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Photonuclear Reactions: Modern Status of the Data*

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Abstract—Photonuclear reaction data play an important role in basic and applied research. Radiation shielding design, radiation transport analysis, activation analysis, astrophysical nucleosynthesis, safeguards and inspection technologies, human body radiotherapy absorbed dose calculations, beam monitoring in heavy-ion dissociation research at ultrarelativistic energies, etc., could be mentioned. However, there exist quite evident systematic discrepancies in both shapes and magnitudes between photonuclear cross sections measured in various laboratories. These discrepancies noticeably reduce the accuracy and reliability of data. A systematic overview of various types of data contained in the international database is given. The modern status of the data is discussed. The reasons for significant discrepancies between various photonuclear data are analyzed and methods to reduce them are suggested. *© 2004 MAIK "Nauka/Interperiodica".*

INTRODUCTION

The absolute majority of data on photonuclear reaction cross sections in the energy range of giant dipole resonance (GDR) have been obtained [1–5] in experiments with bremsstrahlung (BR) and quasi-monoenergetic photons produced by annihilation in flight of relativistic positrons (QMA). There are evident systematical discrepancies in both shapes and magnitudes between the data obtained not only in experiments of different types, but in experiments of the same type as well. The discrepancies are larger than statistical uncertainties and obviously depend on the experimental method explored. Though the majority of cross-section data were obtained quite long ago, they are included in the contemporary large database [6] and still extensively used. Thus, the current status of photonuclear research on the whole, as well as the accuracy and reliability of each set of data, becomes understandable only after a careful analysis of existing systematical disagreements and of the ways to take them into account. Large databases give a good possibility for such an analysis.

1. TWO MAIN TYPES OF PHOTONUCLEAR EXPERIMENTS

1.1. Experiments with Electron Bremsstrahlung Photons

The bremsstrahlung spectrum is a continuous one and, therefore, a direct measurement of a reaction cross section is not possible with it, but only a reaction yield $Y(E_{jm})$. The latter is a cross section $\sigma(k)$ with a threshold $E_{\rm th}$ depending on a photon energy k and folded with the photon spectrum $W(E_{jm}, k)$ with the endpoint energy E_{jm}:

$$Y(E_{jm}) = \frac{N(E_{jm})}{\varepsilon D(E_{jm})} = \alpha \int\limits_{E_{\rm th}}^{E_{jm}} W(E_{jm}, k)\sigma(k)dk. \quad (1)$$

Reaction cross section σ can be obtained from the experimental yield Y using one of the well-known mathematical methods (Penfold–Leiss, Tikhonov regularization, etc.). All of them have been developed especially to produce the effective photon spectrum (the apparatus function) that looks like (Fig. 1*b*) a sufficiently narrow line. However, a constructed apparatus function has a complex shape, which can produce additional uncertainties in shape, magnitude, and position of a cross section.

1.2. Experiments with Quasimonoenergetic Annihilation Photons

As an alternative to the procedure of solving inverse ill-posed problem (1), QMA experiments have been developed [5] [the majority of data have been obtained at Livermore (USA) and Saclay (France)]. They consist in producing annihilation photons with the energy $E_\gamma = E_{e^+} + 0.511$ MeV by fast positrons. Since annihilation photons always are accompanied by positron bremsstrahlung, a QMA experiment is carried out in three steps (Fig. 1—^{63}Cu$(\gamma, n)^{62}$Cu reaction [7]): (i) measurements of the yield $Y_{e^+}(E_j)$

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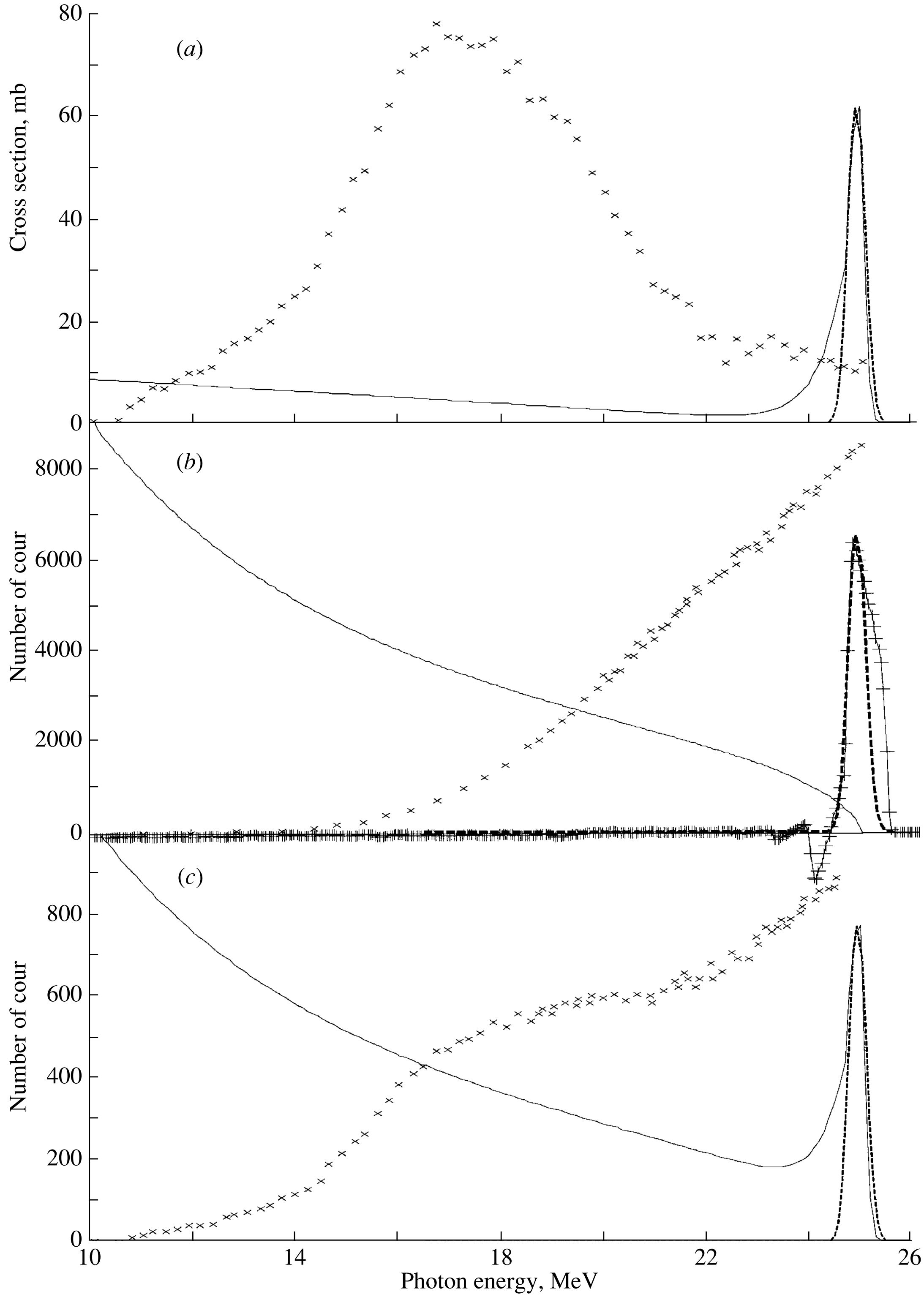

