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Evaluation of Reliable Cross Sections of Partial and Total Photoneutron Reactions for the ^{139}La Nucleus

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Abstract—Cross sections of partial photoneutron reactions free of the shortcomings of different ways of determining the multiplicity of neutrons used on beams of quasi-monoenergetic annihilation photons are evaluated for ^{139}La. The experimental-theoretical method of evaluation of partial reaction cross sections satisfying proposed data reliability criteria is used to obtain new data on the cross sections of reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*). It is shown that noticeable deviations of experimental cross sections from evaluated values are due to the unreliable sorting of neutrons between channels with multiplicities of 1, 2, and 3.

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INTRODUCTION

Studies of data on the cross sections of the partial photoneutron reactions [1, 2, 13, 14] have shown that most of the data obtained using beams of quasi-monoenergetic annihilation photons by different experimental means for photoneutron multiplicity sorting contain noticeable systematic errors caused by the ambiguity of determining the multiplicity of the detected neutrons from their kinetic energy.

In different ranges of incident photon energies, deliberately introduced criteria for the presence of systematic errors, represented by transitional multiplicity functions

$$F_i = \sigma(\gamma,in)/\sigma(y,xn) = \sigma(\gamma,in)/[\sigma(\gamma,1n) + 2\sigma(\gamma,2n) + 3\sigma(\gamma,3n) + \ldots], \quad (1)$$

have values greater than those the physically permissible 1.00, 0.50, 0.33, ... for i = 1, 2, 3, ..., respectively. The $F_i^{\exp}$ ratios over the indicated limiting values testifies to the physically unreliable neutron distribution between reactions (γ, 1*n*) and (γ, 2*n*), (γ, 2*n*) and (γ, 3*n*), and so on, due to the presence of large systematic uncertainties in the determined neutron multiplicities.

To gather data on cross sections of the partial photoneutron reaction that are free of these systematic uncertainties, an experimental-theoretical method for evaluation of partial reaction cross sections was proposed in [2, 14].

The method is based on using data on the cross section of the neutron yield reaction as the initial experimental information:

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

which is rather independent of the problems of experimental neutron multiplicity sorting, since it includes all emitted neutrons. The cross section of the neutron yield reaction is decomposed into partial reaction sections (γ, 1*n*), (γ, 2*n*) and (γ, 3*n*) using data of the photonuclear reaction combined model (CM) [3, 4]. Partial reaction cross sections σ^{eval}(γ, *in*) are evaluated using calculated transitional functions F_i^{theor} versus energy and the experimental $\sigma^{\exp}$(γ, *xn*) photoneutron yield reaction cross sections:

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

Evaluated data on the cross sections for partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*), and for total photoneutron reaction

$$\sigma(\gamma,sn) = \sigma(\gamma,1n) + \sigma(\gamma,2n) + \sigma(\gamma,3n)\ldots, \quad (4)$$

which is a good approximation of the photoabsorption reaction cross-section for medium and heavy nuclei, were obtained earlier using the method described above for a large number of medium and heavy nuclei: ^{92,94}Zr, ^{115}In, $^{116-124}$Sn, ^{159}Tb, $^{186-192}$Os, ^{197}Au, ^{181}Ta, ^{208}Pb, and ^{209}Bi [1, 2, 13–15]. Based on a comparison of the evaluated data, and of the results from alternative experiments using the activation approach for ^{181}Ta, ^{197}Au, and ^{209}Bi, it was shown that both the presence of F_i^{theor} ratios that exceed the limit values described above and the marked discrepancy between $F_i^{\exp}$ and F_i^{theor} testify to the unreliability of the experimental data. In addition, since the F_i ratios contain only the values of reaction cross sections, reliable F_i^{theor} functions should be positive values.

The aim of this work was to analyze the reliability of experimental data and evaluate reliable cross sections of partial and total photoneutron reactions for ^{139}La.

