GIANT DIPOLE RESONANCE: WHAT IS KNOWN ABOUT?

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Introduction

It is well-known that photonuclear reaction data are very important for such basic research as investigations of structure and dynamic of atomic nucleus and nuclear reaction mechanisms. Moreover many photonuclear reaction data are widely used for variety of applications (radiation shielding design, radiation transport analysis, activation analysis, astrophysical nucleosynthesis, safeguards and inspection technologies, human body radiotherapy absorbed dose calculation, etc.). Various features of photonuclear reactions are needed, but reaction cross section energy dependence (excitation function - probability of interaction of definite energy photons with nucleus) is the most important.

Absolute majority of photonuclear reaction cross section data have been obtained /1 – 4/ in two different type experiments using electron bremsstrahlung and quasimonoenergetic photons produced by annihilation in flight of relativistic positrons. Unfortunately there are many clear systematical disagreements both in shape and magnitude between data obtained in different experiments. Very shortly the main of them can be described as following: as a rule reaction cross sections obtained in quasimonoenergetic annihilation (QMA) experiments in comparison with that obtained in bremsstrahlung (BR) experiments looks like as much more smooth and smaller. Additionally the disagreements between the same type experiments data certainly exist also. These disagreements are systematical certainly: they very clear depend on the experimental method used.

Though majority of photonuclear reaction cross section data has been obtained quite long ago they are included into the modern databases /5/ and extensively used till now. Therefore modern status of photonuclear research as whole and accuracy and reliability of each data obtained can be understandable only on the analysis of systematical disagreements and of the ways to take them into account.

The big databases developed /6/ give to one possibility for systematical overview of all data collected.

1. Two main types of photonuclear experiments

1.1. Experiments with electron bremsstrahlung photons

Historically first measurements have been carried out using beams of photons from electron bremsstrahlung. The experiments of this type were carried out at many laboratories, but majority of them - at Moscow State University (Moscow, Russia), Russia Academy of Science Institute of Nuclear Research (Moscow, Russia), Melbourne University (Australia).

Bremsstrahlung spectrum is continuous and therefore not direct reaction cross section was measured in experiment but only reaction yield - cross section folded with photon spectrum:

$$Y(E_{jm}) = \frac{N(E_{jm})}{\varepsilon D(E_{jm})} = \alpha \int_{Eth}^{Ejm} W(E_{jm},k)\sigma(k)dk, \tag{7}$$

where $\sigma(k)$ is cross section value at photon energy k of reaction with threshold E_{th};

$W(E_{jm},k)$ is electron bremsstrahlung spetrum;

$N(E_{jm})$ reaction event number;

$D(E_{jm})$ bremsstrahlung dose;

ε detector efficiency;

α normalization constant.

The information on cross section σ is obtained from the experimental yield Y using one of special mathematician methods ("photon difference", "inverse matrix", Penfold-Leiss (with constant or variable bins), "Cook least structure", "Tikhonov regularization", etc.). All of them have been developed specially to produce the effective photon spectrum (experiment apparatus function) that looks like (Fig. 1) as quite enough monoenergetic function (line).

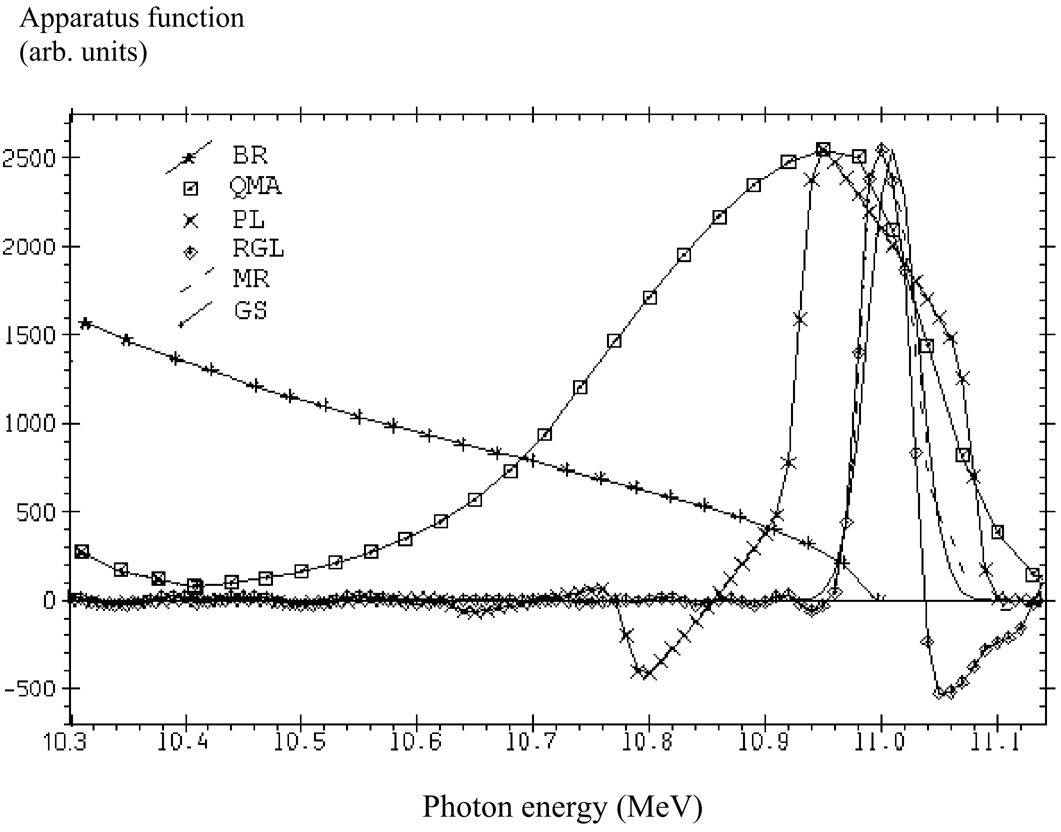

Fig. 1. Various methods of photonuclear reaction cross section obtaining methods apparatus functions (photon effective spectra):

