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Physical Criteria for the Reliability of Data on the Photodisintegration of the ^{89}Y Nucleus

V. V. Varlamov*, A. I. Davydov, V. N. Orlin, and N. N. Peskov

Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia
**e-mail: Varlamov@depni.sinp.msu.ru*

Abstract—Experimental photonuclear reaction cross sections obtained in experiments using quasimonoenergetic annihilation, monoenergetic tagged photons, and bremsstrahlung γ-radiation are analyzed using physical criteria for the reliability of data on the ^{89}Y nucleus. It is found that the reliability of data on the cross sections of partial reactions (γ, 1*n*) and (γ, 2*n*), obtained by means of photoneutron multiplicity sorting, is highly doubtful. Reliable cross sections of reactions (γ, 1*n*) and (γ, 2*n*) are obtained using the experimental–theoretical method (ETM) for evaluating using both experimental cross sections of neutron yield reaction $\sigma^{\rm exp}(\gamma, xn)$ that are free of neutron multiplicity problems, and theoretically calculated $F_i^{\rm theor}$ ratios of the cross sections of definite (*i*) partial reactions to cross section $\sigma^{\rm theor}(\gamma, xn)$. It is shown that the evaluated cross sections differ noticeably from the experimental data.

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INTRODUCTION

The results from analyzing [1–7] experimental data on the cross sections of partial photoneutron reactions (γ, 1*n*), (γ, 2*n*) and (γ, 3*n*) of large numbers of medium and heavy nuclei, obtained by means of neutron multiplicity sorting in experiments with quasimonoenergetic annihilation photons [8–12], show that in many cases the results are not reliable. It has been shown that in many energy ranges, these cross sections do not satisfy objective physical reliability criteria for the cross sections of partial photoneutron reactions [1], since they contain significant systematic errors in experimental determination of the multiplicity of neutrons by their measured kinetic energies.

The unreliability of the experimental data obtained by the means described above is mainly confirmed by the F_i ratios introduced as reliability criteria

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

for the respective cross section of partial reaction $\sigma(\gamma, in)$ to the cross section of neutron yield reaction $\sigma(\gamma, xn)$,

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

exceeding limits 1.00, 0.50, 0.33, ... physically allowed by definition for $i = 1, 2, 3, \ldots$ in broad ranges of photon energies. Physically forbidden negative values in the cross sections of different reactions, primarily (γ, 1*n*), are usually observed in the same energy ranges.

It was shown in [1–7] that the shortcomings of photoneutron multiplicity sorting are the main reasons for the registered systematic errors. Owing to the similarity between the energies of neutrons produced in reactions of various multiplicities, the redistribution of a considerable number of them among the cross sections of reactions with different numbers of emitted neutrons is observed, for which there is no physically valid explanation. As a result, $\sigma(\gamma, 1n)$ is unreliably reduced, reaching forbidden negative values; $\sigma(\gamma, 2n)$ grows just as unreliably to values at which $F_2^{\rm exp} > 0.50$.

The experimental–theoretical method (ETM) [1] was proposed to avoid the effects of the above systematic errors in the experimental determination of neutron multiplicity, and to estimate reliable cross sections of partial reactions. On the one hand, it uses experimental cross sections of neutron yield reaction (2) that are free of the problems of neutron multiplicity determination; on the other, it uses the relations of the combined model (CM) of photonuclear reactions [13–15], which successfully describes cross sections of the neutron yield reaction in the range of medium and heavy nuclei.

