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Photodisintegration of ^{127}I: Systematic Uncertainties of Experiments and Data Evaluated Using Physical Criteria

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Abstract: The experimental data for photoneutron reaction cross sections for ^{127}I obtained using beams of quasimonoenergetic annihilation photons and the method of neutron multiplicity-sorting at Livermore (USA) and Saclay (France) were analyzed using objective physical data reliability criteria. It was found that data of both laboratories contain significant systematic uncertainties and therefore are not reliable. New data for partial and total photoneutron reactions cross sections for ^{127}I satisfied physical criteria of data reliability were evaluated using experimental-theoretical method based on both experimental neutron yield reaction cross-section and results of calculation in the combined photonucleon reaction model (CPNRM). The neutron yield reaction cross-section obtained at Saclay (France) was used in evaluation procedure. The newly evaluated cross sections for partial (γ, 1n), (γ, 2n) and (γ, 3n) reactions for ^{127}I were used for discussion in detail the problems of significant disagreements between experimental data for many nuclei obtained at Saclay and Livermore. It was found that systematic uncertainties of experimental data for the (γ, 1n), (γ, 2n), and (γ, 3n) reactions cross sections for ^{127}I obtained at both laboratories are of different nature. One of the reasons of noticeable systematic uncertainties of cross sections obtained are the shortcomings of the procedures used to separate counts into 1n, 2n, and 3n events. At the same time it was shown that the main reason of significant disagreements between new evaluated data and data obtained at Livermore experiment for ^{127}I is the loss of many neutrons from the (γ, 1n) reaction. This situation is analogous to those in Livermore experiments for ^{75}As and ^{181}Ta.

Keywords: ^{127}I, Partial Photoneutron Reactions, Data Reliability Criteria, Systematic Uncertainties, Experimental-Theoretical Method, New Evaluated Cross Sections

1. Introduction

The majority of cross sections of partial photoneutron reactions, primarily (γ, 1n), (γ, 2n), and (γ, 3n), for many nuclei was obtained at the Lawrence Livermore National Laboratory (USA) and the Centre d'Etudes Nucleaires of Saclay (France) using quasimonoenergetic annihilation photon beams and the method of photoneutron multiplicity-sorting [1–6]. For 19 nuclei, ^{51}V, ^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, $^{116, 117, 118, 120, 124}$Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, ^{238}U, the relevant data were obtained in both laboratories [7–9]. The significant systematic disagreements between cross sections of the (γ, 1n) and (γ, 2n) reactions for those nuclei were found: as a rule the (γ, 1n) reaction cross sections are larger at Saclay, but the (γ, 2n) cross sections vice versa are larger at Livermore, up to 100%. The averaged ratios of integrated cross sections obtained at Saclay to those obtained at Livermore $<R^{int}_{S/L}>=<R^{int}_S/R^{int}_L>$ for 19 nuclei mentioned above are 1.08 in the cases of (γ, 1n) and 0.83 in the cases of and (γ, 2n) reactions.

There are three very interesting cases in the systematic under discussion: ^{75}As, ^{181}Ta, and ^{127}I. In the case of ^{75}As $R^{int}_{S/L}$ ratios for both partial reactions (γ, 1n) and (γ, 2n) are relatively large and very close to each other ($R^{int}_{S/L}(1n)$=1.21, $R^{int}_{S/L}(2n)$=1.22). In the case of ^{181}Ta those ratios are significantly different ($R^{int}_{S/L}(1n)$=1.25 and $R^{int}_{S/L}(2n)$=0.89).

In the case of ^{127}I the ratio $R^{int}_{S/L}(1n)=1.34$ is the largest value in the systematic mentioned above.

At the same time the averaged disagreement between the neutron yield reaction cross-section,

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

values obtained in various laboratories for many nuclei is about 10% [7–9]. It means that there are noticeable systematic uncertainties in partial reaction cross sections main reasons of which are the definite shortcomings of the neutron multiplicity-sorting method used.

In order to resolve the problems of systematic disagreements between data obtained in various experiments the cases of ^{181}Ta [10] and ^{75}As [11, 12] were investigated in detail using the experimental-theoretical method for evaluating the partial reaction cross sections [13]. In this method the experimental neutron yield reaction cross-section $\sigma^{exp}(\gamma, Sn)$, rather independent from the neutron multiplicity-sorting problems because all outgoing neutrons are included, is decomposed into partial reaction cross sections $\sigma^{eval}(\gamma, in)$

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

using the ratios,

$$F_i^{theor}=\sigma^{theor}(\gamma, in)/[\sigma^{theor}(\gamma, 1n)+2\sigma^{theor}(\gamma, 2n)+3\sigma^{theor}(\gamma, 3n)+\ldots], \quad (3)$$

calculated for partial reactions (γ, in) with definite neutron multiplicity factors i=1, 2, 3,... in the combined photonucleon reaction model (CPNRM) [14, 15]. The CPNRM is based on the statistical approach, uses a combination of preequilibrium exciton model and particle evaporation process to calculate probabilities of formation of specific final nuclei after absorption of a photon and additionally considers deformation of nucleus and isospin splitting of its giant dipole resonance.

This treatment means that the competitions between partial reactions are in accordance with the CPNRM equations and their correspondent sum (1) $\sigma^{eval}(\gamma, Sn)$ is equal to the experimental once $\sigma^{exp}(\gamma, Sn)$.

