, 2*n*) was overestimated so much that F_2^{exp} went beyond the limit of 0.50. Thus, the data presented in Fig. 1 provide evidence of he unreliability of the cross sections of partial reactions (γ, 1*n*) and (γ, 2*n*), since these cross sections fail to meet the objective physical reliability criteria.

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

The experimental–theoretical evaluation method proposed in [1, 2] provides an opportunity to obtain data on partial cross sections of photoneutron reactions that are unaffected by the shortcomings of experimental techniques for neutron multiplicity sorting.

Reliable evaluated data on competing reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) are obtained in the following way:

(i) cross sections $\sigma^{\text{theor}}(\gamma, 1n)$, $\sigma^{\text{theor}}(\gamma, 2n)$, and $\sigma^{\text{theor}}(\gamma, 3n)$ calculated theoretically using the combined model of photonuclear reactions [3, 4] are combined (1) into cross section $\sigma^{\text{theor}}(\gamma, xn)$ of the neutron yield reaction;

(ii) transition functions $F_i^{\text{theor}}(E)$, which characterize the contributions of reactions that produce *i* neutrons to cross section σ(γ, *xn*), are calculated for each photon energy *E*;

(iii) evaluated cross sections $\sigma^{\text{eval}}(\gamma, in)$ of partial reactions are determined for each neutron multiplicity *i* using the energy dependences of transition functions $F_i^{\text{theor}}(E)$ and experimental data on total cross section $\sigma^{\text{exp}}(\gamma, xn)$ of the photoneutron yield reaction:

$$\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}}\sigma^{\text{exp}}(\gamma, xn). \quad (5)$$

2.1. Photoneutron Yield Reaction (γ, xn)

The quality of the fit between the experimental data and the cross sections of the photoneutron yield reaction (γ, *xn*) calculated using the combined model of photonuclear reactions takes on particular importance in the proposed method for evaluation of cross sections of partial photoneutron reactions that satisfy the introduced objective physical data reliability criteria. At the preliminary stage of evaluation of cross sections of partial reactions, the best possible fit between the experimental and theoretical neutron yield cross sections is obtained.

The theoretical cross section $\sigma^{\text{theor}}(\gamma, xn)$ calculated using the model [3, 4] is compared in Fig. 2 to the cross sections determined in experiments with quasi-monoenergetic annihilation photons [5] and bremsstrahlung radiation [6]. It can be seen that the former experimental cross section agrees fairly well with the results of calculations, while the latter cross section differs considerably from $\sigma^{\text{theor}}(\gamma, xn)$. In view of this and the fact that the cross section of only one partial reaction (γ, 1*n*) was determined in [6], the cross section $\sigma^{\text{exp}}(\gamma, xn)$ obtained in [5] was used as the initial one for evaluation (5), since the authors of [5] measured the cross sections of three partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*).

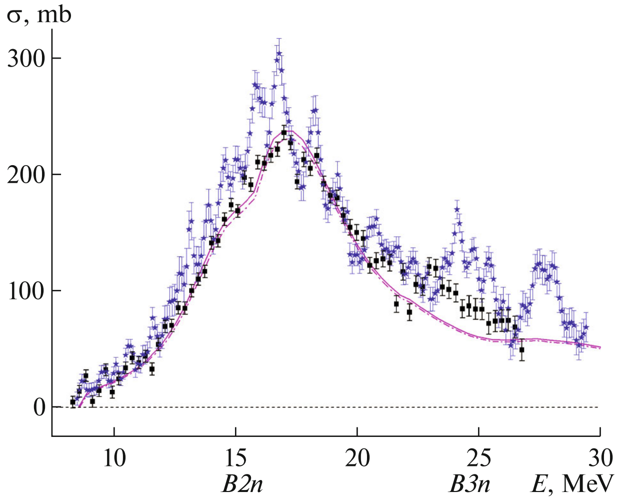

Fig. 2. Comparison of the initial (dashed curve) and corrected (solid curve) theoretical [3, 4] cross sections of photoneutron yield reaction (γ, *xn*) with the experimental data from [5] (squares) and [6] (asterisks).