Fig. 1. Experimental yields [7] of ^{63}Cu(γ, n) ^{62}Cu reaction ($\times$), appropriate effective photon spectra (solid curves), and the apparatus function obtained by the reduction method (dashed curves): (a) the yield difference $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(k)$ (2), i.e., the difference between spectra of photons produced by positrons and electrons, respectively; (b) the yield $Y_{e^-}(E_j)$ and the electron bremsstrahlung spectrum [the apparatus function obtained by the Penfold–Leiss method is also presented (+)]; (c) the yield $Y_{e^+}(E_j)$ and the spectrum of photons produced by positrons (the sum of bremsstrahlung and annihilation processes).

of the reaction induced by photons from both the annihilation and the bremsstrahlung of e^+; (ii) measurements of the yield $Y_{e^-}(E_j)$ of the reaction induced by photons from the e^- bremsstrahlung; (iii) the subtraction (the bremsstrahlung spectra is assumed to be identical for e^- and e^+)

$$Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(k). \qquad (2)$$

The difference (2) is interpreted as a reaction cross section "measured directly."

The following points should be mentioned: (i) There is no beam of QMA photons in reality: the QMA photons arise only as a difference of two real spectra. (ii) The apparatus function (Fig. 1a) of an experiment is obtained individually because it depends on conditions of both the measurements (i.e., on yields—Y_{e^+}, Y_{e^-}). (iii) The production of positron annihilation γ quanta is a result of a few successive processes [bremsstrahlung production ($e^- + A \to A + e^- + \gamma$); production of pairs ($\gamma + A \to A + e^- + e^+$); positron annihilation ($e^+ + e^- \to 2\gamma$)]. Due to this, the number of quasimonoenergetic photons appears to be small, and hence the statistical accuracy of measured yields, as well as their normalizations, is also low. (iv) An apparatus function has a complex shape and is spread over a wide energy range, so the result of (2) is really not a cross section, but again a yield.

2. MAIN DISCREPANCIES BETWEEN REACTION CROSS SECTIONS OBTAINED WITH BR AND QMA PHOTONS

As follows from the above discussion, conditions of these two types of experiments are different and this is the reason for a significant disagreement in their results.

2.1. Total Photoneutron Reaction (γ, xn) Cross-Section Shape (Structure, Resolution)

As a typical example of well-known discrepancies under discussion, photoneutron reaction $^{16}O(\gamma, xn)$ total cross sections obtained in the BR [8] and QMA experiments [9, 10] can be pointed out. There are well-separated resonances in all three cross sections obtained with a high enough energy resolution (200 [8], 180–200 [9], and 200–300 keV [10]). However, all the QMA resonances have larger widths and smaller amplitudes than the appropriate BR ones. The QMA data look like smoothed versions of the BR data. Absolute values of the BR data [8] and the Saclay QMA data [9] are close: integrated cross sections for the same integration limits are 36.90 and 34.52 MeV mb, respectively, but the Livermore QMA data [10] [(1.12–1.20) × 27.64 MeV mb] became close enough to the other two only after additional normalization (the factor 1.12 will be discussed later).

An additional example of discrepancies concerned is a detailed comparison [11] of resonances in the $^{18}O(\gamma, xn)$ reaction cross section obtained with BR [11] and QMA photons [12]: all the resonances have larger amplitudes ($\langle A_{BR}/A_{QMA}\rangle = 1.17$) and smaller widths ($\langle \Gamma_{QMA}/\Gamma_{BR}\rangle = 1.35$) in the BR cross sections than in the QMA cross sections. Integrated cross sections for the energy range 8–28 MeV are also different: $\sigma^{int}_{BR} = 187.12$ MeV mb and $\sigma^{int}_{QMA} = 167.33$ MeV mb (the ratio is again ∼1.12).

The general systematics[3)] [13] of the disagreements is shown in Fig. 2 for a special parameter named "structureness" that describes as a whole the deviation of each reaction cross section from its significantly smoothed value (with a smearing parameter Δ about 1 MeV) for the whole energy range D:

$$S = \frac{1}{N}\sum_{i=1}^{N}\frac{(\sigma_i - \langle\sigma_i\rangle)^2}{\langle\langle\sigma\rangle\rangle^2}, \qquad (3)$$

where

$$\langle\sigma_i\rangle = \frac{1}{\Delta}\int\limits_{E_i-\Delta/2}^{E_i+\Delta/2}\sigma(k)dk, \quad \langle\langle\sigma\rangle\rangle = \frac{1}{D}\int\limits_{D}\sigma(k)dk$$

are averaged cross sections.