The ratios F_i^{exp} determined in analogy to F_i^{theor} (3) were proposed [13] to be the objective physical criteria of partial photoneutron reaction cross-section data reliability. Follow the definitions (3) F_i must not have values higher than 1.00, 0.50, 0.33 respectively for i=1, 2, 3. Larger F_i^{exp} values mean that experimental cross sections definitely have noticeable systematic uncertainties and therefore are not reliable. The second criterion of data reliability is that because the ratios F_i include only the cross-section terms they must be definitely positive. The third reliability criterion was obtained after the comparison in detail the newly evaluated partial photoneutron reaction cross sections $\sigma^{eval}(\gamma, in)$ (2) for ^{181}Ta [10], ^{197}Au [12] and ^{209}Bi [16] with the results of measurements of multi-neutron reaction yields using bremsstrahlung beams and activation method [17–19], in which the direct identification of specific partial reaction is based on final nucleus features. It was found that for all three nuclei mentioned evaluated partial reaction cross sections $\sigma^{eval}(\gamma, in)$ agree with data obtained using activation method and therefore are reliable.

For many nuclei ($^{63, 65}$Cu, ^{75}As, $^{76-82}$Se, $^{90-94}$Zr, ^{115}In, $^{112-124}$Sn, ^{133}Cs, ^{138}Ba, ^{159}Tb, $^{186-192}$Os, ^{197}Au, ^{208}Pb, ^{209}Bi and some others) it was found that in many cases experimental partial reaction cross sections do not satisfy the proposed data reliability criteria [10–13, 15–26]. It was shown that in general the main reason of noticeable disagreements between partial reaction cross sections obtained at Livermore and Saclay is the difference between procedures used to separate counts into $1n$ and $2n$ events. In the cases of ^{75}As and ^{181}Ta it was found [10, 12] that there are additional significant systematic uncertainties of other nature.

In this article systematic uncertainties of different nature existed in experimental data for ^{127}I because of using the method of photoneutron multiplicity sorting at Saclay and Livermore are discussed in detail.

2. Neutron Yield Reaction Cross-Section Data for ^{127}I

It was mentioned above that the averaged disagreement between neutron yield reaction cross sections (1) obtained in various experiments for many nuclei in general is relatively small, about 10%. For ^{127}I this is not in case. The correspondent cross sections $\sigma(\gamma, Sn)$ are presented in Figure 1 in comparison with the results of calculation in the CPNRM [14, 15].

It is very important to underline that there are significant disagreements between $\sigma^{exp}(\gamma, Sn)$ obtained at Livermore and Saclay in the energy range below the threshold of $(\gamma, 2n)$ reaction $B2n=E^{int}=16.29$ MeV where only reaction $(\gamma, 1n)$ exists and one have no neutron multiplicity-sorting problems. The values of respective integrated cross-section and center of gravity values are presented in Table 1 together with the relevant data calculated in the CPNRM. One can see that the disagreement between $\sigma^{exp}(\gamma, Sn)$ obtained at Livermore [27] and Saclay [28] is about 36% (1143.19/837.86).

In Figure 1 one can see that calculated $\sigma^{theor}(\gamma, Sn)$ is much closer to Saclay [28] $\sigma^{exp}(\gamma, Sn)$ than to Livermore [27] one. Therefore Saclay data namely were used in the evaluation procedure (2). Centers of gravity $E^{c.g.}$ of calculated $\sigma^{theor}(\gamma, Sn)$ and experimental $\sigma^{exp}(\gamma, Sn)$ [28] are near identical. Therefore for better agreement between both cross sections the calculated $\sigma^{theor}(\gamma, Sn)$ was slightly corrected in magnitude, multiplied by 1.10=1143.19/1034.39.

This corrected σ^{theor} cross-section was used for obtaining the ratios F_i^{theor} (3) and the evaluated cross sections $\sigma^{eval}(\gamma, in)$ in accordance with equation 2.

Table 1. *^{127}I experimental [27, 28] and calculated [14, 15] integrated (up to energy E^{int}) cross sections σ^{int} and centres of gravity $E^{c.g.}$ for neutron yield reaction cross-section $\sigma^{exp}(\gamma, Sn)$ for photon energies up to $E^{int}=B2n=16.29$ MeV.*

	σ^{int}, MeV mb	$E^{c.g.}$, MeV
σ^{exp}, Saclay [28]	1143.19±10.48	13.98±0.23
σ^{theor}, CPNRM	1034.39±29.98	13.98±1.21
σ^{theor}, CPNRM corr.	1143.64±22.93	13.97±1.21
σ^{exp}, Livermore [27]	837.86±3.77	14.03±0.27

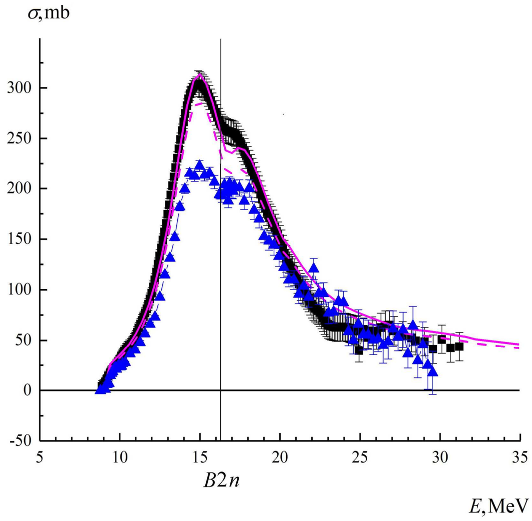

Figure 1. *Comparison of the experimental (Livermore [27], triangles, and Saclay [28], squares) neutron yield reaction cross sections $\sigma^{exp}(\gamma, Sn)$ for ^{127}I with the cross sections calculated in the CMPNR [14, 15] (before (dotted line) and after (solid line) correction (see further)).*

3. The Objective Physical Criteria for ^{127}I Partial Photoneutron Reaction Data Reliability

As it was mentioned above the ratios F_i^{exp} obtained using experimental cross sections in analogy to the calculated F_i^{theor} (2) were proposed [13] as objective physical criteria of partial photonuclear reaction cross-section reliability. The ratios $F_{1,\,2,\,3}^{exp}$ for ^{127}I obtained using the experimental data of Livermore [27] and Saclay [28] are presented in Figure 2 together with calculated $F_{1,\,2}^{theor}$ data [14, 15].