Prior to inserting function F_i^{theor} into (5), the theoretical cross section was corrected somewhat (shifted by 0.03 MeV toward lower energies and multiplied by a factor of 1.03) in order to obtain the best possible agreement between the experimental [5] and theoretical cross sections in the region of the primary maximum. The corresponding numerical values of integrated reaction cross sections are listed in Table 1. The corrected theoretical cross sections and the experimental–theoretical approach were used to evaluate the cross sections of partial reactions.

2.2. Evaluated Cross Sections of Partial Reactions that Satisfy the Data Reliability Criteria

The cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) evaluated using the experimental–

Table 1. The centers of gravity $E^{\text{c.g.}}$ of the cross section and integrated cross sections σ^{int} of reaction ^{98}Mo(γ, *xn*)

	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb
Energy region	$E^{\text{int}} = 11.8–20.0$ MeV	
Experiment [5]	16.47	1363.20 ± 8.80
Theory (initial)	16.50	1324.31 ± 30.78
Theory (corrected)	16.47	1363.25 ± 31.76
Experiment [6]	16.28	1535.06 ± 11.27

Note: Integration was performed starting from an energy of 11.8 MeV, since the experimental cross-section data [5] have a considerable scatter in the starting interval.

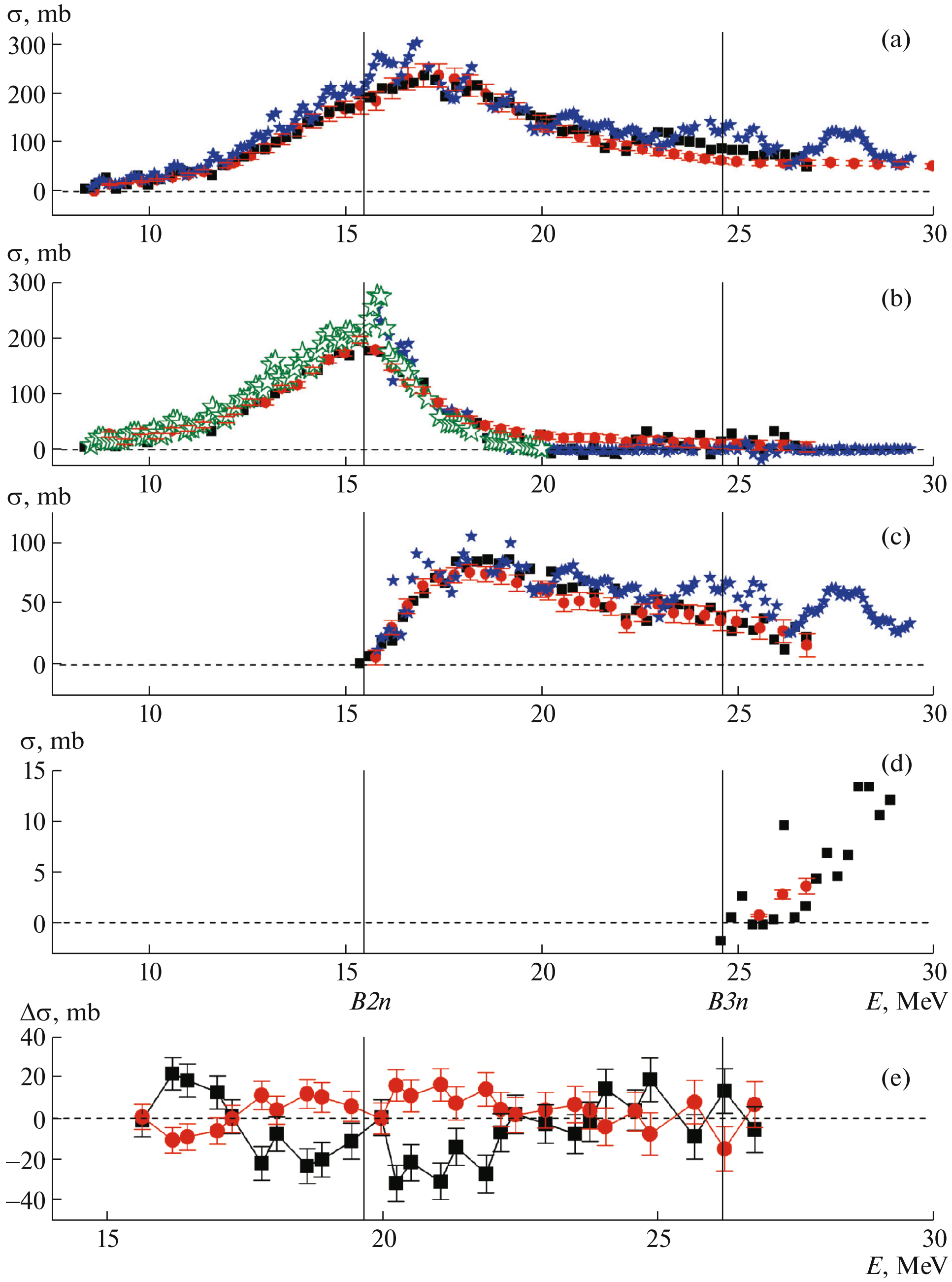

Fig. 3. Comparison of evaluated and experimental data on the cross sections of total and partial photoneutron reactions for ^{98}Mo: (a–d) evaluated (dots) and experimental (squares [5] and asterisks [6]) cross sections σ(γ, *xn*), σ(γ, 1*n*), σ(γ, 2*n*), and σ(γ, 3*n*), respectively; (e) differences between the evaluated and experimental [5] cross sections of reactions (γ, 1*n*) (squares) and (γ, 2*n*) (dots).