In Fig. 2, the ratios S/S_L are presented, where S values are calculated for data from various laboratories, whereas S_L is for the Livermore QMA data (some other QMA data are used also). Data clearly separate into two groups: BR ($\langle S/S_L\rangle = 4.35$) and QMA ($\langle S/S_L\rangle = 1.22$). This means that, in all the QMA laboratories, an estimation of energy resolution using the width of the annihilation line (in many cases 250–400, sometimes 500, more rarely 150–300 keV) does not give a real resolution: the QMA cross sections are oversmoothed. This is confirmed by the value $\langle S/S_L\rangle = 4.22$ for data obtained in [14] using a tagged photon (TP) technique (the TP apparatus function is close to the Gauss shape).

Since in reality a QMA cross section (2) is only a yield (1), a real cross section can be obtained [15–18] only after an additional processing by the use of a real apparatus function and the reduction method [19, 20]. Actually, this is not a method of solving an inverse ill-posed problem (1) to unfold a cross section from a yield. The reduction method transforms data obtained with some experimental apparatus function (Fig. 1) into those which would have been measured

[3)] It contains more than 500 total photoneutron (γ, xn) cross sections for nuclei from ^3H to ^{238}U.

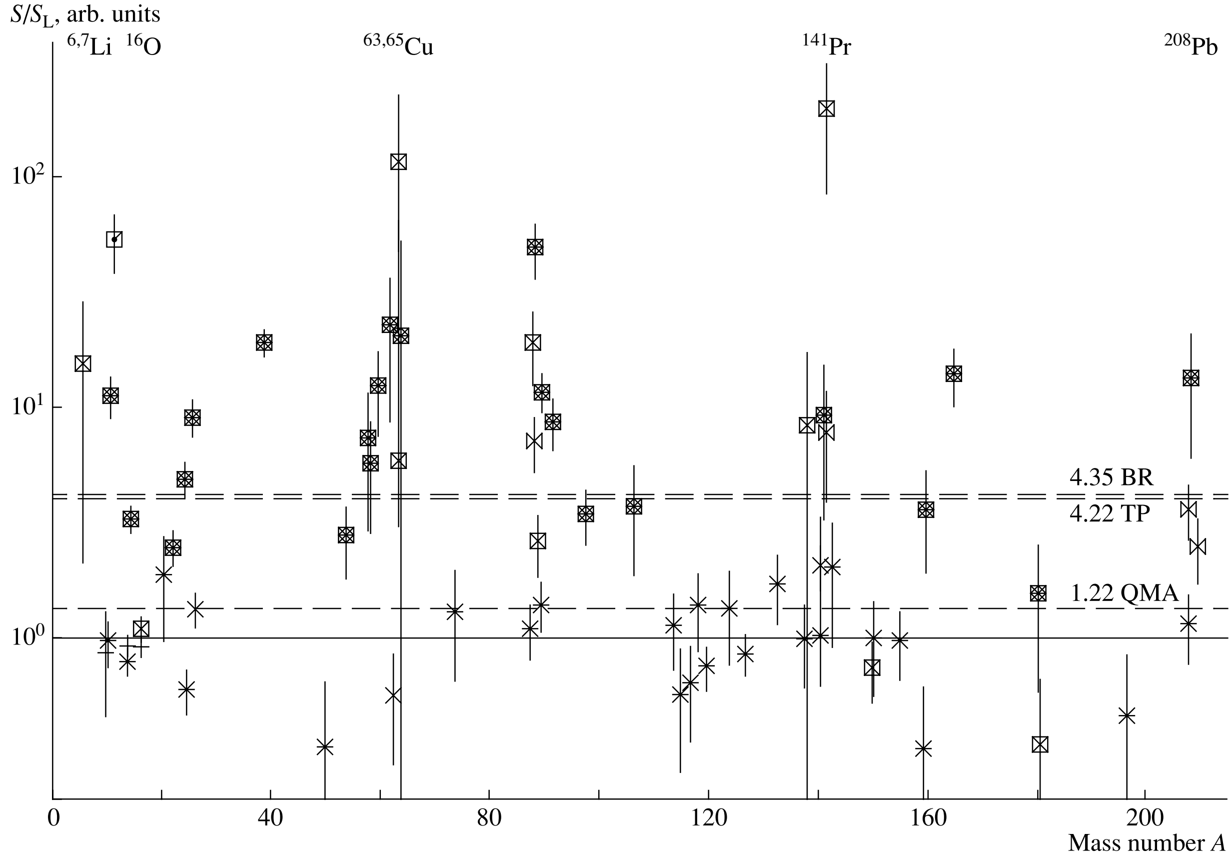

Fig. 2. The systematics of ratios S/S_L (see text) obtained for the total photoneutron reaction cross section data: BR data [(⊠) Moscow, (⊠) Melbourne (Australia), (⊡) other]; QMA data [(⋇) Saclay (France), (+) Giessen (Germany), (×) other]; TP data [(⋈) Illinois (USA)].

by means of an apparatus function of another quality (the better, e.g., the Gauss line with an exactly known energy resolution). As a result, one gets the most reasonably achievable monoenergetic representation of a reaction cross section from a reaction yield.

A reaction yield (1) measured using an apparatus function A and written in an operator form reads

$$y = A\sigma + \nu. \quad (4)$$

Then after the simple transformation

$$Ry = R(A\sigma + \nu) = U\sigma + (RA - U)\sigma + R\nu = \sigma^{\text{eval}} \quad (5)$$

with a special operator R [18, 19],

$$R = U(\Sigma^{-1/2}A)^{-}\Sigma^{-1/2} = U(A^{*}\Sigma^{-1}A)^{-}A^{*}\Sigma^{-1}, \quad (6)$$

it can be transformed into the evaluated cross section

$$\sigma^{\text{eval}} = Ry = U\sigma + R\nu, \quad (7)$$

which represents the "measured" cross section with the apparatus function U of a needed quality.