One can see that $F_{1,\,2}^{exp}$ values obtained for Saclay data [28] up to energy 22.5 MeV are very close to $F_{1,\,2}^{theor}$ values, but in energy range ~21.0–28.0 MeV F_2^{exp} values are noticeably systematically larger in comparison with F_2^{theor} values. Additionally in the energy range ~29.0–31.2 MeV F_3^{exp} values are systematically noticeably larger in comparison with F_3^{theor} values. It means that one have some doubts in reliability of Saclay data [28].

At the same time there are much more serious doubts in reliability of Livermore data [27]. At energies ~21.0–27.0 MeV one can see physically forbidden F_1^{exp} negative values (-0.1, -0.2, -0.3, and others). At energies higher ~22.0 MeV F_1^{exp} are significantly larger in comparison with F_1^{theor}. In two last data points F_1^{exp} have values exceeding 1.00 (such values are physically forbidden because mean that the part is bigger than the whole!). There are unreliable values $F_2^{exp} > 0.50$ in the energy ranges ~21.0–22.0 and ~25.0–26.0 MeV.

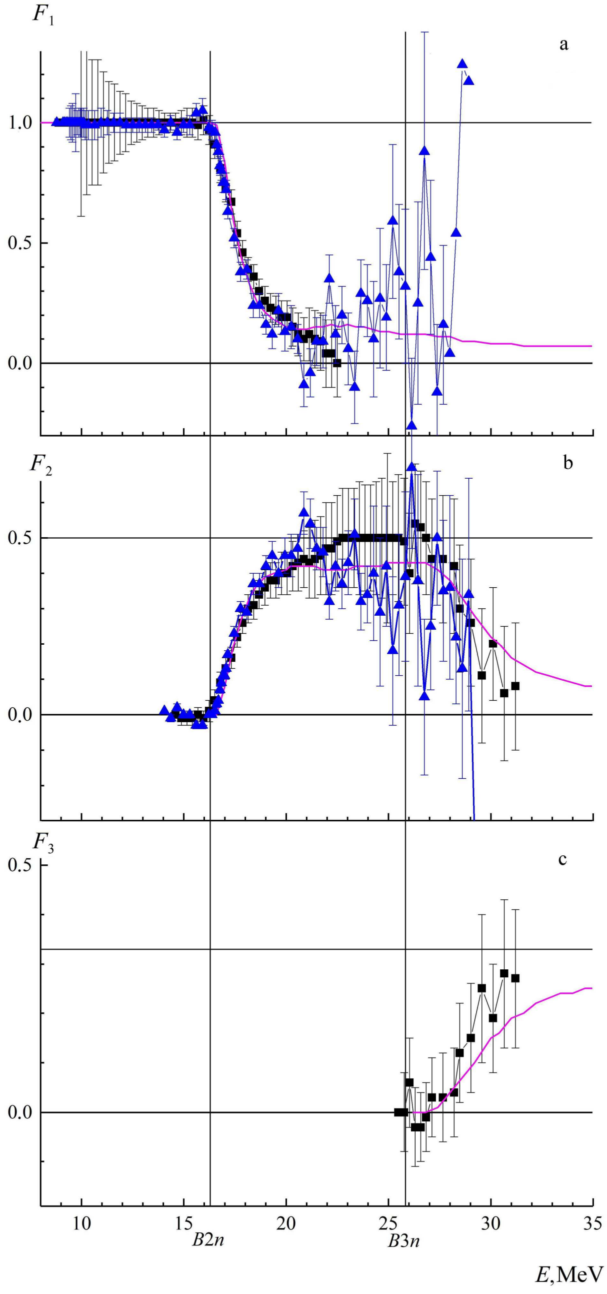

Figure 2. *F_1^{exp} (a), F_2^{exp} (b), and F_3^{exp} (c) data obtained for ^{127}I using experimental data (Livermore [27], triangles and Saclay ([28], squares) in comparison with calculated data $F_{1,\,2}^{theor}$ (model [14, 15], lines).*

Moreover ratios F_2^{exp} are systematically noticeably smaller in comparison with F_2^{theor} at energies higher ~22.0 MeV, though in agreement with definition (3) they must decrease starting at the energy of (γ, 3n) reaction threshold $B3n$=25.83 MeV. In the energy range ~22–29 MeV underestimations of (γ, 2n) reaction cross sections ($F_2^{exp} < F_2^{theor}$) clearly correlate with overestimation of (γ, 1n) reaction cross sections ($F_1^{exp} > F_1^{theor}$).