BR	electron bremsstrahlung (example for end-point energy E_γ^{max} = 11 MeV);
QMA	QMA-photons spectrum (annihilation line width – 350 keV);
PL	Penfold-Leiss method (data processing bin – 100 keV);
RGL	Tikhonov regularization method (data processing bin – 50 keV);
MR	method of reduction (energy resolution – 50 keV);
GS	Gauss line with width (FWHM) 50 keV.

It must be pointed out that for this type of experiments:

- apparatus function is constructed as enough narrow line independently of experiment conditions; moreover experimentalists try to carry out experiment for conditions clear to those used in apparatus function calculations;
- spectrum of quasimonoenergetic photons in various methods is obtained by various special procedures each of that can be interpreted as “specific difference”;
- apparatus function has complex (not ideal, for example, Gauss line) shape that can produce some additional uncertainties in cross section shape, magnitude and position.

1.2. Experiments with quasimonoenergetic photons obtained by annihilation in flight of relativistic positrons

As an alternative to procedure of solving inverse ill-post problem (7) the method of quasimonoenergetic photons obtaining by annihilation in flight of relativistic positrons has been developed. This method consists in producing a quasimonoenergetic annihilation photons with energy E_γ

= E_{e+} + 0.76 MeV (3/4 of the rest mass of the annihilating pair) by fast positrons that strike a thin, low – Z target. The facilities have been constructed at several laboratories in USA, France and Germany, but majority of data has been obtained at USA National Lawrence Livermore Laboratory and at France Centre d'Etudes Nucleaires de Saclay.

Because annihilation photons always are accompanied by positron bremsstrahlung, experiment is carried out by three steps:

1) measurement of the reaction yield $Y_{e+}(E_j)$ - event number N^+ (7) of the reaction under the action of photons from positron both bremsstrahlung and annihilation;
2) measurement of the reaction yield $Y_{e-}(E_j)$ - event number N^- (7) of the reaction under the action of photons from electron bremsstrahlung;
3) subtraction (under appropriate normalization and with assumption that bremsstrahlung spectra are identical for electrons and positrons)

$$Y_{e+}(E_j) - Y_{e-}(E_j) = Y(E_j) \approx \sigma(k) \qquad (8)$$

and interpretation of that difference as reaction cross section under investigation.

It must be pointed out that for this type of experiments:

- there are no beam of quasimonoenergetic photons; spectrum of those photons is obtained as difference: "positron bremsstrahlung + annihilation" – "electron bremsstrahlung";
- in each concrete experiment apparatus function (Fig. 1) is obtained individually because it directly depends on conditions of both measurement results (yields - $Y_{e+}(E_j)$, $Y_{e-}(E_j)$) and their normalization and subtraction procedures;
- because positron annihilation in flight occurs in many steps (bremsstrahlung production from high-energy electrons strike a thick, high-Z converter ($e^- + A \rightarrow A + e^- + \gamma$); pairs production by bremsstrahlung photons ($\gamma + A \rightarrow A + e^- + e+$); positron annihilation in thin, low-Z target ($e+ + e- \rightarrow 2\gamma$)) number of quasimonoenergetic photons, measured yields statistical accuracy, and hence normalization accuracy are small;
- because of all things mentioned the apparatus function of this type experiment has very complex shape and be spread in wide energy range; therefore the result (8) is not the cross section really but the yield only again; cross section obtaining demands additional processing using real apparatus function.

2. Main disagreements of reaction cross sections obtained using BR- and QMA-photons

Things described show that the conditions of two type experiments under discussion are quite different. So it is not so surprisingly that as soon as first results can be compared have been obtained in both type experiments the significant disagreements were found out both in shape and value of identical reactions cross sections. It is very important to point out that the differences between experimental cross sections are bigger (in many cases much more) than statistical uncertainties.

2.1. Disagreements of total photoneutron reaction cross sections (γ,xn)

2.1.1. Shape (structure, resolution)

The detailed comparison of total photoneutron reaction cross sections $^{16}O(\gamma,xn)$ obtained in one BR- /7/ and two QMA-experiments /8, 9/ are presented on Fig. 2. There are well-separated powerful resonances in all three cross sections obtained with enough high energy resolution (/7/ - 200 keV, /8/ - 180 – 200 keV and /9/ - 200 – 300 keV). But one can see that though all clear maxima and minima are presented in all three cross sections, all resonances differ both in shave and value: all QMA-resonances have larger widths and smaller amplitudes than appropriate BR-ones.