The main result of processing using the reduction method is that the structure of a QMA cross section became much clearer and closer to that of a BR cross section. This is seen after processing of the QMA results (Fig. 3*e*) for ^{63}Cu(γ, n) ^{62}Cu reaction [7] and a comparison for the same energy resolution of 210 keV of all three cross sections (2) obtained by the reduction method with the result of the BR experiment [21]. The inverse operation of smoothing of cross sections from Figs. 3*b*–3*d* gives [22] the real QMA result (Fig. 3*e*): the energy resolution is only ~1.3 MeV (i.e., 4 times worse than the estimated width of the annihilation line). The same processing of ^{197}Au(γ, xn) reaction data [23] gives a real resolution value of 1.6 MeV (i.e., 3 times worse than the declared one).

2.2. Magnitude of a Total (γ, xn) Reaction Cross Section (Absolute Value)

Integrated cross section data. There are definite discrepancies between absolute values of data obtained at different laboratories using both the BR

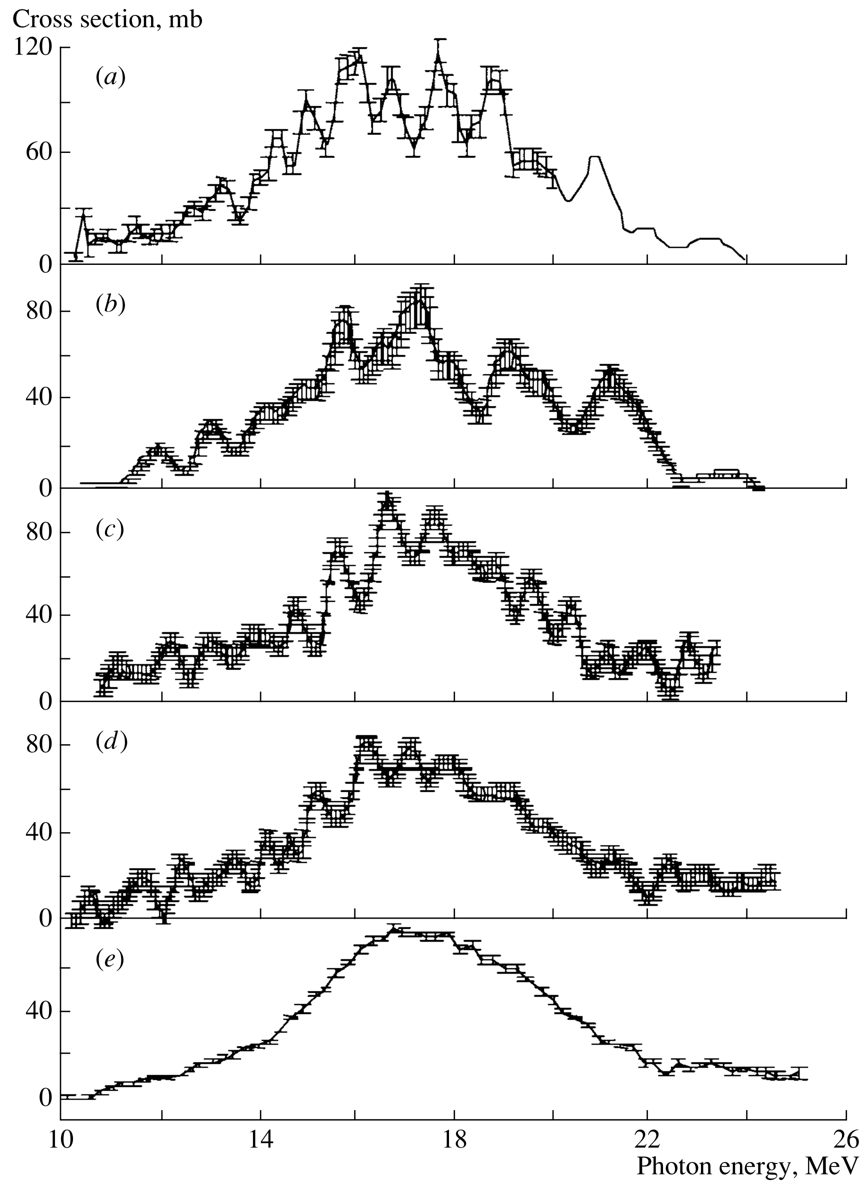

Fig. 3. Cross sections of ^{63}Cu$(\gamma,n)\,^{62}$Cu reaction obtained by various methods: (a) the BR experiment [21] (energy resolution 210 keV); (b) the result of processing of QMA yield (2) $Y_{e^-}(E_j)$ [7] (the method of reduction for energy resolution 210 keV); (c) the result of processing of QMA yield (2) $Y_{e^+}(E_j)$ [7] (the method of reduction for energy resolution 210 keV); (d) the result of processing of QMA yield difference (2) $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(k)$ [20] (the method of reduction for resolution 210 keV); (e) the published [7] QMA yield difference (2) $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(k)$ (the energy resolution 200–400 keV is declared).

and QMA photon beams. In addition to the data for ^{16,18}O presented above, other examples are presented in Table 1, where a comparison of the integrated QMA (γ, xn) reaction cross sections [1] from Livermore and Saclay is given. These four cases [1] are taken because of very close integration energy limits $E_\gamma^{\max}$ or vise versa—integrated cross section values $\sigma^{\rm int}$ (many other similar discrepancies can be found in [1] as well). One can easily estimate that, in all cases, the values from the Saclay experiments are higher than those from the Livermore ones by 6–16%.