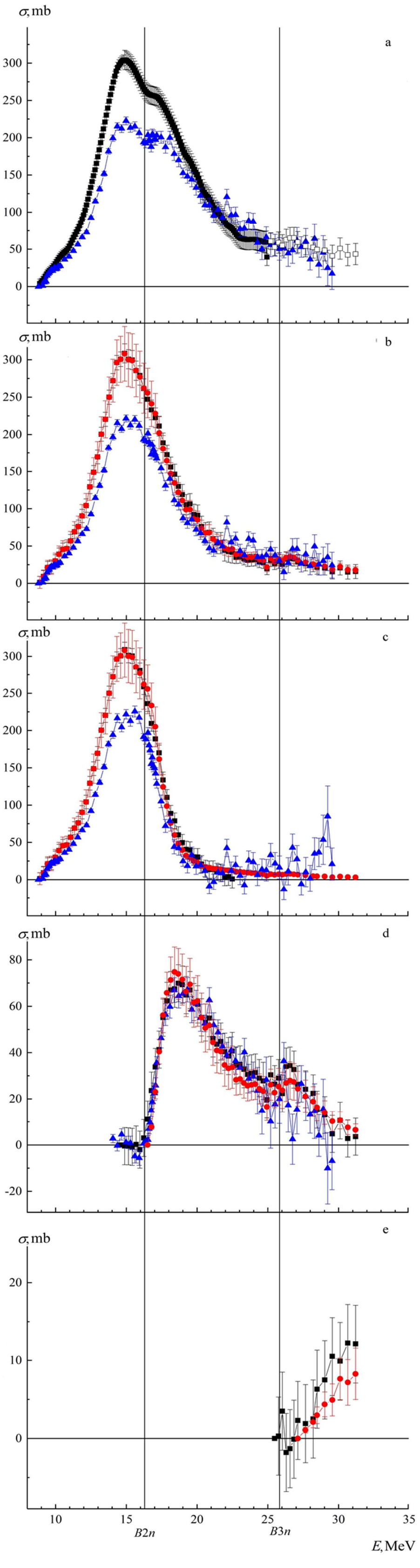

Figure 3. *The comparison of the evaluated (circles) and the experimental ([27], triangles and [28], full squares from database [1, 6], and calculated sum (1) of partial reaction cross sections, open squares) cross sections of the reactions on* ^{127}*I: (a) σ(γ, Sn), (b) σ(γ, tot), (c) σ(γ, 1n), (d) σ(γ, 2n), (e) σ(γ, 3n).*

It is important to point out that $\sigma(\gamma, 3n)$ was not obtained at Livermore [27] and therefore one has no relevant F_3^{exp} values. Because at energies higher $B3n$=25.83 MeV there are correlated overestimation of F_1^{exp} and underestimation of F_2^{exp} in comparison with the correspondent $F_{1,2}^{\mathrm{theor}}$ and at the same time absence of F_3^{exp}, one can be forced to suspect that noticeable part of neutrons from (γ, 2*n*) reaction and all neutrons from (γ, 3*n*) reaction was unreliably (erroneously) identified as neutrons from (γ, 1*n*) reaction.

4. The Newly Reliable Partial Reaction Cross Sections Evaluated for ^{127}I Using the Experimental-Theoretical Method

The newly cross sections of partial (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) reactions and total photoneutron reaction,

$$\sigma(\gamma,\ \mathrm{tot})=\sigma(\gamma,\ 1n)+\sigma(\gamma,\ 2n)+\sigma(\gamma,\ 3n), \qquad (4)$$

evaluated using experimental-theoretical method (2) and based on the corrected experimental Saclay data for $\sigma^{\mathrm{exp}}(\gamma, Sn)$ [28] are compared with experimental data of Saclay and Livermore in Figure 3. The correspondent integrated cross-section values for all evaluated cross sections for ^{127}I under discussion are presented in Table 2.

Some special notes are needed before discussion in detail the obtained data.

All experimental data at Livermore [27] were obtained up to energy 29.5 MeV [1, 6]. At the same time at Saclay [28] the cross sections of partial and total reactions were obtained [1, 6] in different energy ranges (the reasons of such differences were not explained):

1. $\sigma^{\mathrm{exp}}(\gamma, Sn)$ up to energy 25.0 MeV;
2. $\sigma^{\mathrm{exp}}(\gamma, 1n)$ up to energy 22.5 MeV;
3. $\sigma^{\mathrm{exp}}(\gamma, 2n)$ and $\sigma^{\mathrm{exp}}(\gamma, 3n)$ up to energy 31.2 MeV.

Because of that the relevant sum $\sigma^{\mathrm{calc}}(\gamma, Sn)=\sigma^{\mathrm{exp}}(\gamma, 1n)+2\sigma^{\mathrm{exp}}(\gamma, 2n)+3\sigma^{\mathrm{exp}}(\gamma, 3n)$ was used in the evaluation procedure (2) instead of $\sigma^{\mathrm{exp}}(\gamma, Sn)$ [1, 6, 28]. This calculated sum $\sigma^{\mathrm{calc}}(\gamma, Sn)$ gave to us the opportunity for evaluation of partial reaction cross sections in the energy region up to the maximally possible value 31.2 MeV. In Figure 3a one can see that at energies up to 25.0 MeV this newly calculated sum for $\sigma^{\mathrm{calc}}(\gamma, Sn)$ agrees with relevant data $\sigma^{\mathrm{exp}}(\gamma, Sn)$ [1, 6, 28] and that the experimental cross sections of the reactions (γ, tot), (γ, 1*n*) and (γ, 2*n*) obtained at Saclay [28] are relatively close to the evaluated cross sections.

There are noticeable disagreements in the case of (γ, 3*n*) reaction. Although associated uncertainties are overlapping, all disagreements are systematic and therefore the relevant integrated cross sections (presented in last line of Table 2) definitely disagree.