TRANSITIONAL PHOTONEUTRON MULTIPLICITY FUNCTIONS F_i FOR ^{139}La

The photodisintegration of ^{139}La was studied in two experiments on the quasi-monoenergetic annihilation photon beams at Saclay (France) [5, 6]. Figure 1 shows the energy dependences of transitional neutron multiplicity functions as ratios of $F_i^{\rm exp}$ (1), obtained using the data in [5, 6] for ^{139}La, to the data for $F_i^{\rm theor}$ in [3, 4]. We can conclude that except for several values near ~20 MeV which almost coincide, $F_i^{\rm exp}$ and $F_i^{\rm theor}$ differ markedly over the considered range of energies,.

It is worth noting that the $F_{1,2,3}^{\rm theor}$ functions calculated in [3, 4] using the CM at different energies are physically reliable and correspond fully to definition (1):

—Up to threshold $B2n$ = 16.27 MeV of reaction (γ, $2n$), $F_1^{\rm theor} = 1$. After channel $2n$ opens, $F_1^{\rm theor}$ diminishes in correspondence with the competition from the growing $\sigma(\gamma, 2n)$ and shrinking $\sigma(\gamma, 1n)$ cross sections, gradually tending to zero.

—In the same range of energies, $F_2^{\rm theor} = 0$. After channel $2n$ opens, $F_2^{\rm theor}$ grows in correspondence with the competition from the growing $\sigma(\gamma, 2n)$ and shrinking $\sigma(\gamma, 1n)$ cross sections, approaching a value of 0.50 from below but never reaching it, and then diminishes when channel $3n$ opens in correspondence to the emerging contribution from $3\sigma(\gamma, 3n)$ in the denominator of relation (1).

—Up to threshold $B3n$ = 25.41 MeV of reaction (γ, $3n$) , $F_3^{\rm theor} = 0$. At higher energies, it increases in correspondence to the competition from the growing $\sigma(\gamma, 3n)$ and shrinking $\sigma(\gamma, 2n)$ cross sections.

At the same time, the experimental $F_{1,2}^{\rm exp}$ ratios differ markedly from the corresponding theoretical $F_{1,2}^{\rm theor}$ ratios:

—The $F_i^{\rm exp}$ ratios obtained for the data of both experiments in [5, 6] are close to the $F_i^{\rm theor}$ ratios calculated using the model in [3, 4] only at energies of ~20 MeV.

—Noticeable divergence between $F_i^{\rm exp}$ and $F_i^{\rm theor}$ is observed at both low and high energies.

In addition, ratio $F_i^{\rm exp}$ noticeably exceeds $F_2^{\rm theor}$ at energies of up to ~20 MeV, and the difference between them is much greater at high energies. The behavior of $F_2^{\rm exp}$ relative to $F_2^{\rm theor}$ mirrors that of $F_1^{\rm exp}$ with respect to $F_1^{\rm theor}$, since $F_2^{\rm theor}$ exceeds $F_2^{\rm exp}$ at energies lower than ~20 MeV, and the divergence between them is much greater at high energies. It should be emphasized that at energies above ~21.5 MeV (~4 MeV below B3n), $F_2^{\rm exp}$ begins to diminish noticeably, though definition (1) offers no reason for this.