The cross sections of partial reactions are eevaluated as

$$\sigma^{\rm eval}(\gamma, in) = F_i^{\rm theor}\sigma^{\rm exp}(g, xn). \quad (3)$$

In the ETM, relations between the cross sections of partial reactions are determined from the $F_i^{\rm theor}$ ratios calculated in the CM, while their respective sum $\sigma^{\rm eval}(\gamma, xn)$ is $\sigma^{\rm exp}(\gamma, xn)$. The examples of ^{181}Ta and ^{209}Bi nuclei in [16, 17] show that the cross sections of partial reactions evaluated in this way agree with the

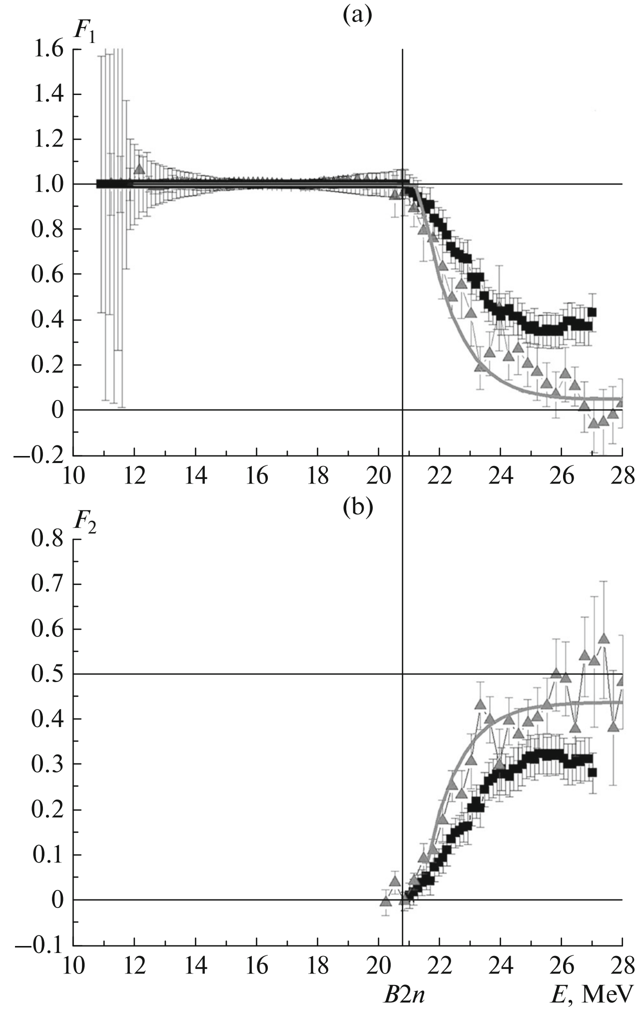

Fig. 1. Comparison ((a), (b) for i = 1, 2) of the energy dependences of F_i^{exp} ratios obtained using experimental data (triangles denote [19]; squares, [20]) and the values of F_1^{theor} calculated in the CM [13–15] (lines) for the ^{89}Y nucleus.

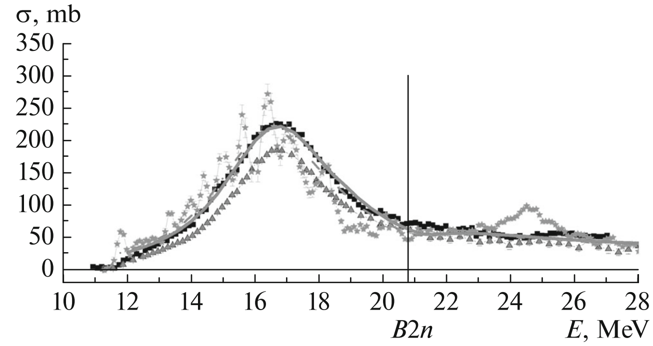

Fig. 2. Comparison of experimental (triangles denote [18]; squares, [19]; stars, [20]) and theoretical [13–15] (dashed line, below $B2n$; solid line, over $B2n$) data for the cross sections of reaction ^{89}Y(γ, xn).

results obtained via the alternative experimental method of induced activity, in which a definite partial reaction is identified using not outgoing neutrons but the produced final nuclei.

In this work, the above approach was used to evaluate the cross sections of partial reactions (γ, 1n) and (γ, 2n), and the total photoneutron reaction (which differs from yield reaction (2))

$$(\gamma, sn) = (\gamma, 1n) + (\gamma, 2n) \tag{4}$$

for the ^{89}Y Nucleus. This nucleus is of special interest from the viewpoint of experimental and evaluated partial reaction cross section reliability, since its data have been obtained using both bremsstrahlung γ-radiation [18] and quasimonoenergetic annihilation photon beams [19, 20], and with beams of monoenergetic tagged photons [21].