In Figure 3 one can see that at Livermore [27] the experimental cross sections of the reactions (γ, *Sn*), (γ, tot), and (γ, 1*n*) are significantly smaller in comparison with correspondent evaluated cross sections in energy range before $B2n$=16.29 MeV where there are no problems of neutron multiplicity-sorting. Vice versa at energies Eγ > 22 MeV the cross sections of $\sigma^{exp}(\gamma$, tot) and $\sigma^{exp}(\gamma, 1n)$ reactions are systematically larger in comparison with respective evaluated cross sections.

At the same time there are no noticeable disagreements between experimental and evaluated data for (γ, 2n) reaction. So definite underestimation of $\sigma^{exp}(\gamma, 1n)$ in comparison with evaluated once without the relevant overestimation of $\sigma^{exp}(\gamma, 2n)$ means that the main reason for such kind disagreements could not be the only difference between procedures used to separate counts into 1n and 2n events [10–13, 16–26] mentioned above.

Moreover though at energies up to $B2n$=16.29 MeV F_1^{exp} values for data obtained at Livermore are near unity (Figure 2a), it could gives to one an opportunity to have in mind the idea that that the reason of significant difference between Livermore data and Saclay and evaluated data in principle could not be the simple error in normalization. Such relative proximity of experimental and evaluated values means that assumption of simple normalization error is not correct. After the simple normalization the normalized and evaluated (γ, 1n) reaction cross sections became agree at low energies but disagree at high energies and normalized (γ, 2n) reaction-section became significantly disagree with relevant evaluated once.

Table 2. *Integrated cross sections σ^{int} (in MeV mb) of the evaluated cross sections for ^{127}I compared with the experimental data [27, 28].*

React.	**Liv. [27]**	**Saclay [28]**	**Eval.**	**Liv.-corr. [27] **)**
E^{int}=$B2n$=16.29 MeV				
γ, Sn	837.86 (3.77)	1143.19 (10.48)*)	1142.82 (23.20)	1127.85 (20.98)
γ, tot	838.16 (3.44)	1143.78 (9.84)	1142.82 (23.20)	1127.85 (20.98)
γ, 1n	839.54 (4.29)	1144.37 (9.15)	1142.82 (23.20)	1127.85 (20.98)
E^{int}=$B3n$=25.83 MeV				
γ, Sn	1999.73 (13.00)	2426.28 (19.61)*)	2393.77 (29.86)	2622.38 (36.15)
γ, tot	1607.82 (10.35)	2014.04 (16.97)	2008.23 (28.89)	2134.17 (27.17)
γ, 1n	1207.74 (13.99)	1601.74 (13.74)	1622.70 (26.63)	1645.96 (23.43)
γ, 2n	391.48 (7.87)	412.15 (9.79)	385.53 (9.54)	488.21 (13.76)
E^{int}=31.20 MeV				
γ, Sn	2164.61 (18.19)	2708.07 (25.29)*)	2661.26 (31.42)	2805.87 (41.36)
γ, tot	1719.56 (14.47)	2139.52 (19.99)	2146.73 (29.10)	2237.01 (29.03)
γ, 1n	1294.80 (20.86)	1601.74 (13.74)	1650.24 (26.67)	1668.16 (23.56)
γ, 2n	444.63 (11.01)	506.78 (13.27)	478.43 (11.47)	568.58 (17.01)
γ, 3n		30.88 (5.64)	18.04 (2.07)	

*) Experimental neutron yield reaction cross-section $\sigma^{exp}(\gamma, Sn)$ [28] used as the initial one for the evaluation procedure (2).

**) Normalized Livermore data [27] (look further).

As it was suspected above after discussion of F_{123}^{exp} values presented in Figure 2, noticeable overestimation of the $\sigma^{exp}(\gamma, 1n)$ in comparison with $\sigma^{eval}(\gamma, 1n)$ and vice versa underestimation of $\sigma^{exp}(\gamma, 2n)$ in comparison with $\sigma^{eval}(\gamma, 2n)$ at energies higher than $B3n$=25.83 MeV could be the results of unreliable (erroneous) sorting of neutrons from the undetermined reaction (γ, 3n) between determined (γ, 1n) and (γ, 2n) reactions. Using the data of Table 2 integrated cross sections of the reactions (γ, 1n), (γ, 2n) and (γ, 3n) can be obtained for energy range Eγ=25.83-31.20 MeV (Table 3).

Table 3. *^{127}I integrated cross sections σ^{int} (in MeV mb) of the experimental [27] and evaluated cross sections for energy range Eγ=25.83 - 31.20 MeV.*

Reaction	**Livermore [27]**	**Evaluation**
γ, 1n	87.06 (1294.80-1207.74)	27.54 (1650.24-1622.70)
γ, 2n	53.15 (444.63-391.48)	92.90 (478.43-385.53)
γ, 3n	no data	18.04

The unreliable overestimation of the experimental (γ, 1n) reaction cross-section in comparison with the evaluated one, 59.52 (87.06-27.54) MeV mb, is very close to the sum of underestimation for (γ, 2n) reaction cross-section 39.75 (92.90-53.15) MeV mb and evaluated (γ, 3n) cross-section, 18.04 MeV mb (39.75+18.04=57.79 MeV mb). This could be the direct confirmation of the assumption that the sum of all neutrons from not obtained (γ, 3n) reaction and noticeable part of neutrons from (γ, 2n) reaction was unreliably (erroneously) identified as neutrons from (γ, 1n) reaction.

It is very important to point out that the analogous situation with unreliable sorting of neutrons between obtained experimentally σ(γ, 2n) and not obtained σ(γ, 3n) was investigated in detail before for ^{159}Tb [29].