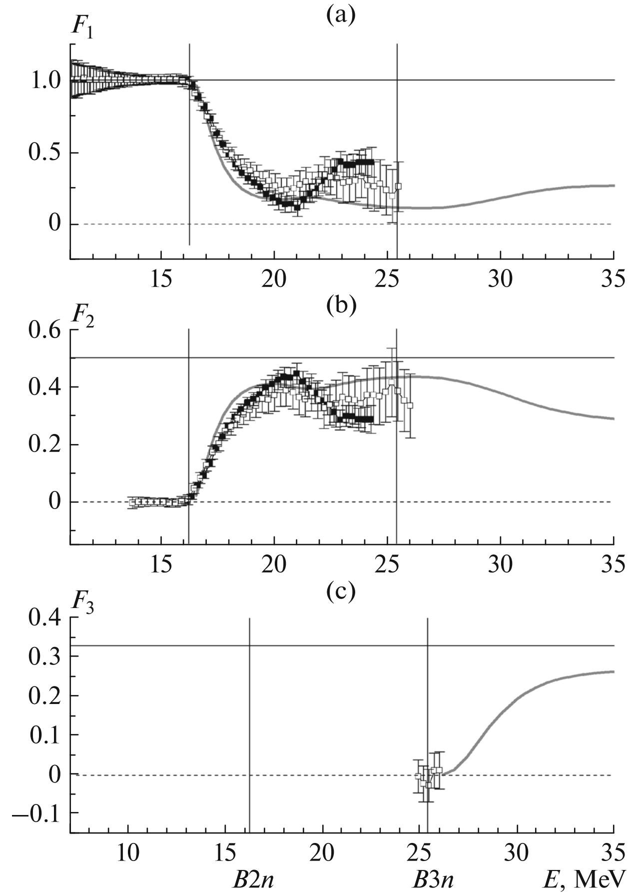

Fig. 1. Comparison of transitional functions $F_i^{\rm exp}$ of multiplicity in (1), found experimentally (■ [5]; □ [6]) and $F_i^{\rm theor}$ (lines) calculated using the CM in [3, 4]: (a) F_1, (b) F_2, (c) F_3.

The increase in $F_1^{\rm exp}$ corresponding to the diminution of $F_2^{\rm exp}$ testifies to the uncertain transmission of some neutrons from reaction (γ, $2n$) to reaction (γ, $1n$).

Such correlations demonstrate that the experimental separation of neutrons between the above partial reactions was not entirely reliable.

Table 1. Centers of gravity E^{cg} and integrated cross sections σ^{int} of reaction ^{139}La (γ, *xn*)

	E^{cg}, MeV	σ^{int}, MeV mb
Enegry range	E^{int} = 10.0–16.00 MeV	
Experiment in [5]	14.08	1202.33 ± 3.96
Theory (initial)	13.97	1170.22 ± 5.15
Theory (adjusted)	14.08	1201.82 ± 5.86
Experiment in [6]	14.08	1077.52 ± 4.78

EXPERIMENTAL-THEORETICAL METHOD FOR EVALUATION OF PARTIAL PHOTONEUTRON REACTION CROSS SECTIONS

The experimental-theoretical method was proposed in [1, 2] for obtaining data on partial photoneutron reaction cross sections, independent of the shortcomings of experimental procedures for neutron multiplicity sorting. Reliable data on competing reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) are obtained in the manner described below:

—Reaction cross sections $\sigma^{theor}(\gamma, 1n)$, $\sigma^{theor}(\gamma, 2n)$, and $\sigma^{theor}(\gamma, 3n)$ calculated in the CM [3, 4] are combined according to (2) into cross section $\sigma^{theor}(\gamma, xn)$ of the reaction yield.

—Transitional functions $F_i^{theor}(E)$ describing the contributions to the cross sections of the reactions $\sigma(\gamma, xn)$ with the formation of *i* neutrons are calculated for each value of photon energy *E*.