A systematics of integrated cross sections. A systematics of ratios of integrated cross sections was obtained [13, 15, 16] for (γ, xn) reaction cross sections measured for energy ranges of incident photons between the thresholds of (γ, n) and $(\gamma, 2n)$ reactions. Specially calculated ratios $R^{\rm int}_{\rm syst} = \sigma^{\rm int}_{\rm var.lab}(\gamma, xn)/\sigma^{\rm int}_{\rm L}(\gamma, xn)$ of data from various laboratories to that from Livermore are presented in

Table 1. Comparison of the experimental QMA data on integrated (γ, xn) cross sections from Saclay (upper values) and Livermore (lower values)

Nucleus	^{51}V	^{75}As	^{90}Zr	^{165}Ho
$(E_\gamma^{\rm int})^{\rm max}$ [MeV]	27.8/27.8	26.2/29.5	25.9/27.6	26.8/28.9
$\sigma_{\rm S}^{\rm int}/\sigma_{\rm L}^{\rm int}$	$689/654 = 1.06$	$1306/1130 \geq 1.16$	$1309/1158 \geq 1.13$	$3667/3385 \geq 1.08$

Table 2. Recommended [23] normalization factors F to improve agreement of the Saclay and Livermore data

Nucleus	Rb	^{89}Sr	^{89}Y		^{90}Zr		^{91}Zr	^{92}Zr	^{93}Nb	^{94}Zr	^{127}I	^{197}Au	^{206}Pb	^{207}Pb	^{208}Pb		^{209}Bi
Lab.	S	S	S	L	S	L	L	L	S	L	S	S	L	L	L	S	L
F	0.85 ± 0.03	0.85 ± 0.03	0.82	1.0	0.88	1.0	1.0	1.0	0.85 ± 0.03	1.0	0.8	0.93	1.22*	1.22*	1.22*	0.93	1.22*

* The Livermore data increasing instead of the Saclay data decreasing.

Fig. 4. The results definitely confirm that, as a rule, the Livermore cross sections are smaller than the others: the values $R_{\rm syst}^{\rm int}$ are concentrated near the mean value $\langle R_{\rm syst}^{\rm int}\rangle = 1.12$ (just mentioned above). The QMA data from Saclay are more consistent with the data (both QMA and BR) of other laboratories.

Absolute values of reaction cross sections. Cross sections of photonuclear reactions on nuclei $^{\rm nat}$Zr, ^{127}I, ^{141}Pr, ^{197}Au, and $^{\rm nat}$Pb measured earlier at Livermore have been specially remeasured [24]. Remeasured data were used for a detailed comparison of absolute values of photoneutron cross sections in 14 nuclei (Table 2) with the aim to solve the evident problem of appreciable discrepancies between the data of different laboratories, primarily Livermore and Saclay. It was pointed out that "this comparison implies the Livermore experiment error either in the photon flux determination or in the neutron detection efficiency or in both." The major recommendations to put data into consistency were somewhat dual: (i) to decrease the Saclay data for various nuclei by factor $F = 0.8$–0.93 (Table 2); (ii) to increase the Livermore data for ^{206,207,208}Pb and ^{209}Bi (indicated by asterisks) by a factor of 1.22 to achieve agreement with data from experiments with tagged photons [14].

3. DISCREPANCIES BETWEEN CROSS SECTIONS OF PARTIAL PHOTONEUTRON REACTIONS (γ, n) AND $(\gamma, 2n)$ OBTAINED WITH QMA PHOTONS AT SACLAY AND LIVERMORE

Besides the discrepancies in $(\gamma, xn) = (\gamma, n) + (\gamma, np) + 2(\gamma, 2n)$ cross sections, there are certain discrepancies between cross section values of partial reactions (γ, n) and $(\gamma, 2n)$ [1]. It was found for 12 nuclei (^{89}Y, ^{115}In, ^{117,118,120,124}Sn, ^{133}Cs, ^{159}Tb, ^{165}Ho,^{181}Ta, ^{197}Au, ^{208}Pb) [25] that, while the integrated (γ, n) cross section from Saclay is higher than that from Livermore, the integrated $(\gamma, 2n)$ cross section is lower (Table 3). For example, the (γ, xn) data from Livermore and Saclay for the nucleus ^{159}Tb differ [1] only by 6%, but the (γ, n) data from Saclay are 37% higher than the corresponding Livermore data [25]. At the same time, the $(\gamma, 2n)$ data are lower by 47%.

These data were accurately recalculated [26] and supplemented with similar data for the other seven nuclei (^{51}V, ^{75}As, ^{90}Zr, ^{116}Sn, ^{127}I, ^{232}Th, ^{238}U). The complete systematics of integrated cross section ratios (Saclay/Livermore) for 19 nuclei is presented in Fig. 5. As a rule, the ratios of the (γ, n) data (squares) are noticeably larger than 1.0, but those for the $(\gamma, 2n)$ reaction (triangles) are less. On the basis of a detailed comparison [25] of (γ, n) and $(\gamma, 2n)$ data with the data from (e, n) and $(e, 2n)$ reactions measured for ^{181}Ta using both the neutron multiplicity sorting and the residual activity measurement methods [27–29], it was shown that discrepancies are produced by the difference in the neutron multiplicity sorting procedure. The Saclay procedure was not correct, and therefore the $(\gamma, 2n)$ data were underestimated [some events were interpreted as (γ, n) ones]. Correspondingly, the data for the (γ, n) reaction were overestimated.

The method to correct data [25, 26] is very simple and clear. Since $(\gamma, xn) = (\gamma, n) + 2(\gamma, 2n)$, the ratio $R = \sigma_{\rm S}(\gamma, xn)/\sigma_{\rm L}(\gamma, xn)$ must be used for joint correction of data from Saclay and Livermore. With this factor, one obtains the following expression of the corrected Saclay $(\gamma, 2n)$ cross section $\sigma_{\rm S}^*(\gamma, 2n)$:

$$R\sigma_{\rm L}(\gamma, 2n) = \sigma_{\rm S}^*(\gamma, 2n) = \sigma_{\rm S}(\gamma, 2n) \quad (8)$$