5. The Reasons of Disagreements Between Partial Reaction Cross Sections for ^{127}I

To find the possible reasons of disagreements between Saclay and Livermore ^{127}I data under discussion the comparison of competitions between various total and partial reactions was studied in detail using ratios of respective integrated cross-section values $\sigma^{int}_{eval}/\sigma^{int}_{exp}$, calculated for evaluated and experimental cross sections using the data presented in Table 2.

Because as was pointed out there are serious problems in the sorting of neutrons from all partial reactions at Livermore at energies higher $B3n$, the ratios $\sigma^{int}_{eval}/\sigma^{int}_{S\ [28]}$ and $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$ were calculated using relatively Saclay and Livermore data for energies between $B2n$ and $B3n$ in which the maximal competition between (γ, 1n) and (γ, 2n) reactions exists and are presented in Table 4.

Table 4. *The ratios of integrated cross sections $\sigma^{int}_{eval}/\sigma^{int}_{S/L}$ for ^{127}I calculated using evaluated and experimental (initial, [27, 28] and corrected (look further)) data for energies up to E^{int}=B3n=25.83 MeV.*

Reaction	$\sigma^{int}_{eval}/\sigma^{int}_{S\ [28]}$	$\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$	$\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]\ corrected}$
γ, Sn	0.99 (2393.77/2426.28)	1.20 (2393.77/1999.73)	0.91 (2393.77/2622.38)
γ, tot	1.00 (2008.23/2014.04)	1.25 (2008.23/1607.82)	0.94 (2008.23/2134.17)
γ, 1n	1.01 (1622.70/1601.74)	1.33 (1622.70/1217.74)	0.97 (1622.70/1645.95)
γ, 2n	0.94 (385.53/412.15)	0.98 (385.53/391.48)	0.79 (385.53/488.21)

It is very important to point out that $\sigma^{int}_{eval}/\sigma^{int}_{exp}$ values for all total and partial reaction cross sections obtained at Saclay and Livermore are quite different.

At Saclay $\sigma^{int}_{eval}/\sigma^{int}_{S\ [28]}$ values for all reactions under discussion, (γ, Sn), (γ, tot), (γ, 1n), and (γ, 2n), are about unity and near to each other. This means that in experiment [28] for ^{127}I in analogy to experiments for many other nuclei investigated before [10–13, 16–26] obtained partial photoneutron reaction cross sections contain only the small systematic uncertainties the reason of which is the shortcoming of procedures used to separate counts into 1n and 2n events.

At Livermore the ratio $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$ values are noticeably larger in comparison with Saclay values and in addition they systematically increase during the transitions from (γ, Sn)=(γ, 1n)+{2 (γ, 2n)} reaction to (γ, tot)=(γ, 1n)+{1 (γ, 2n)} once and after that to (γ, 1n)=(γ, 1n)+{0 (γ, 2n)} once: $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$=1.20, 1.25, and 1.33, respectively. It means that the larger the fraction of the simple σ(γ, 1n) reaction in the complex reaction cross sections the higher the degree to which the latter is underestimated. At the same time for σ(γ, 2n), in which the fraction of the σ(γ, 1n) naturally is equal to zero, the $\sigma^{int}_{eval}/\sigma^{int}_{L}$=385.53/391.48=0.98 ≈ 1.

The ratio $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$ for (γ, 2n) reaction is very small (2%), but for (γ, 1n) reaction is very large (33%). It means that namely the very large underestimation of the cross-section for reaction (γ, 1n) is responsible for a substantial (by 20%) underestimation of the cross-section for the reaction (γ, Sn) clearly seen in Figure 2. One is forced to conclude that in Livermore experiment [27] many neutrons from (γ, 1n) reaction were lost. This could be resulted from some problems of neutron detection efficiency at different neutron energies.

As was mentioned above, the disagreements under discussion could not be explained by relatively simple errors in normalization of data because decreasing the disagreement between cross sections of (γ, 1n) reaction will be followed by increasing the disagreement between cross sections of (γ, 2n) reaction. To confirm this assumption all experimental Livermore [27] cross sections were normalized to the Saclay [28] data by multiplying all to 1.36=1143.19/837.86 using the data of the Tables 1 and 2 for energy range before $B2n$=16.29 MeV in which all cross sections must be identical.

The correspondent ratios $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$ obtained using the corrected Livermore data are presented in the last column of Table 4. One can see that after such correction (normalization) the cross sections of (γ, Sn), (γ, tot), and (γ, 1n) reactions became much closer to the relevant evaluated data with relatively small (9%, 6%, and 3%) differences respectively, but at the same time the cross-section of (γ, 2n) reaction became significantly (up to 21%) larger in comparison with evaluated cross-section.

In Figure 4 the differences

$$\Delta\sigma=\sigma^{eval}-\sigma^{exp}, \tag{5}$$

between the evaluated and the experimental (and additionally normalized) data obtained separately for both partial reactions (γ, 1n) and (γ, 2n) before and after normalization of Livermore data [27] are presented.