theoretical method (5) with cross section $\sigma^{\mathrm{exp}}(\gamma, xn)$ [5] that serve as the initial experimental reference are compared in Fig. 3 with the corresponding experimental data [5, 6]. It was already noted that the cross sections of (γ, *xn*), (γ, *sn*), and (γ, 1*n*) were obtained experimentally in [6]; therefore, we used (4) to determine the cross section of the reaction (γ, 2*n*). The integrated characteristics of experimental and evaluated cross sections of all partial and total reactions discussed in the present study are listed in Table 2.

The overall pattern of the discrepancies between the evaluated reaction cross sections that satisfy the introduced reliability criteria and the experimental cross sections, which do not satisfy these criteria, is as follows.

In the energy region below the *B*2*n* threshold of reaction (γ, 2*n*), which is unaffected by the issues of neutron multiplicity sorting, the discrepancy is rather small: the difference between integral cross sections is 4.0% (510.98 and 531.51 MeV mb). At higher energies the reactions (γ, 1*n*) and (γ, 2*n*) compete with each other and the data for both reactions differ significantly. In the case of (γ, 1*n*), $\sigma^{\text{int-eval}}$(γ, 1*n*) is 9.4% larger than $\sigma^{\text{int-exp}}$(γ, 1*n*) (886.44 and 970.03 MeV mb [5]), while cross section $\sigma^{\text{int-eval}}$ for (γ, 2*n*) is 16.2% smaller than $\sigma^{\text{int-exp}}$(γ, 2*n*) (519.60 and 447.06 MeV mb [5]). These large differences of unlike signs illustrate the causes of the considerable systematic uncertainties of the experimental results reported in [5]: a certain number of neutrons were erroneously transferred from channel 1*n* to channel 2*n*.

The differences between the evaluated and experimental [5] cross sections determined separately for reactions (γ, 1*n*) and (γ, 2*n*) are shown in Fig. 3e. The above-mentioned correlation of discrepancies between the evaluated and experimental data is clearly seen.