DATA RELIABILITY CRITERIA FOR THE CROSS SECTIONS OF PARTIAL PHOTONEUTRON REACTIONS

In [19, 20], the cross sections of partial reactions ^{89}Y(γ, 1n)^{88}Y and ^{89}Y(γ, 2n)^{87}Y were obtained via photoneutron multiplicity sorting, with beams of quasimonoenergetic annihilation photons.

Figure 1 compares the energy dependences of F_i^{exp} ratios (1) obtained from the data presented in [19, 20] to F_i^{theor} ratios calculated in the CM [13–15]. It is clear that the energy dependences of the F_i^{exp} ratios based on the data of both experiments [19, 20] differ considerably. Here, F_i^{exp} [19] seems to be close to F_i^{theor} at energies below ~26 MeV. At energies of ~26–28 MeV, however, F_2^{exp} [19] exceeds the physically reliable limit 0.50, and F_1^{exp} becomes negative. As a result, there are serious doubts concerning the reliability of the experimental data [19]. The energy relations of F_i^{exp} [20] ratios do not contain physically doubtful values, but their reliability is still in doubt, since they are somewhat inconsistent with F_i^{theor}.

The evaluation of the reliability of the cross sections of partial reaction ^{89}Y(γ, 1n)^{88}Y and ^{89}Y(γ, 2n)^{87}Y in the ETM is of great interest.

EVALUATING RELIABLE CROSS SECTIONS OF PARTIAL PHOTONEUTRON REACTIONS

Data on Photoneutron Yield Reaction ^{89}Y(γ, xn)

When using the ETM to evaluate the cross sections of partial photoneutron reactions that meet our objective physical criteria of data reliability, their consistency with the experimental data for cross sections of the photoneutron yield reaction (γ, xn) calculated in the CM is especially important [1–7].

Figure 2 compares experimental [18–20] and theoretical [13–15] (before and after correction) cross sec-