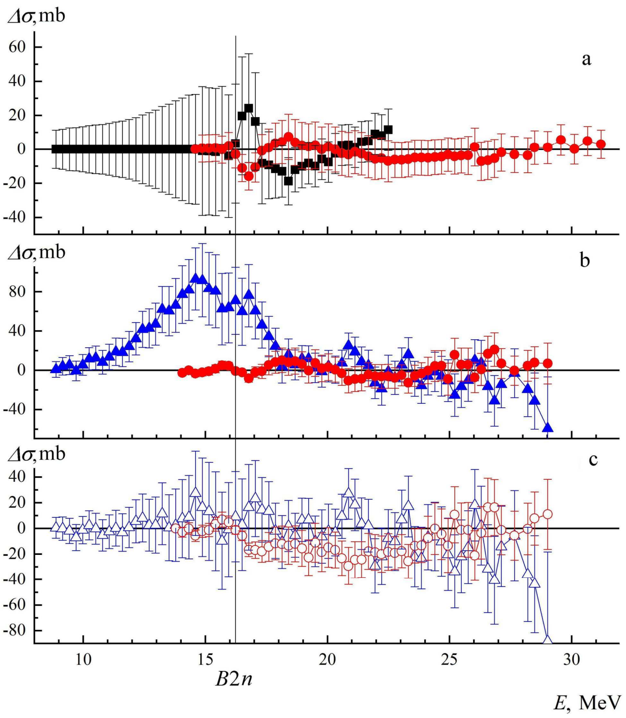

Figure 4. *Comparison of the differences Δσ (5) between the evaluated and the experimental cross sections for ^{127}I: (a) for data [28] (squares for reaction (γ, 1n), circles – (γ, 2n)), (b) for data [27] (full triangles for the reaction (γ, 1n), full circles – (γ, 2n)), (c) the analogous data for corrected Livermore data [27] (open triangles for the (γ, 1n), open circles for (γ, 2n) reactions.*

One can see that at energies before $B2n$=16.29 MeV the evaluated cross sections are relatively close to the Saclay data

[28]. At higher energies some disagreements exist (Figure 4a). The differences $\Delta\sigma$ (5) obtained for Saclay data look as “reflected in a mirror” with average deviation from zero of about several mb. Although associated uncertainties are overlapping, all disagreements are systematic and therefore one can talk about definite disagreements. Those clearly demonstrate the reason of this kind “traditional” [10–13, 16–26] systematic uncertainties in the experiments discussed, e.g., the unreliable uncertainties in sorting of a certain number of neutrons between 1n and 2n channels because of not direct dependence of measured neutron kinetic energy and its determined multiplicity.

For Livermore data [27] the situation is completely different. As it was shown above there is noticeable difference between $\sigma(\gamma, 1n)$ obtained at Livermore and Saclay at energies below the threshold $B2n$ (Figure 4b). The experimental $(\gamma, 1n)$ reaction cross-section is significantly less in comparison with the evaluated cross-section with the biggest deviation $\Delta\sigma$ $(\gamma, 1n)$ ~100 mb. But at energies higher than ~21 MeV the experimental $(\gamma, 1n)$ reaction cross-section is vice versa noticeably larger in comparison with the evaluated one: the average deviation is about 30 mb, the biggest ones are ~40-50 mb. At the same time at all energies the difference $\Delta\sigma$ $(\gamma, 2n)$ is relatively small (the average deviation is about several mb).

In Figure 4c the differences $\Delta\sigma$ (5) obtained using the corrected normalized Livermore $\sigma^{exp}(\gamma, Sn)$ [27], which is relatively close to that of Saclay, are presented. One can see that the energy dependencies of $\Delta\sigma(\gamma, 1n)$ and $\Delta\sigma(\gamma, 2n)$ look absolutely different in comparison with previous once (Figure 4b). At energies up to $B2n$=16.29 MeV the difference $\Delta\sigma(\gamma, 1n)$ became significantly smaller in comparison with previous values, at energies between $B2n$ and ~22 MeV $\Delta\sigma(\gamma, 1n)$ is relatively the same as before and at higher energies $\Delta\sigma(\gamma, 1n)$ has values noticeably larger in comparison with previous values. At the same time in complete agreement with previous conclusions the difference $\Delta\sigma(\gamma, 2n)$ has the values significantly larger in comparison with previous once: in the energy range between $B2n$ and ~25 MeV the average value is ~25-30 mb, several extreme deviations are ~40, 50, 80 mb. It means that additional normalization of experimental Livermore data [27] does not exclude the traditional disagreements because of difference of procedures used to separate counts into $1n$ and $2n$ events.

6. Comparison of Data for ^{127}I with Those for ^{181}Ta and ^{75}As

As it was mentioned above, there are three interesting cases in the systematic of disagreements between Livermore and Saclay data, ^{127}I, ^{181}Ta, and ^{75}As.

The cases of ^{181}Ta [10] and ^{75}As [12] were investigated in detail before. It was shown that for both nuclei additionally to the traditional [10–13, 16–26] disagreements between the partial reaction cross sections obtained at Livermore and Saclay because of difference of procedures used to separate counts into $1n$ and $2n$ events, one can see the presence of systematic uncertainties of other nature. It was found that in both cases there are the significant disagreements for $(\gamma, 1n)$ reaction cross sections but at the same time relatively proximity of data for $(\gamma, 2n)$ reaction cross sections. It was shown that in the relevant Livermore experiments for ^{75}As [30] and ^{181}Ta [31] the competitions of the ratios of integrated cross sections $\sigma^{int}_{eval}/\sigma^{int}_{S/L}$ calculated using evaluated and experimental data presented in Table 5 are generally very similar to those found in the case of ^{127}I.

In the absolute analogy to the case of ^{127}I for both ^{75}As and ^{181}Ta the evaluated data are in general closer to experimental Saclay [32, 33] not to Livermore [30, 31] data. For both ^{181}Ta and ^{75}As similar to that was found for ^{127}I the larger the fraction of the $\sigma(\gamma, 1n)$ reaction in the cross-section for the reactions (γ, Sn), (γ, tot), and $(\gamma, 1n)$, the higher the degree to which the latter is underestimated (1.24 → 1.30 → 1.46 in the case of ^{181}Ta and 1.27 → 1.30 → 1.34 in the case of ^{75}As). For $\sigma(\gamma, 2n)$ the $\sigma^{int}_{eval}/\sigma^{int}_{L}$ are significantly smaller - 1.05 in the case of ^{181}Ta and 1.14 in the case of ^{75}As.