It is important to point out that absolute values of BR-data /7/ and QMA-data of Saclay /8/ are close: integrated cross sections for the same integration limits are 36.90 34.62 MeV•mb (QMA-data looks like smoothed versions of BR-data). At the same time QMA-data of Livermore /9/ became close 31.01 (1.12•27.64) MeV•mb to both mentioned only after additional normalization (factor 1.122 will be discussed later).

Additional numerical example of discrepancies concerned could be obtained from the detailed comparison /10/ of ^{18}O(γ,xn) reaction cross sections for obtained using BR- /10/ (University of Melbourne, Australia) and QMA-photons /11/ (Livermore). Despite authors /10/ say about good agreement between experimental data, it is very clear that almost all resonances have larger amplitudes (resonance amplitude ratio mean value $<A_{BR}/A_{QMA}> = 1.17$) and smaller widths (resonance width ratio mean value $\Gamma_{QMA}/\Gamma_{BR}> = 1.35$) in

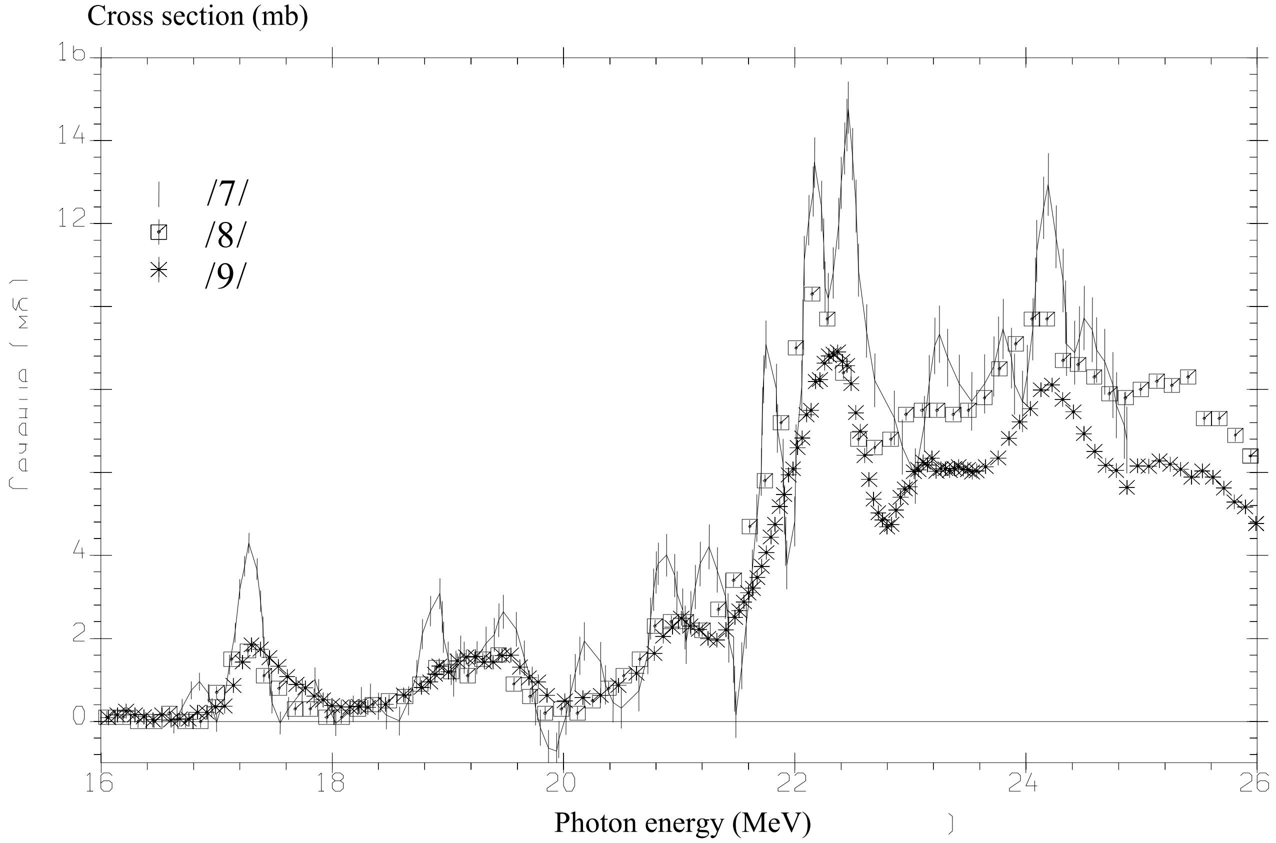

Fig. 3. The comparison of total photoneutron reaction cross sections ^{16}O(γ,xn) obtained in one BR-experiment (Moscow State University) /7/ and two typical QMA-experiments /8, 9/, carried out at Saclay (France) and Livermore (USA).

BR- than in QMA-photon cross sections. Moreover the integrated cross section values for incident photons energies 8 – 28 MeV are different also: $\sigma^{int}_{BR} = 187.12$ MeV•mb and $\sigma^{int}_{QMA} = 167.33$ MeV•mb (corresponding ratio is close to 1.12 again).

The general systematics of such kind disagreements is shown on Fig. 3 for special parameter "structureness" that describes as whole the difference of each experimental cross section from itself but significantly (with resolution about 1 MeV) smoothed:

$$S = \frac{1}{N}\sum_{i=1}^{N}\frac{(\sigma_i - <\sigma_i>)^2}{<<\sigma>>^2}, \tag{9}$$

$$<\sigma_i> = \frac{1}{\Delta}\int_{E_i-\frac{\Delta}{2}}^{E_i+\frac{\Delta}{2}}\sigma(k)dk, \tag{10}$$

$$<<\sigma>> = \frac{1}{D}\int_{D}\sigma(k)dk, \tag{11}$$

where D is the complete energy region.