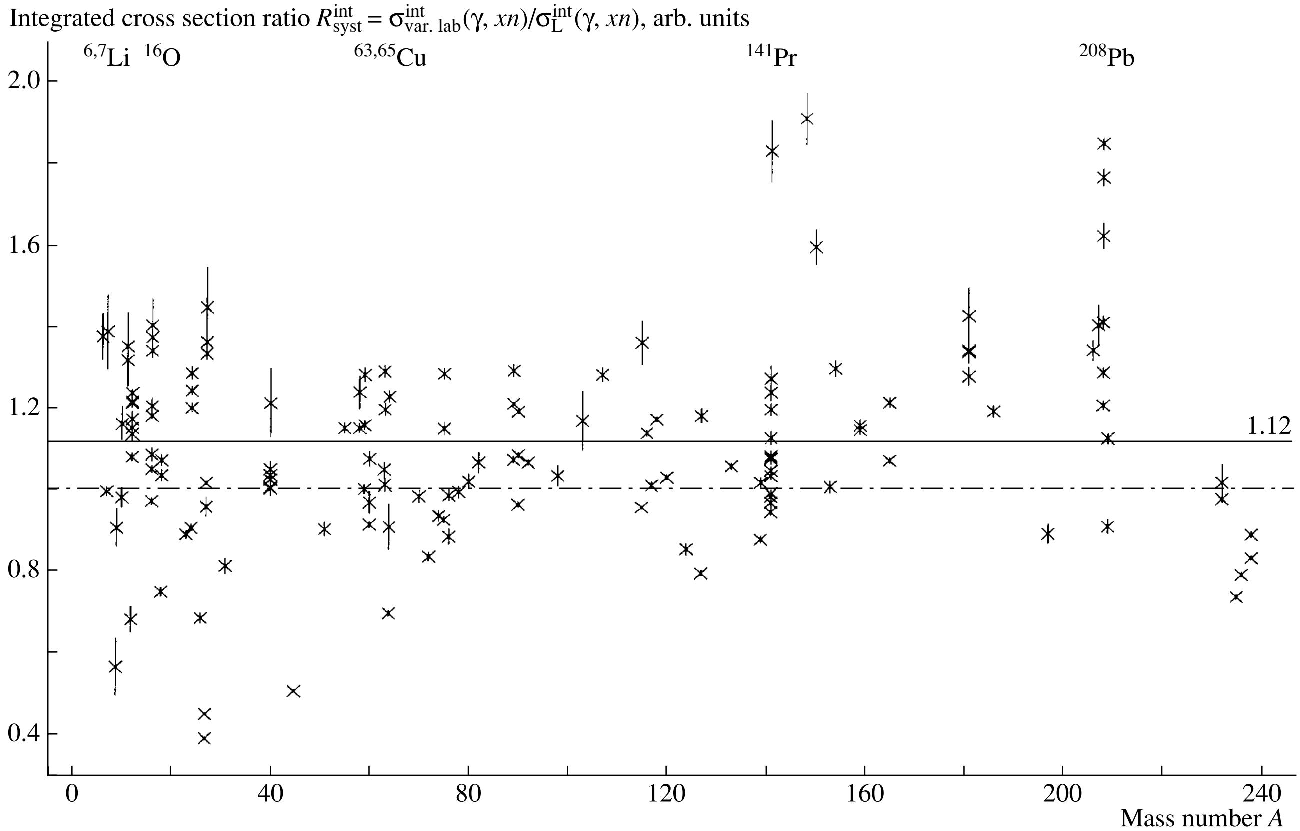

Fig. 4. The complete systematics [13, 15, 16] of ratios $R^{int}_{syst} = \sigma^{int}_{var.lab}(\gamma, xn)/\sigma^{int}_{L}(\gamma, xn)$ of the total integrated cross sections of photoneutron reaction in various nuclei obtained with various photon beams at various laboratories and with QMA photons at Livermore. The cross sections are calculated up to thresholds of $(\gamma, 2n)$ reaction. Solid line—the mean value $\langle R^{int}_{syst}\rangle = 1.12$; dashed line—$R^{int}_{syst} = 1.0$.

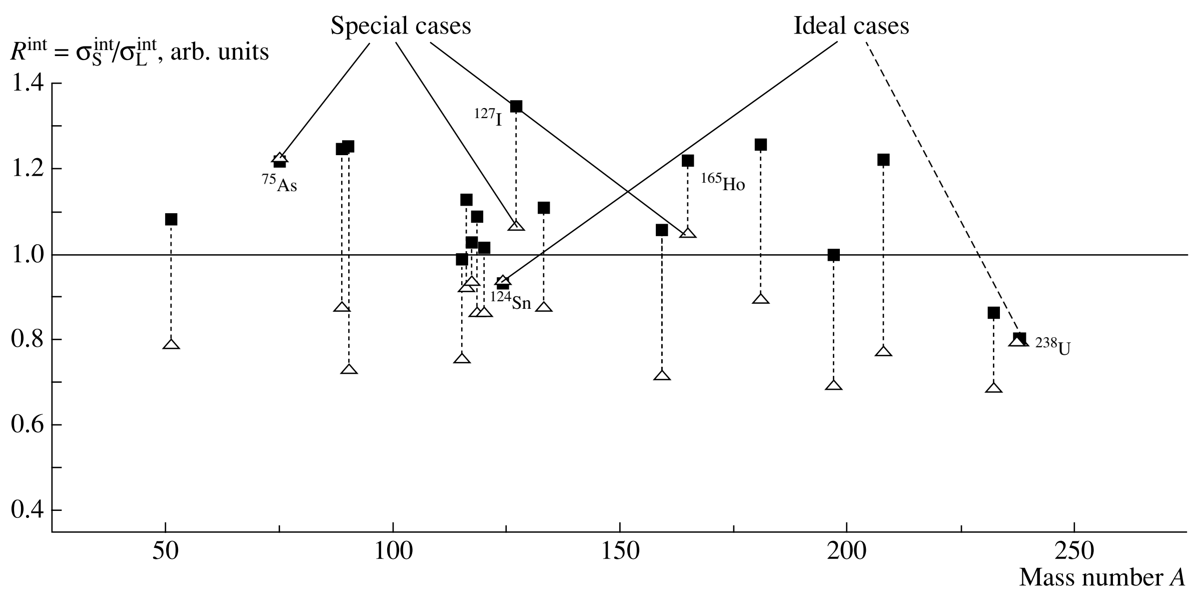

Fig. 5. The systematics [26] of values $R^{int}(n) = \sigma^{int}_{S}(\gamma, n)/\sigma^{int}_{L}(\gamma, n)$ (■) and $R^{int}(2n) = \sigma^{int}_{S}(\gamma, 2n)/\sigma^{int}_{L}(\gamma, 2n)$ (△). Special cases—$(\gamma, 2n)$ cross section ratios are more than 1.0. Ideal cases—(γ, n) and $(\gamma, 2n)$ cross section ratios are near. Special cases and ideal cases were processed individually [26].