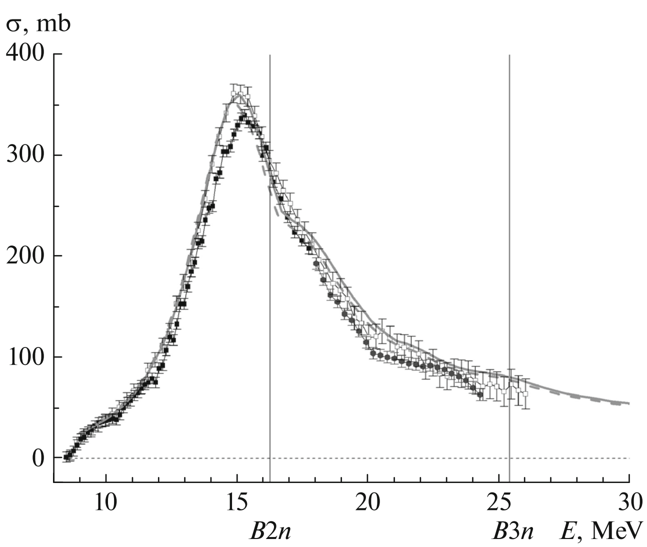

Fig. 2. Initial (dashed line) and adjusted (solid line) theoretical cross sections [3, 4] of photoneutron yield reaction (γ, *xn*), compared to experimental data (■ [5]; □ [6], up to energies of 18 MeV; ● [6] over the energy range of ~18–24 MeV (obtained here using the corresponding summation in (2)).

—Evaluated cross sections $\sigma^{eval}(\gamma, in)$ of partial reactions (3) are obtained using transitional functions $F_i^{theor}(E)$ and experimental data on cross section σ^{exp} (γ, *xn*) of the photoneutron yield reaction for each value of the multiplicity of *i* neutrons.

Photoneutron Yield Reaction (γ, xn)

When using the proposed method for evaluation of partial photoneutron reaction cross sections that satisfy the introduced objective physical data reliability criteria, the maximum closeness between and experimental data and the cross sections of photoneutron yield reaction (γ, *xn*) calculated in the CM is of great importance. Experimental and theoretical cross sections are put into consistency with each other as much as possible at the preliminary stage of estimating partial reaction cross sections.

Figure 2 compares data on cross section $\sigma^{theor}(\gamma, xn)$ [3, 4] obtained in experiments with quasi-monoenergetic annihilation photons [5, 6] and calculated in the CM. We can see that both experimental cross sections coincide fairly well with the results from calculations. Since the cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) were determined in the experiment in [5], and only those of reactions (γ, 1*n*) and (γ, 2*n*) were determined in the experiment in [6], cross section $\sigma^{exp}(\gamma, xn)$ determined in the experiment in [5] was used as the initial one for evaluating procedure (3).

Note that total photoneutron reaction cross section (4) and yield reaction cross section (2) in the experiment in [6] were obtained for energies of up to 18 MeV. In the range of ~18–24 MeVe, we obtained data for cross sections (2) and (3) using correspondent summing of the cross sections of partial reactions (γ, 1*n*) and (γ, 2*n*).

Before using function F_i^{theor} in evaluation procedure (3), the main maximum of the cross section was adjusted slightly by shifting it 0.106 MeV toward higher energies and multiplying it by 1.003 in order to achieve the best consistency between experiment [5] and theory in its range. The corresponding numerical values for the integrated cross sections of the reaction are listed in Table. 1. The adjusted theoretical sections were used to evaluate the partial reaction cross sections in our experimental-theoretical method.

Evaluated Cross Sections of Partial Reactions Satisfying the Criteria of Data Reliability

Cross sections of partial reactions (γ, 1*n*), (γ, 2*n*) and (γ, 3*n*), evaluated using experimental- theoretical method (3) using cross sections $\sigma^{exp}(\gamma, xn)$ [5] as the initial experimental data, are compared in Fig. 3 to the corresponding experimental data in [5, 6]. Table 2 shows the integrated characteristics of the experimen-