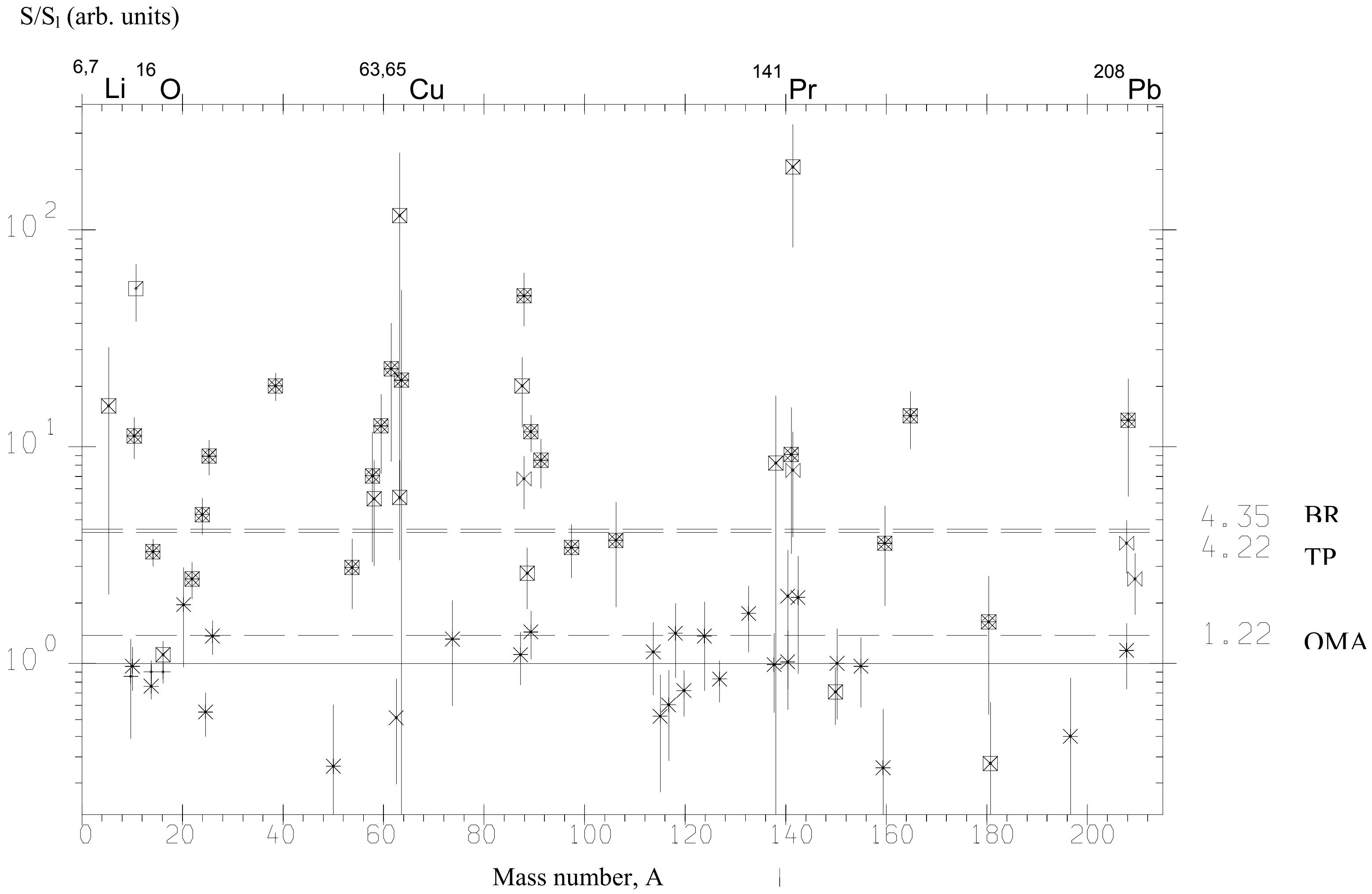

Fig. 3. Systematics of cross section "structurenes" **S/S$_l$** ratios obtained for total photoneutron reaction cross section data:

BR-data (⊠ - Moscow, ⊠ - Melbourne (Australia), □ - other);

QMA-data (✳ - Saclay (France), + - Giessen (Germany), × - other);

TP-data (⋈ - Illinois (USA)).

The ratios S/S_l are presented, where S were calculated for various laboratories data and S_l - for Livermore QMA-data (on cases when there were no Livermore data, S/S_s and S/S_g ratios were calculated using Saclay (France) and Giessen (Germany) data correspondingly). All data are separated very clear into two groups: BR-data (mean value $<S/S_l> = 4.35$) and QMA-data (mean value $<S/S_l> = 1.22$). This means that in all three QMA-laboratories (Livermore, Saclay, Giessen) estimation of energy resolution using calculated annihilation line width (in may cases 250 – 400 keV, sometimes 500 keV, more rarely 150 – 300 keV) do not give the real resolution: all QMA-cross sections are oversmothed. This is directly confirmed by the $<S/S_l> = 4.22$ value for data obtained /19/ at Illinois (USA) using tagged photons (TP-apparatus function is close to Gauss line).