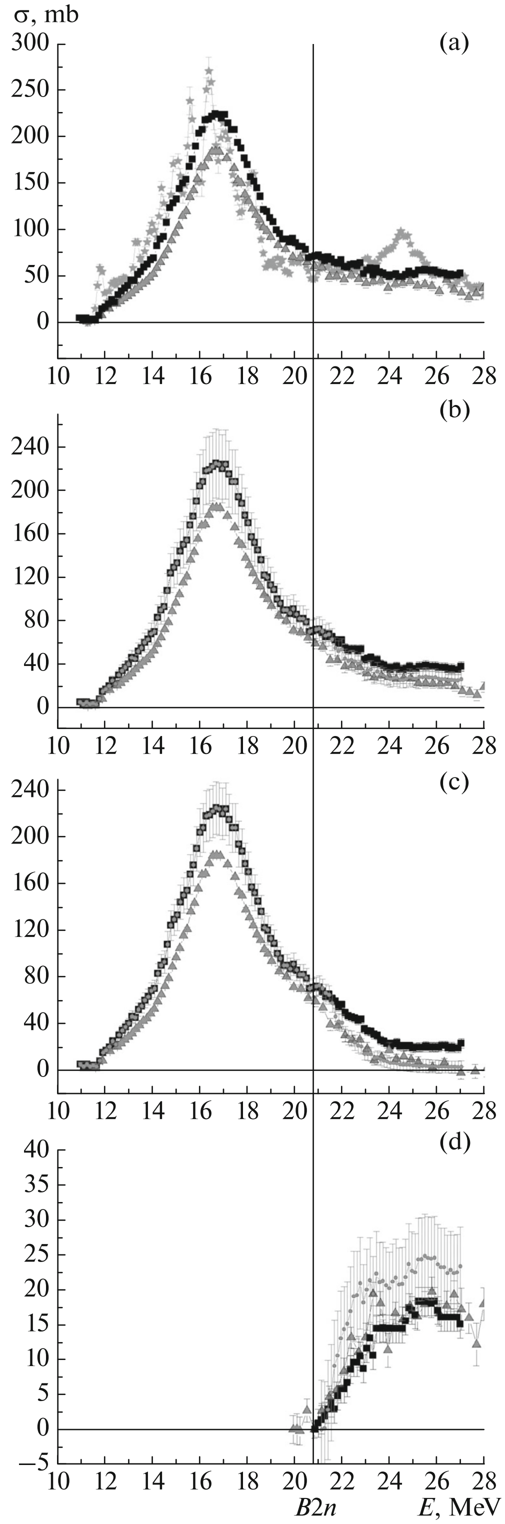

Fig. 3. Comparison of the evaluated (dots) and experimental (triangles denote [19], squares, [20]) cross sections of total and partial photoneutron reactions on the ^{89}Y nucleus: (a) σ(γ, *xn*); (b) σ(γ, *sn*); (c) σ(γ, 1*n*); (d) σ(γ, 2*n*). Fig. 2a also shows the cross section of reaction (γ, *xn*) obtained using bremsstrahlung γ-radiation [18] (stars).

tions of reaction (γ, *xn*) for the ^{89}Y nucleus. The respective energy centers of gravity and integral cross sections are presented in Table 1. The results from theoretical calculations seemed to be closest to the results from the experiment [20], so they were chosen as the initial data for evaluating the cross sections of partial reactions within ETM (2) described.

Since the agreement between the experimental [20] and theoretical [13–15] cross sections of reaction ^{89}Y(γ, *xn*) was not ideal, the latter was preliminarily corrected: it was shifted 0.2 MeV toward higher energies and multiplied by coefficient 1.1. The data presented in Fig. 2 and Table 1 show that the agreement between the experimental and evaluated cross sections used in procedure (2) greatly improved after the correction.

Evaluated Cross Sections of Partial Reactions (γ, 1n) and (γ, 2n), and of Total Photoneutron Reaction (γ, sn) Compared to the Experimental Data

The evaluated cross sections of partial reactions (γ, 1*n*) and (γ, 2*n*), and of total photoneutron reaction (4) for the ^{89}Y nucleus, are presented in Fig. 3, along with the cross sections of photoneutron yield reaction (γ, *xn*) [20]. The integral properties of the experimental and evaluated cross sections of the considered partial and total reactions are given in Table 2.

It should be noted that discrepancies between the results from experiments in [19, 20] are of an apparently systematic character and definitely depend on the errors of neutron multiplicity sorting. The ratios of the integral cross sections of reaction (γ, *xn*) obtained at Saclay and Livermore for both energy ranges are therefore different (1.25 = 1067.28/854.19 and 1.32 = (1129.34–854.19)/(1429.36–1067.28)). At the same time, these differences are much greater for reactions (γ, 1*n*) and (γ, 2*n*), and are along different lines. In the energy range above threshold *B*2*n* of reaction (γ, 2*n*), the ratio of respective integral cross sections for reaction (γ, 1*n*) is 1.96 ((1280.88–1067.27)/(963.30–854.13)); for reaction (γ, 2*n*), it is 0.87 (74.24/85.37). In addition, the absolute values of the cross sections of reaction (γ, 2*n*) obtained at Saclay and Livermore (at, e.g., the energy of 26 MeV at which both of them peak) are similar (~17 mb), and the absolute values of cross sections of reaction (γ, 1*n*) differ considerably: ~20 mb at Saclay and ~3–6 mb at Livermore.