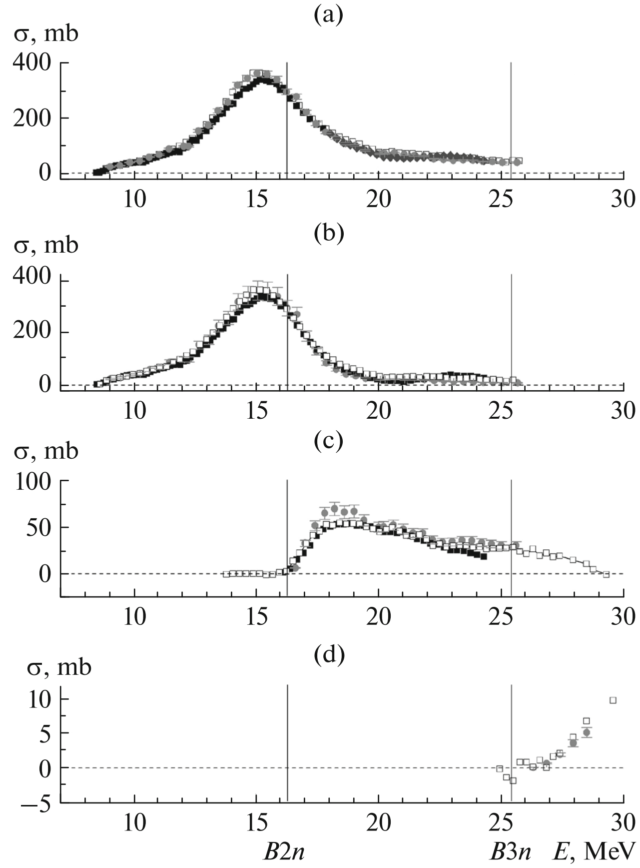

Fig. 3. Calculated (●) and experimental (■ [5]; □ [6], up to energies of 18 MeV; ◆ [6], at energies of ~18–24 MeV) cross sections of total and partial photoneutron reactions on ^{139}La: (a) σ(γ, *sn*), (b) σ(γ, 1*n*), (c) σ(γ, 2*n*), (d) σ(γ, 3*n*).

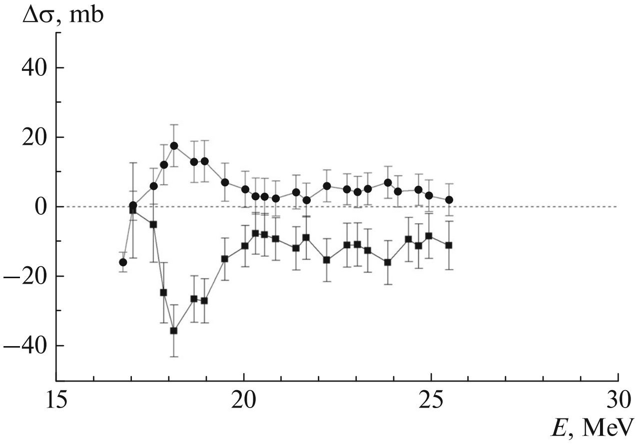

Fig. 4. Difference between calculated and experimental [5] cross sections of reactions (■) $\Delta\sigma_1$(γ, 1*n*) and (●) $\Delta\sigma_2$(γ, 2*n*).

tal and evaluated sections for all considered partial and total reactions.

On the whole, the divergence between the evaluated cross sections of reactions that satisfy the introduced reliability criteria and experimental cross sections that do not satisfy these criteria is described below.

At energies below threshold *B*2*n* of reaction (γ, 2*n*), where there is no problem in neutron multiplicity sorting, the difference between experimental [5] and theoretical integral cross sections is only 1.6% (1343.46 and 1322.35 MeV, respectively). At the high energies where reactions (γ, 1*n*) and (γ, 2*n*) compete with each other, the data on both differ markedly: $\sigma^{\text{int-eval}}(\gamma, 1n) < \sigma^{\text{int-exp}}(\gamma, 1n)$ by 6.0% (1763.54 and 1871.03 MeV mb, respectively) [5], while $\sigma^{\text{int-eval}}(\gamma, 2n) > \sigma^{\text{int-exp}}(\gamma, 2n)$ by 12.4% (389.17 and 340.73 MeV mb, respectively) [5]. Such great and opposite-direction divergences between the cross sections of reactions (γ, 1*n*) and (γ, 2*n*) demonstrate convincingly the reasons for the subtantial systematic uncertainties in experiments [5], which are due to the unreliable transmission of a large number of neutrons from channel 2*n* to channel 1*n*.