As is following from that mentioned above QMA-cross sections in reality are not cross section namely, but only yields again – the foldings (1) of cross section with apparatus function and can be obtained only after additional processing (“unfolding” or “reduction” using real apparatus function. In many /12 - 16/ such kind processing the method of reduction /17, 18/ was used. Very shortly, that is not the method of solving inverse ill-posed problem (7) of cross section unfolding from yield. It just transforms the data obtained with some experimental apparatus function (Fig. 1) into the form those data would have being measured by means of apparatus function of other (better) quality, for example Gauss line with exactly known energy resolution. Thus using the method of reduction it is possible to find the most reasonably achievable monoenergetic representation for the reaction cross section using the reaction yield experimental data.

The reaction yield measured (7) using the apparatus function A is written in operator form

$$y = A\sigma + \nu \qquad (12)$$

and than using the simple transformation

$$Ry = R(A\sigma + \nu) = U\sigma + (RA - U)\sigma + R\nu = \sigma^{eval.} \qquad (13)$$

with the special operator /17, 18/

$$R = U(\Sigma^{-1/2}A)^{-}\Sigma^{-1/2} = U(A^{*}\Sigma^{-1}A)^{-}A^{*}\Sigma^{-1} \qquad (14)$$

is transformed into the evaluated cross section

$$\sigma^{eval} = Ry = U\sigma + R\nu \qquad (15)$$

that represents “the measurement” of cross section using needed quality apparatus function U.

The main result of investigations is that after such kind processing the structure (parameters of “structurenes”) of QMA-cross sections became much more closer to that obtained in BR-cross sections. As an example all three (two intermediate and one final (2)) typical QMA-results /20/ are presented on Fig. 4 and cross section data obtained using method of reduction from all three of them are compared on Fig. 5 with the result of typical BR-experiment /21/.

It must be pointed out that result presented on Fig. 5d was obtained after the processing of the QMA-result (Fig. 5e) to the representation with resolution (210 keV) very similar to that was declared by authors /20/. Moreover that result looks like very similar to that of for intermediate results (8) processing with the same resolution. Inverse operation of smoothing of Figs. 5b, c, d results gives /22/ that the real energy resolution of QMA-result (Fig. 5e) is only about 1.3 MeV (about 4 (!) times worse than was estimated using the width of calculated annihilation line in photon spectrum). Analogous processing /22/ of ^{197}Au(γ,xn) reaction data /23/ gives real resolution 1.6 MeV (3 times worse than declared).

2.1.2. Magnitude (absolute value)

Integrated Cross Section Data.

There are definite discrepancies between data obtained using the same method but at different laboratories. It’s true for experiments using both BR- and QMA-photons. For example the comparison of the integrated cross section data /1/ for QMA- total photoneutron (γ,xn) reaction cross sections obtained at Livermore (USA) and Saclay (France) is shown in Table 1. The only 5 cases /1/ for very close integration energy limits E_γ^{max} or vise versa integrated cross section values σ^{int} are presented (many other similar discrepancies exist /1/ but they are not look so evident because of large differences in the integration energy limits). One can easily estimate that in all of them the values obtained at Saclay are higher than that obtained at Livermore for about 10 – 15 %. For practically the same integration limits E_γ^{max} for ^{51}V the ratio $R^{int}_{exp}(\gamma,xn) = \sigma^{int}_S(\gamma,xn)/\sigma^{int}_L(\gamma,xn)$ is equal to 689/654 = 1.06. Because of $E_\gamma^{max}{}_S <$

$E_\gamma^{max}{}_L$ this ratio for ^{75}As is not less than 1306/1130 = 1.16, for ^{90}Zr - not less than 1309/1158 = 1.13, for ^{165}Ho – not less than 3667/3385 = 1.08. For ^{133}Cs this ratio is near 1 but for 5 MeV difference in range of integration.