In agreement with the above on the causes of the registered systematic errors of neutron multiplicity sorting, the comparison of experimental and evaluated cross sections of reactions (γ, 1*n*) and (γ, 2*n*) presented in Fig. (3) suggests certain conclusions on the reliability of the considered data:

• In both experiments [19, 20], it seems a surprisingly large number of neutrons were lost in reaction (γ, 2*n*), since both experimental cross sections are

Table 1. Energy centers of gravity $E^{c.g.}$ and integral cross sections σ^{int} of te cross sections of reaction ^{89}Y(γ, *xn*), calculated for different energy ranges

	$E = B2n = 20.83$ MeV		$E = 27.02$ MeV	
	$E^{c.g.}$, MeV	σ^{int}, MeV mb	$E^{c.g.}$, MeV	σ^{int}, MeV mb
Experiment [18]	16.35 (0.14)	1029.70 (5.60)	18.46 (0.11)	1429.60 (5.69)
Experiment [19]	16.93 (0.05)	854.19 (1.95)	18.59 (0.13)	1129.34 (4.89)
Experiment [20]	16.81 (0.04)	1067.28 (2.15)	18.56 (0.05)	1429.36 (3.45)
Theory–initial	16.76 (1.36)	1099.54 (17.92)	18.34 (1.08)	1395.90 (18.12)
Theory–corrected	16.80 (1.40)	1080.39 (17.80)	18.56 (1.07)	1429.41 (18.13)

Table 2. Integral cross sections σ^{int} (in MeV mb) of evaluated cross sections of total and partial photoneutron reactions on the ^{89}Y Nucleus, compared to the experimental data in [18–20]

(γ, *xn*)		
	$E = B2n = 20.83$ MeV	$E = 27.02$ MeV
Experiment [18]	1029.70 (5.60)	1429.60 (5.69)
Experiment [19]	854.19 (1.95)	1129.34 (4.89)
Experiment [20]*	1067.28 (2.15)	1429.36 (3.45)
Evaluation	1067.28 (10.78)	1413.41 (19.65)
(γ, *sn*)		
Experiment [19]	854.91 (2.05)	1048.66 (5.62)
Experiment [20]	1067.28 (2.15)	1355.12 (3.44)
Evaluation	1067.28 (15.10)	1301.3 (16.10)
(γ, 1*n*)		
Experiment [19]	854.13 (1.87)	963.30 (4.92)
Experiment [20]	1067.28 (2.15)	1280.88 (3.20)
Evaluation	1067.28 (10.78)	1189.04 (11.48)
(γ, 2*n*)		
Experiment [19]		85.37 (1.92)
Experiment [20]		74.24 (1.28)
Evaluation		112.19 (11.27)

* Experimental cross section [20] was the initial value for evaluation.

considerably smaller in the energy range $E > B2n$ than the evaluated cross section (Fig. 3d).

• In experiment [20], neutrons lost from reaction (γ, 2*n*) were identified as participating in reaction (γ, 1*n*), since the experimental [20] cross section of reaction (γ, 1*n*) was larger in the energy range $E > B2n$ than the evaluated cross section (Fig. 3c).

• In contrast to experiment [20], neutrons lost from reaction (γ, 2*n*) in experiment [19] were not identified as neutrons from reaction (γ, 1*n*), and were thus truly lost, since the experimental [19] and evaluated cross sections of reaction (γ, 1*n*) in the energy range $E < B2n$ were quite similar, and no there was no unfounded additional yields of neutrons.

• In the energy range $E < B2n$, ratio $F_1^{exp} = 1$ [19], indicating that all neutrons did indeed belong to reaction (γ, 1*n*). The cross section of reaction (γ, 1*n*) in [19] was considerably (~30%) smaller than the experimental and evaluated cross sections of the same reaction in