The differences between the evaluated and experimental [5] sections were determined separately for reactions (γ, 1*n*) and (γ, 2*n*),

$$\Delta\sigma_1(\gamma,1n) = \sigma^{\text{exp}}(\gamma,1n) - \sigma^{\text{eval}}(\gamma,1n), \quad (5)$$

$$\Delta\sigma_2(\gamma,2n) = \sigma^{\text{eval}}(\gamma,2n) - \sigma^{\text{exp}}(\gamma,2n), \quad (6)$$

and are shown in Fig. 4. The abovementioned correlation of the divergence between evaluated and theoretical cross-sections apparent from the transmission of a large number of neutrons from channel 2*n* to channel 1*n* is pronounced.

The relationship between the evaluated and experimental [6] partial reaction cross sections is similar. At energies below threshold *B*2*n* of reaction (γ, 2*n*), the experimental [6] integrated cross section is 12.5% smaller than the theoretical one (1343.46 and 1175.09 mb respectively). At higher energies, integrated cross sections $\sigma^{\text{int-eval}}(\gamma, 1n)$ and $\sigma^{\text{int-exp}}(\gamma, 1n)$ for reaction (γ, 1*n*) differ by only 4.1% (1763.54 and 1691.60 MeV mb, respectively). At the same time, the discrepancy between $\sigma^{\text{int-eval}}(\gamma, 2n)$ and $\sigma^{\text{int-exp}}(\gamma, 2n)$ data for (γ, 2*n*) reaction is fairly large, reaching 24.5% (389.17 and 293.65 MeV mb).

A comparison of the data in Figs. 1 and 3 testifies to large systematic uncertainties in neutron multiplicity sorting. The abovementioned systematic errors in the energy range of ~21–24 MeV correlate with one another. There is an abrupt drop in function F_2^{exp} and a marked rise in function F_1^{exp}. In correspondence with the differences between F_i^{exp} and F_i^{theor} as functions of energy, the experimental data in [5, 6] for the cross sections of reaction (γ, 1*n*) are unreliably overestimated, due to the contribution from many neutrons which multiplicity 1 was attributed unreliably. The

Table 2. Integrated sections σ^{int} of evaluated cross sections of total and partial photoneutron reactions for the ^{139}La nucleus, compared to experimental data [5, 6]

	$E^{int} = B2n = 16.27$ MeV		
Reaction	evaluation	experiment [5]	experiment [6]
(γ, *xn*)	1343.46 ± 12.68	1321.84 ± 4.30	1175.49 ± 5.46
(γ, *sn*)	1343.46 ± 12.68	1322.09 ± 9.61	1175.29 ± 5.46
(γ, 1*n*)	1343.46 ± 38.05	1322.35 ± 9.61	1175.09 ± 5.46
	$E^{int} = B3n = 25.41$ MeV		
Reaction	Evaluation	Experiment [5]	Experiment [6]
(γ, *xn*)	2541.89 ± 14.59	2549.16 ± 9.03	2278.76 ± 10.17
(γ, *sn*)	2152.72 ± 14.59	2210.31 ± 18.42	1985.18 ± 10.17
(γ, 1*n*)	1763.54 ± 41.04	1871.03 ± 18.42	1691.60 ± 10.17
(γ, 2*n*)	389.17 ± 9.55	340.73 ± 9.22	293.65 ± 3.79
Reaction	$E^{int} = 27.00$ MeV		
	Evaluation	Experiment [5]	Experiment [6]
(γ, *xn*)	2584.47 ± 14.66	2567.93 ± 9.21	2278.76 ± 10.17
(γ, *sn*)	2176.09 ± 14.66	2222.52 ± 18.71	1985.18 ± 10.17
(γ, 1*n*)	1768.28 ± 41.05	1876.16 ± 18.71	1691.60 ± 10.17
(γ, 2*n*)	407.23 ± 9.87	378.98 ± 9.81	293.65 ± 3.79

experimental cross sections of reaction (γ, 2*n*) are thus equal unreliably underestimated.