Table 5. *The ratios of integrated cross sections $\sigma^{int}_{eval}/\sigma^{int}_{S/L}$ calculated for ^{181}Ta [10, 31, 32] and ^{75}As [12, 30, 33].*

Reaction	^{181}Ta (E^{int}=$B3n$=25.00 MeV)		^{75}As (E^{int}=$B3n$=26.2 MeV)	
	$\sigma^{int}_{eval\ [10]}/\sigma^{int}_{S\ [32]}$	$\sigma^{int}_{eval\ [10]}/\sigma^{int}_{L\ [31]}$	$\sigma^{int}_{eval\ [12]}/\sigma^{int}_{S\ [33]}$	$\sigma^{int}_{eval\ [12]}/\sigma^{int}_{L\ [30]}$
γ, Sn	1.00	1.24	0.99	1.27
γ, tot	0.96	1.30	1.00	1.30
γ, $1n$	0.88	1.46	1.02	1.34
γ, $2n$	1.16	1.05	0.92	1.14

Therefore it can be concluded that in Livermore experiments for ^{127}I [27], ^{75}As [30] and ^{181}Ta [31] many neutrons from the $(\gamma, 1n)$ reaction were lost.

The very important difference between the cases of ^{127}I and ^{181}Ta and ^{75}As is that differences $\Delta\sigma(\gamma, 2n)$ between evaluated and experimental data are relatively small (2% and 5%, correspondingly) for the first two nuclei and noticeably large (14%) for the third one. Because in accordance with all things discussed above one is forced to conclude that at Livermore in the cases of ^{127}I [27] and ^{181}Ta [30] many neutrons from $(\gamma, 1n)$ reactions were lost, in the case of ^{75}As [31] many neutrons not only from $(\gamma, 1n)$ but from $(\gamma, 2n)$ reaction also were lost. Therefore it can be concluded that experimental Livermore data for ^{75}As [31], ^{127}I [27], and ^{181}Ta [30] are in general unreliable.

7. Summary and Conclusions

Using the objective physical data reliability criteria – the ratios F_i=$\sigma(\gamma, in)/\sigma(\gamma, Sn)$ of the specific partial reaction cross sections $\sigma(\gamma, in)$ to the neutron yield cross-section $\sigma(\gamma, Sn)$ [13], the experimental cross sections obtained for ^{127}I at

Livermore [27] and Saclay [28] were analyzed. It was shown that in analogy to the results of many previous investigations [10–13, 16–26] the data of both laboratories contain noticeable systematic uncertainties. The experimental-theoretical method (2) for evaluating the partial reaction cross sections $\sigma^{eval}(\gamma, in)=F_i^{theor}\sigma^{exp}(\gamma, Sn)$, based on the experimental Saclay neutron yield reaction cross sections $\sigma^{exp}(\gamma, Sn)$ [28] and the ratios F_i^{theor} (3) calculated in the combined photonuclear reactions model CPNRM [14, 15], was used for evaluating the new cross sections for the (γ, 1*n*), (γ, 2*n*), and (γ, 3*n*) reactions for ^{127}I, which satisfied data reliability physical criteria. It was shown that there are noticeable systematic uncertainties of cross sections obtained at both Saclay and Livermore because of shortcomings of the procedures used to separate counts into 1*n*, 2*n*, and 3*n* events.

It was found additionally that the competitions of the ratios $\sigma^{int}_{eval}/\sigma^{int}_{exp}$ of integrated cross sections of the reactions (γ, *Sn*), (γ, tot), (γ, 1*n*) and (γ, 2n) calculated for energies before *B*3*n* using data obtained at Saclay and Livermore are quite different.

At Saclay all ratios $\sigma^{int}_{eval}/\sigma^{int}_{S\ [28]}$ are near unity. At Livermore the ratio $\sigma^{int}_{eval}/\sigma^{int}_{L\ [27]}$ is near unity only for (γ, 2n) reaction. For other reactions those ratios are significantly larger. Moreover the larger the fraction of the $\sigma(\gamma, 1n)$ reaction, the higher the degree to which the latter is underestimated, 1.20 → 1.25 → 1.33 for the reactions (γ, *Sn*), (γ, tot), and (γ, 1*n*), correspondingly. Using those data and data for the differences $\Delta\sigma=\sigma^{eval}-\sigma^{exp}$ (5) between evaluated and experimental cross sections it was shown that the main reason of such significant systematic uncertainties of data obtained in Livermore is that many neutrons from the reaction ^{127}I(γ, 1*n*) [27] were lost in analogy to the situations for reactions ^{75}As(γ, 1*n*) [30] and ^{181}Ta(γ, 1*n*) [31].

So, one is forced to conclude that the experimental cross sections of (γ, *Sn*), (γ, tot), and (γ, 1*n*) reactions obtained at Livermore for ^{127}I [27] contain significant uncertainties not only because the definite shortcomings of the procedures used to separate counts into 1*n* and 2*n* events but also because the loss of many neutrons from (γ, 1*n*) reaction.

So one is forced to conclude that experimental Livermore data for ^{127}I [27] similar to those for ^{75}As [30] and ^{181}Ta [31] obtained using the photoneutron multiplicity-sorting method are obviously unreliable because of the presence of significant systematic uncertainties from erroneous transportation of many neutrons from one partial channel to another and additionally from the loss of many neutrons. Therefore the results obtained using alternative experimental methods are needed [11, 12].

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