Interestingly, the experimental values reported in [6] are considerably higher than the evaluated ones in both energy regions. Specifically, the experimental [6] integrated cross section in the energy region below the *B*2*n* threshold of reaction (γ, 2*n*) is 14.9% larger than the evaluated integrated cross section (610.68 and 531.51 MeV mb). At higher energies, the data for reaction (γ, 1*n*) are fairly close (integrated cross sections $\sigma^{\text{int-eval}}$(γ, 1*n*) and $\sigma^{\text{int-exp}}$(γ, 1*n*) differ just by 1.2% (981.86 and 970.03 MeV mb)). At the same time, the data for reaction (γ, 2*n*) differ greatly: the discrepancy between $\sigma^{\text{int-eval}}$(γ, 2*n*) and $\sigma^{\text{int-exp}}$(γ, 2*n*) is as large as 32.4% (591.78 and 447.06 MeV mb).

It follows from the comparison of data in Figs. 1 and 3 that considerable differences between the evaluated and experimental cross sections of partial reactions are observed exactly in those regions of photon energies where the experimental data do not satisfy the reliability criteria. It was already noted that this is true for the energy region of ~17.0–22.0 MeV. In accordance with the differences between the energy dependences of ratios F_i^{exp} and F_i^{theor}, the experimental [5] cross sections of reaction (γ, 1*n*) are underestimated (so much that forbidden negative values occur) due to the subtraction of the contribution of a large number of neutrons with a multiplicity of 2 erroneously ascribed to them. Consequently, the experimental cross sections for reaction (γ, 2*n*) are overestimated, which results in the observation of implausible values of $F_2^{\text{exp}} > 0.50$. The experimental [5] cross sections of reaction (γ, 3*n*) at energies up to ~26 MeV are underestimated (physically forbidden negative values occur) due to the subtraction of the contribution of a large number of neutrons with a multiplicity of 2 or 1 erroneously ascribed to them. In the energy region of ~26–27 MeV, the experimental [5] cross section is, on the contrary, much larger than the evaluated one, since a significant number of neutrons were erroneously transferred from channel 2*n* to channel 3*n*.

Table 2. The integrated evaluated cross sections σ^{int} of total and partial photoneutron reactions for ^{98}Mo in comparison with the experimental data from [5, 6]

	$E^{\text{int}} = B2n = 15.47$ MeV		
Reaction	Evaluated data	Experiment [5]	Experiment [6]
(γ, *xn*)	509.83 ± 7.31	511.57 ± 6.38	610.68 ± 8.46
(γ, 1*n*)	531.51 ± 7.91	510.98 ± 6.35	610.68 ± 8.74
	$E^{\text{int}} = B3n = 24.62$ MeV		
Reaction	Evaluated data	Experiment [5]	Experiment [6]
(γ, *xn*)	1846.81 ± 34.31	1924.13 ± 12.54	2204.23 ± 13.16
(γ, 1*n*)	970.03 ± 15.26	886.44 ± 10.95	981.86 ± 12.06
(γ, 2*n*)	447.06 ± 13.06	519.60 ± 6.01	591.78 ± 17.33
	$E^{\text{int}} = 27.00$ MeV		
Reaction	Evaluated data	Experiment [5]	Experiment [6]
(γ, *xn*)	2002.38 ± 34.99	2111.70 ± 14.83	2461.76 ± 14.47
(γ, 1*n*)	1016.77 ± 18.90	946.35 ± 12.41	1012.36 ± 12.26
(γ, 2*n*)	538.80 ± 16.81	577.52 ± 7.43	706.48 ± 27.04

It was demonstrated in earlier studies [1, 2, 7–12], where a large number of medium and heavy nuclei were examined, that such discrepancies are induced by a major feature of photoneutron reactions: a complex and ambiguous relationship between the multiplicity of neutrons and their energy. This feature is neglected in the method of neutron multiplicity determination used in [5]. It was found in [13] that the energy spectrum of photoneutrons changes only slightly as GDR channels with an increasing number of emitted neutrons open up (the almost unshifted primary maximum remains in the energy region of ~0.5–1.0 MeV).