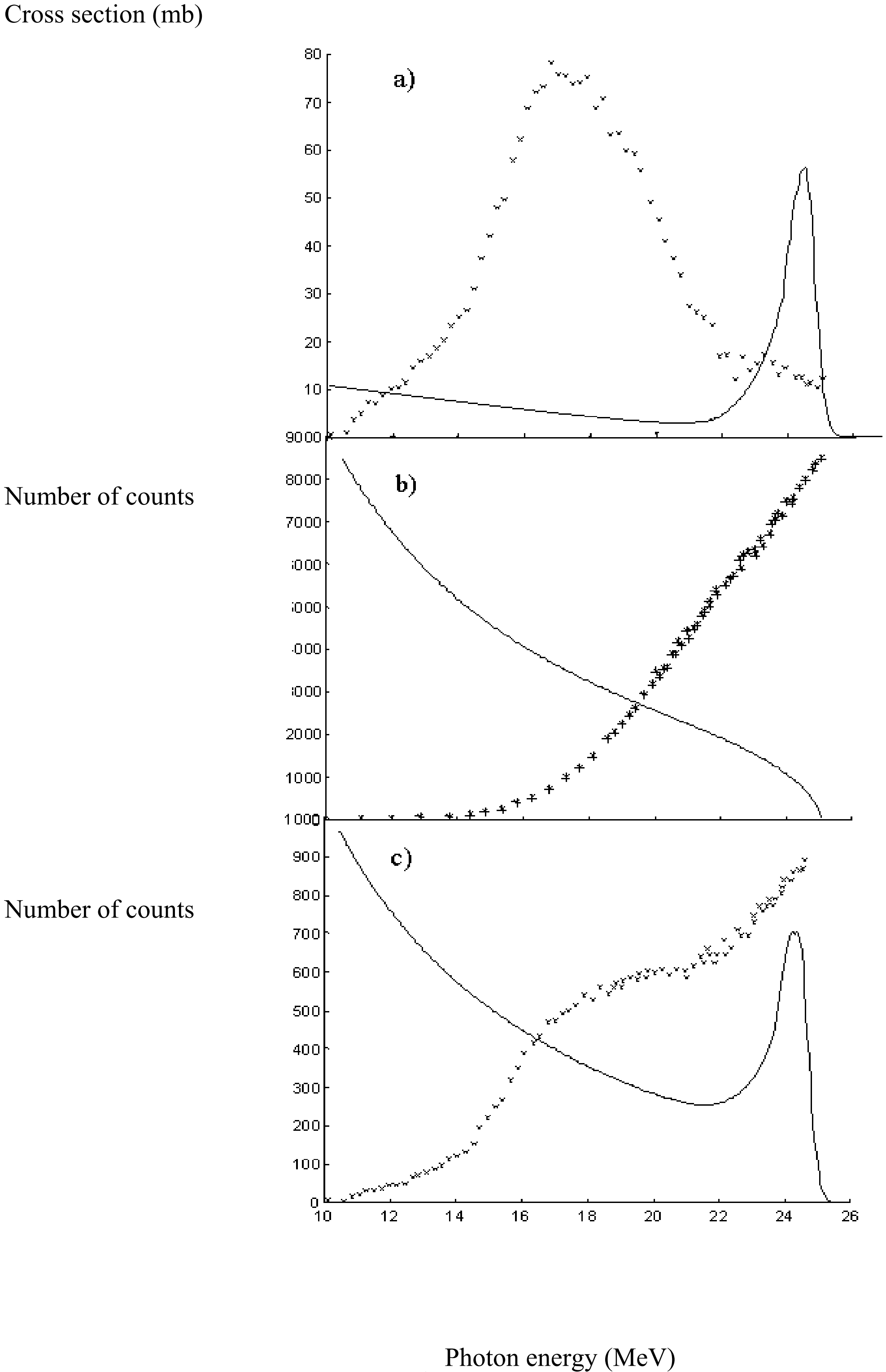

Fig. 4. Experimental yields /20/ of [illegible] and appropriate effective photon spectra (points):

a) yield difference $Y_{e+}(E_j)$ - Y_{e}-$(E_j) = Y(E_j) \approx \sigma(k)$ (2)) and difference between spectra of photons produced by positrons and electrons correspondingly;

b) yield Y_e-(E_j) and electron bremsstrahlung spectrum;

c) yield $Y_{e+}(E_j)$ and spectrum of photons produced by positrons (sum of bremsstrahlung and annihilation).

Cross section (mb)