$$+\frac{1}{2}(\sigma_{\rm S}(\gamma,n) - R\sigma_{\rm L}(\gamma,n)).$$

Expression (8) reflects the main idea described above: a part of the Saclay (γ, n) cross section $(\sigma_{\rm S}(\gamma,n) - R\sigma_{\rm L}(\gamma,n))/2$ is added ("transmitted back") to the Saclay $(\gamma, 2n)$ cross section $\sigma_{\rm S}(\gamma, 2n)$. The Saclay (γ, n) cross section can be corrected by subtraction of the $R\sigma_{\rm L}(\gamma, n)$ cross section for energies higher than the threshold of the $(\gamma, 2n)$ reaction. At the same time, the left part of (8) means that the recalculated cross section $\sigma^*_{\rm S}(\gamma, 2n)$ must agree with the Livermore $(\gamma, 2n)$ cross section multiplied by R, i.e., must be equal to $R\sigma_{\rm L}(\gamma, 2n)$.

The corrected cross section ratios for all 19 nuclei (Table 3) together with the integrated cross sections are presented in [26]. As an example, in Fig. 6, we show results of the joint correction of the Saclay and Livermore data for ^{208}Pb.

4. SUMMARY: MODERN STATUS OF WELL-KNOWN DATA

4.1. Important Conclusions

The problems discussed above clarify the "modern" status of well-known published photonuclear data. The value, accuracy, and reliability of all data could be understood only after a special analysis of systematic disagreements, which depend on the explored experimental method. The "modern" status of data under discussion means the following:

Owing to obvious discrepancies between various data, they should be used with caution and strongly individually; special attention has to be paid to the experimental method and data processing procedure explored in every particular case.

The QMA data are strongly oversmoothed (its real energy resolution is a factor of 3–4 worse than the declared one) in comparison with the BR data. The QMA data must be reprocessed using either the reduction method (4)–(7) or a similar one to take into account the real (not enough local) shape of an apparatus function (an effective photon spectrum).

The absolute values of (γ, xn) cross sections measured with the QMA photons at Livermore in general are smaller than those measured with the BR and QMA photons at various other laboratories. As a result, the data on (γ, xn) cross sections from Livermore for 19 nuclei listed above [26] must be corrected; i.e., they should be multiplied by appropriate coefficients $R^{\rm int}(\gamma, xn) = R^{\rm int}(\gamma, n) = \sigma^{\rm int}_{\rm S}(\gamma,n)/\sigma^{\rm int}_{\rm L}(\gamma,n)$ (Table 3), and for other nuclei, by $\langle R^{\rm int}_{\rm syst}\rangle = 1.12$ [13, 15, 16], at least.

Cross sections of the partial photoneutron reactions (γ, n) and $(\gamma, 2n)$ from Saclay experiments are not correct due to exploiting an incorrect neutron multiplicity sorting procedure. They should be recalculated with expression (8).

Table 3. Ratio of integrated cross sections of (γ, n) and $(\gamma, 2n)$ reactions before [1, 25] and after [26] correction

Nucleus	$\sigma^{\rm int}_{\rm S}(\gamma,n)/\sigma^{\rm int}_{\rm L}(\gamma,n)$ [both — MeV mb]		$\sigma^{\rm int}_{\rm S}(\gamma,2n)/\sigma^{\rm int}_{\rm L}(\gamma,2n)$ [both — MeV mb]	
	Before [1, 25]	After [26]	Before [1, 25]	After [26]
^{51}V	1.07*	1.00	0.79*	0.98
^{75}As	1.21*	1.00	1.22*	1.01
^{89}Y	1.33	1.00	0.75	1.05
^{90}Zr	1.26*	0.93	0.73*	1.05
^{115}In	1.09	1.00	0.55	1.02
^{116}Sn	1.10*	1.00	0.92*	0.98
^{117}Sn	0.97	1.00	0.46	0.96
^{118}Sn	1.06	1.00	0.49	0.93
^{120}Sn	0.99	1.00	0.59	0.97
^{124}Sn	0.82	1.00	0.75	1.02
^{127}I	1.34*	1.00	1.07*	0.99
^{133}Cs	1.24	1.00	0.65	1.04
^{159}Tb	1.37	1.00	0.68	0.94
^{165}Ho	1.20	1.00	1.03	1.03
^{181}Ta	1.68**	1.00	0.90	0.93
^{197}Au	1.18	1.00	0.62	1.06
^{208}Pb	1.54**	1.00	0.38	0.98
^{232}Th	0.84*	1.00	0.69*	0.94
^{238}U	0.81*	1.00	0.80*	1.01

* New data from [26].

** Incorrect initial data used.

The Livermore neutron multiplicity sorting procedure is correct. Therefore, the Livermore (γ, n) and $(\gamma, 2n)$ cross sections are consistent with each other as well as with (γ, xn) cross sections, and both sets can be used, but again only after multiplication by coefficients $R^{\rm int}(\gamma, xn)$ or $\langle R^{\rm int}_{\rm syst}\rangle$.