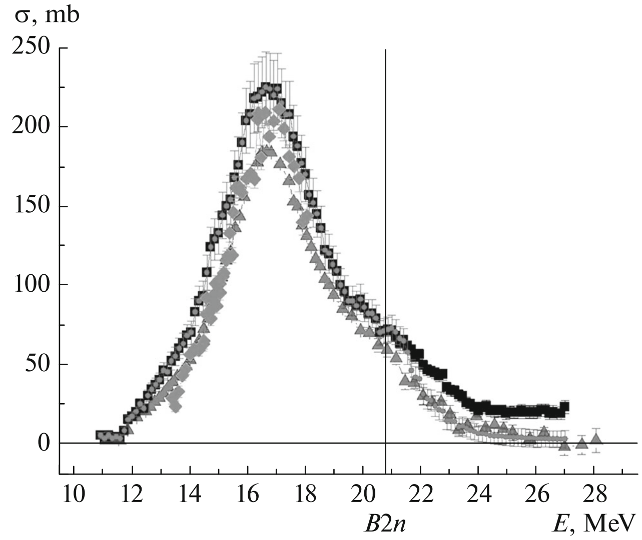

Fig. 4. Comparison of the evaluated (dots) and experimental (triangles denote [19]; squares, [20]; diamonds, [21]) cross sections of reaction $^{89}Y(\gamma, 1n)^{88}Y$.

[20], indicating too that a certain number of neutrons from this reaction were lost in the experiment [19].

Comparison of the Experimental and Evaluated Cross Sections of Reaction $^{89}Y(\gamma, 1n)^{88}Y$

Figure 4 compares the evaluated cross section of reaction $^{89}Y(\gamma, 1n)^{88}Y$ and the experimental data obtained using beams of quasimonoenergetic annihilation [19, 20] and tagged [21] photons. The respective integral cross sections calculated for peak energy of tagged photons $E = 18.1$ MeV are presented in Table 3.

The presented data show that in the energy range below $E < B2n$, the evaluated cross section of reaction $^{89}Y(\gamma, 1n)^{88}Y$ is much closer to experimental cross section [20] than to cross section [19], even though the F_1^{theor} ratios are closer to F_1^{exp} [19] than to the F_1^{exp} ratios [20]. This is due to the discrepancy (Fig. 1) between the cross sections of neutron yield reactions (2) obtained in [19, 20].

Table 3. Integral cross sections σ^{int} (in MeV mb) and energy centers of gravity $E^{\text{c.g.}}$ (MeV) of the evaluated and experimental [19–21] cross sections of the reaction on $^{89}Y(\gamma, 1n)^{88}Y$

	$E^{\text{c.g.}}$, MeV	σ^{int}, MeV mb
Experiment [19]	16.22 (0.03)	574.25 (0.99)
Experiment [20]	16.16 (0.03)	725.02 (1.46)
Experiment [21]	16.29 (0.12)	641.55 (3.44)
Evaluation	16.16 (0.46)	725.02 (9.50)

Note that the evaluated cross section of reaction $^{89}Y(\gamma, 1n)^{88}Y$ differs from the experimental cross section in [21], obtained using tagged photons. This leaves open the question of the reliability of the data obtained in experiment [21].

CONCLUSIONS

Our studies suggest that the experimental cross sections of partial photoneutron reactions for the ^{89}Y Nucleus [19, 20] (and for many others [1–7] obtained by means of neutron multiplicity sorting using beams of quasimonoenergetic annihilation photons) fail to satisfy our objective physical criteria for data reliability. They contain considerable systematic errors caused by unreliable (unfounded) redistribution of neutrons between channels 1*n* and 2*n*.

In the ETM, cross sections of the partial reactions (γ, 1*n*) and (γ, 2*n*), and the total reaction (γ, *sn*), that are free of the above systematic errors and satisfy the objective physical criteria of data reliability can be obtained for the ^{89}Y nucleus. It was shown that in both experiments [19, 20], a large number of neutrons surprisingly lost from reaction (γ, 2*n*). In addition, these neutrons were identified as belonging to reaction (γ, 1*n*) in the experiment in [20], and a large number of neutrons from reactions (γ, 1*n*) and (γ, 2*n*) were lost in the experiment in [19], leading to considerable (~30%) underestimation of the cross section of reaction (γ, 1*n*).

Our results show that in the energy range below $E < B2n$, there are certain differences between the cross section of reaction $^{89}Y(\gamma, 1n)^{88}Y$ evaluated and used as the initial data in [20] and the cross section of reaction $^{89}Y(\gamma, 1n)^{88}Y$ in [21], leaving open the question of data reliability in the experiment in [21].

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