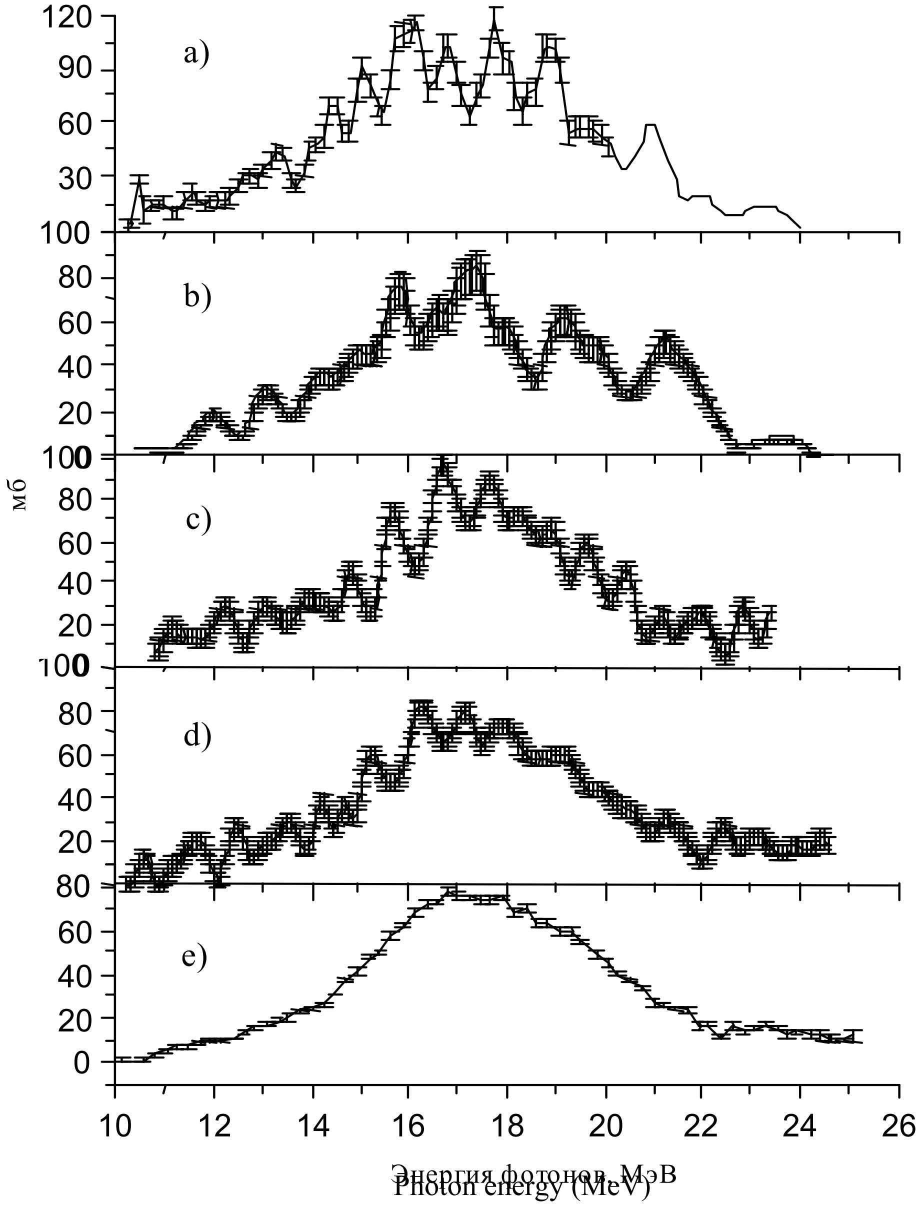

Fig. 5. ^{63}Cu(γ,n)^{62}Cu reaction cross sections obtained by various methods:

a) BR-experiment /21/ (energy resolution 210 keV);

b) result of processing of QMA-yield (2) $Y_e^+(E_j)$ /20/ (method of reduction for resolution 210 keV);

c) result of processing of QMA-yield (2) $Y_e^-(E_j)$ /20/ (method of reduction for resolution 210 keV);

d) result of processing of QMA-yield difference (2) $Y_{e+}(E_j)$ - Y_e-(E_j) = Y(E_j) ≈ σ(k) /20/ (method of reduction for resolution 210 keV);

e) published /20/ QMA-yield difference (2) $Y_{e+}(E_j)$ - Y_e-(E_j) = Y(E_j) ≈ σ(k) (resolution 200 - 400 keV is declared).