As was shown in [1, 2, 7–12] for a large number of medium and heavy nuclei, these differences were due to important feature of photoneutron reactions that was overlooked in the procedure for determining the multiplicity of photoneutrons in the experiment in [5]: the complicated and unclear relationship between the multiplicity of neutrons and their kinetic energy. It was shown in [13] that upon the opening of giant dipole resonance (GDR) channels, the energy spectrum of photoneutrons changes weakly as the number of released neutrons grows (the main maximum is virtually unshifted, remaining in the energy range of ~0.7–1.0 MeV).

CONCLUSIONS

The reliability of data on the photodisintegration of ^{139}La obtained in different experiments was examined using objective physical reliability criteria. It was shown that the cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) obtained in experiments [5, 6] quasi-monoenergetic annihilation photon beams by neutron multiplicity sorting had great systematic uncertainties introduced by the close kinetic energies of neutrons from different partial reactions, which made it difficult to determine neutron multiplicity.

The experimental-theoretical method for evaluation of the partial photoneutron reaction cross sections of partial photoneutron reactions for the ^{139}La nucleus allowed us to find new cross sections of partial reactions (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*), and of total photoneutron reaction (γ, *sn*). All of these satisfied the physical criteria of data reliability.

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REFERENCES

1. Varlamov, V.V., Ishkhanov, B.S., Orlin, V.N., and Troshchiev, S.Yu., *Bull. Russ. Acad. Sci.: Phys.*, 2010, vol. 74, p. 842.
2. Varlamov, V.V., Ishkhanov, B.S., and Orlin, V.N., *Phys. At. Nucl.*, 2012, vol. 75, p. 1339.
3. Ishkhanov, B.S. and Orlin, V.N., *Phys. Part. Nucl.*, 2007, vol. 38, p. 232.
4. Ishkhanov, B.S., and Orlin, V.N., *Phys. At. Nucl.*, 2008, vol. 71, p. 493.
5. Bergere, R., Beil, H., and Veyssiere, A., *Nucl. Phys.*, 1968, vol. 121, p. 427.
6. Beil, H., Bergere, R., Carlos, P., Lepretre, A., et al., *Nucl. Phys.*, 1971, vol. 172, p. 426.
7. Varlamov, V.V., Ishkhanov, B.S., Orlin, V.N., and Peskov, N.N., *Phys. At. Nucl.*, 2016, vol. 79, p. 501.
8. Varlamov, V.V., Davydov, A.I., Makarov, M.A., Orlin, V.N., and Peskov, N.N., *Bull. Russ. Acad. Sci.: Phys.*, 2016, vol. 80, p. 317.
9. Varlamov, V.V., Makarov, M.A., Peskov, N.N., and Stepanov, M.E., *Phys. At. Nucl.*, 2015, vol. 78, p. 746.
10. Belyshev, S.S., Filipescu, D.M., Gheoghe, I., et al., *Eur. Phys. J. A*, 2015, vol. 51, p. 67.
11. Varlamov, V.V., Ishkhanov, B.S., Orlin, V.N., and Stopani, K.A., *Eur. Phys. J. A*, 2014, vol. 50, p. 114.
12. Varlamov, V.V., Ishkhanov, B.S., Orlin, V.N., Peskov, N.N., and Stepanov, M.E., *Phys. At. Nucl.*, 2013, vol. 76, p. 1403.
13. Ishkhanov, B.S., Orlin, V.N., and Troshchiev, S.Yu., *Phys. At. Nucl.*, 2012, vol. 75, p. 253.
14. Varlamov, V.V., Ishkhanov, B.S., Orlin, V.N., and Chetvertkova, V.A., *Bull. Russ. Acad. Sci.: Phys.*, 2010, vol. 74, p. 833.
15. Varlamov, V., Ishkhanov, B., and Orlin, V., *Phys. Rev. C*, 2017, vol. 96, p. 044606.

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