CONCLUSIONS

The reliability of data on photodisintegration of ^{98}Mo obtained in different experiments was examined using objective physical validity criteria. It was demonstrated that the cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) measured in [5] at a beam of quasimonoenergetic annihilation photons using the neutron multiplicity sorting method and in [6] at a bremsstrahlung radiation beam with statistical corrections introduced into the cross section of the neutron yield reaction do not satisfy these criteria. Unreliable sorting of neutrons between channels with different multiplicities result in the emergence of values that exceed the physical upper limits (0.50 and 0.33 for $i = 2$ and 3) or forbidden negative values in the energy dependences of functions F_i^{exp} (the ratios of the cross sections of partial reactions to the cross section of the neutron yield reaction). The discussed significant systematic errors are induced by the similarity of kinetic energies of neutrons from different partial reactions, which complicates the determination of neutron multiplicity.

New cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) and total photoneutron reaction (γ, *sn*) for ^{98}Mo were obtained using the experimental–theoretical method for evaluation of cross sections of partial photoneutron reactions. These cross sections satisfy the physical reliability criteria.

ACKNOWLEDGMENTS

This study was carried out at the Department of Electromagnetic Processes and Atomic Nuclei Interactions of the Skobeltsyn Institute of Nuclear Physics and was supported by the International Atomic Energy Agency (research contract no. 20501, coordinated research project F41032).

The authors wish to thank Professor B.S. Ishkhanov and senior researcher V.N. Orlin for theoretical calculations and help in analyzing and interpreting the obtained data.

REFERENCES

1. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, and S. Yu. Troshchiev, Bull. Russ. Acad. Sci.: Phys. **74**, 842 (2010). doi doi 10.3103/S1062873810060237
2. V. V. Varlamov, B. S. Ishkhanov, and V. N. Orlin, Phys. At. Nucl. **75**, 1339 (2012). doi 10.1134/S1063778812110191
3. B. S. Ishkhanov and V. N. Orlin, Phys. Part. Nucl. **38**, 232 (2007). doi 10.1134/S1063779607020049
4. B. S. Ishkhanov and V. N. Orlin, Phys. At. Nucl. **71**, 493 (2008). doi 10.1134/S1063778808030101
5. H. Beil, R. Bergere, P. Carlos, A. Lepretre, et al., Nucl. Phys. **227**, 427 (1974). doi 10.1016/0375-9474(74)90769-6
6. B. S. Ishkhanov, I. M. Kapitonov, E. V. Lazutin, V. S. Sopov, et al., Sov. J. Nucl. Phys. **11**, 394 (1970).
7. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, and N. N. Peskov, Phys. At. Nucl. **79**, 501 (2016). doi 10.1134/S1063778816040219
8. V. V. Varlamov, A. I. Davydov, M. A. Makarov, V. N. Orlin, and N. N. Peskov, Bull. Russ. Acad. Sci.: Phys. **80**, 317 (2016). doi 10.3103/S1062873816030333
9. V. V. Varlamov, M. A. Makarov, N. N. Peskov, and M. E. Stepanov, Phys. At. Nucl. **78**, 746 (2015). doi 10.1134/S1063778815060150
10. S. S. Belyshev, D. M. Filipescu, I. Gheoghe, et al., Eur. Phys. J. A **51** (6), 67 (2015). doi 10.1140/epja/i2015-15067-2
11. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, and K. A. Stopani, Eur. Phys. J. A **50**, 114 (2014). doi 10.1140/epja/i2014-14114-x
12. V. V. Varlamov, B. S. Ishkhanov, V. N. Orlin, N. N. Peskov, and M. E. Stepanov, Phys. At. Nucl. **76**, 1403 (2013). doi 10.1134/S1063778813110148
13. B. S. Ishkhanov, V. N. Orlin, and S. Yu. Troshchiev, Phys. At. Nucl. **75**, 253 (2012). doi 10.1134/S1063778812020093

Translated by D. Safin