4.2. Important Physical Consequences

The most important physical consequences are the following:

An intermediate GDR structure (peaks with widths on the order of hundreds of keV) exists; the BR data seem to be preferable for detailed study

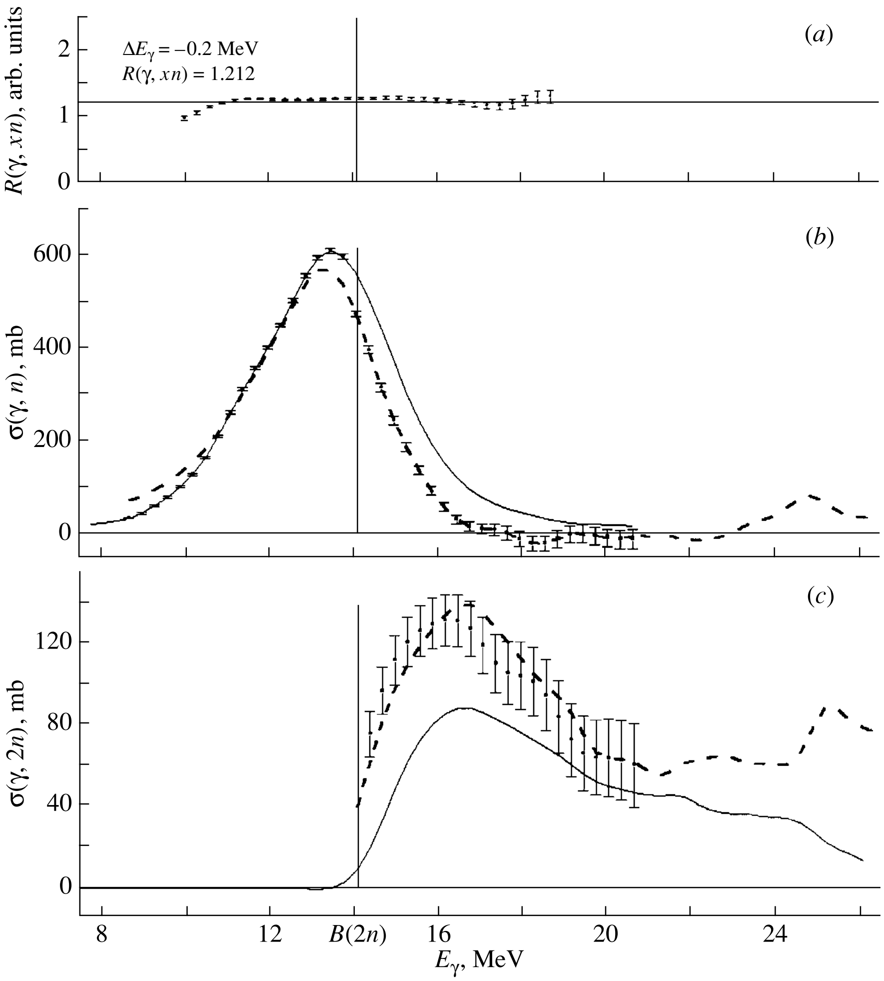

Fig. 6. Results of a joint correction [26] of the total and partial cross sections of photoneutron reactions for ^{208}Pb obtained at Saclay and Livermore: (a) ratios $R(E_\gamma)$ for (γ, xn) reaction cross sections; ΔE_γ and $R(\gamma, xn)$ are presented; (b) (γ, n) cross section [(solid curve) the initial Saclay data $\sigma_{\mathrm{S}}(\gamma, n)$, (dots with error bars) the Saclay evaluated (8) data $\sigma^*_{\mathrm{S}}(\gamma, n)$, (dashed curve) the Livermore evaluated data $R\sigma_{\mathrm{L}}(\gamma, n)$]; ($c$) $(\gamma, 2n)$ reaction cross section data [(solid curve) the initial Saclay data $\sigma_{\mathrm{S}}(\gamma, 2n)$, (dots with error bars) the Saclay evaluated data $\sigma^*_{\mathrm{S}}(\gamma, 2n)$, (dashed curve) the Livermore evaluated data $R\sigma_{\mathrm{L}}(\gamma, 2n)$].

of the GDR structure because the QMA data are strongly oversmoothed. The energy resolution $\sim$ 1.3–1.6 MeV does not allow one to investigate properly the properties of resonance substructures having smaller width. An additional processing of the QMA data reveals that the GDR structure is close to that obtained from the BR data.

It appears that a statistical branch dominates a decay of GDR; the Saclay interpretation [30–33] of high-energy tails of (γ, n) cross sections as a contribution of high-energy neutrons from the GDR nonstatistical decay (this contribution is evaluated to be about 17–30%) seems to be very doubtful because of a small decrease in (γ, n) cross sections at energies higher than the $(\gamma, 2n)$ reaction threshold $B(2n)$; the corrections to the Saclay (γ, n) cross sections discussed above reduce them and put them in agreement with the Livermore data; i.e., the direct decay contribution is not more than 10–12%.

A large extravalue of the integrated cross section $\sigma^{\mathrm{int}}(\gamma, \mathrm{abs}) \approx (1.3\text{–}1.5) \cdot 60NZ/A$ (MeV mb) becomes questionable, being totally due to changing of the effective nucleon mass because of an influence of exchange forces [30–33]; errors in the Saclay procedure of neutron multiplicity sorting seriously affect the corresponding results for the total photoabsorption cross section evaluated by the use of the following combinations of cross section data: $(\gamma, \mathrm{abs}) = (\gamma, sn) + (\gamma, p)$ and $(\gamma, sn) = (\gamma, xn) - (\gamma, 2n)$; it is obvious that errors in $(\gamma, 2n)$ reaction data produce errors in both the (γ, sn) and the (γ, abs) reaction data; the corresponding corrections reduce their values.

Some of the disagreements in the experimental data can be overcome by exploring methods similar to that described in the present paper; up to now, many data have been analyzed, evaluated, and put into consistency. However, new intensive really monoenergetic photon beams (High Intensity Gamma Source—HIGS [34] or similar) combined with effective measurement methods of photon flux, detector efficiency, neutron multiplicity sorting, etc., are needed to obtain really accurate and reliable experimental data for both shapes and magnitudes of total and partial cross sections of photoneutron reaction and photoabsorption, especially for medium and heavy nuclei.

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