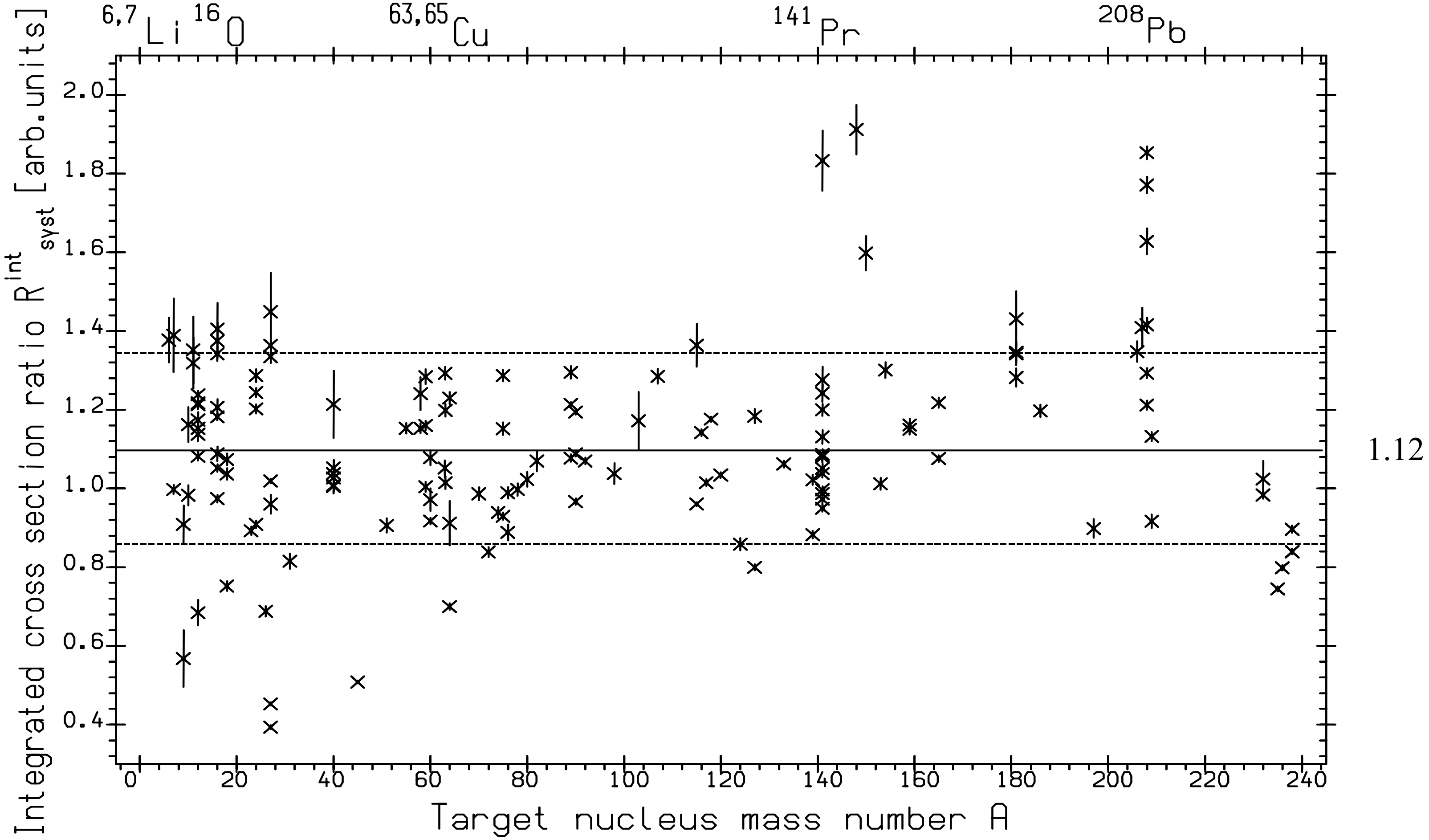

Fig.6. Complete $R^{int}_{syst} = \sigma^{int}_{various\ labs}(\gamma,xn)/\sigma^{int}_{Livermore}(\gamma,xn)$ systematics.

Table 1.
Comparison of QMA-experimental integrated (γ,xn) reaction cross section data of Saclay (top values) and Livermore (bottom values)

Nucleus	^{51}V	^{75}As	^{90}Zr	^{133}Cs	^{165}Ho
$E_{\gamma}^{\text{int-max}}$ (MeV)	27.8 27.8	26.2 29.5	25.9 27.6	*24.2* *29.5*	26.8 28.9
σ^{int} s/$\sigma^{\text{int.}}{}_{L}$	689/654 = 1.06	1306/1130 ≥ 1.16	1309/1158 ≥ 1.13	2484/2505 ≈ *1*	3667/3385 ≥ 1.08

Integrated Cross Section Data Systematics.

The complete systematic of integrated cross sections was obtained /15/ for number (more than 500) of (γ,xn) reaction cross section data for nuclei from ^{3}H to ^{238}U is presented on Fig. 6. To avoid additional errors connected with taking into account photoneutron multiplicity (details will be described later), the integrated cross sections for each nucleus were calculated for incident photon energy ranges between the (γ,n) and (γ,2n) reaction thresholds.

The ratio $R^{\text{int}}_{\text{syst}} = \sigma^{\text{int}}_{\text{various labs}}(\gamma,xn)/\sigma^{\text{int}}_{\text{Livermore}}(\gamma,xn)$ of the data from various laboratories to that from Livermore laboratory, is presented on Fig. 6. The data presented confirm clearly that systematical disagreements exist definitely: one can see that Livermore cross sections are smaller than others - the average value of ratio $\langle R^{\text{int}}_{\text{syst}}\rangle$ certainly is more than 1. In spite of some spreading of the $R^{\text{int}}_{\text{syst}}$ values obtained in various laboratories they are concentrated near the value $\langle R^{\text{int}}_{\text{syst}}\rangle = 1.122 \pm 0.243$. It must be pointed out that this value namely was used before in analysis of disagreements of total photoneutron reaction cross sections ^{16}O(γ,xn) data (Fig. 2).

It is very important to underline that (γ,xn) reaction cross section QMA-data obtained at Saclay in absolute values are more consistent with data of other laboratories obtained using both QMA-photons (at General Atomic, Pennsylvania, Illinois, and Giessen) and BR-photons (primarily at Moscow State University (Russia) and University of Melbourne (Australia)) than with Livermore QMA-data.

Reaction Cross Section Absolute Values.

The photoneutron reaction cross sections for nuclei $^{\text{nat}}$Zr, ^{127}I, ^{141}Pr, ^{197}Au, and $^{\text{nat}}$Pb obtained earlier at Livermore were specially remeasured /24/ in 1987. Data obtained were used for detailed comparison of absolute values of photoneutron reaction cross sections at 14 nuclei, to solve the evident problem of appreciable discrepancies between the data obtained at different laboratories, primarily Livermore and Saclay. The major recommendation was to introduce special normalization (multiplication) factor F for Saclay data presented in the Table 2.

Table 2.
Recommended /23/ normalization factors F to improve Saclay and Livermore data agreement

Nucleus	Laboratory	Factor F /23/ (arb. units)	Factor 1/F (arb. units)
$^{\text{nat}}$Rb	S	0.85 ± 0.03	
$^{\text{nat}}$Sr	S	0.85 ± 0.03	1.18
^{89}Y	S	0.82	1.22
^{89}Y	L	1.0	
^{90}Zr	S	0.88	1.14
^{90}Zr	L	1.0	
^{91}Zr	L	1.0	
^{92}Zr	L	1.0	
^{93}Nb	S	0.85 ± 0.03	1.18
^{94}Zr	L	1.0	
^{127}I	S	0.80	1.25
^{197}Au	S	0.93	1.08
^{206}Pb	L	1.22	
^{207}Pb	L	1.22	
^{208}Pb	L	1.22	
^{208}Pb	S	0.93	1.08
^{208}Bi	L	1.22	

For cases where data from two laboratories have been existed, the recommendation for improvement of data agreement was to decrease Saclay data by about 20%. In other cases (^{206,207,208}Pb, ^{209}Bi nuclei) the overall data improvement recommendation was opposite – to increase Livermore data by 22 %. As the main result of investigations carried out it was mentioned /24/ that "…this comparison implies an Livermore experiments error either in the photon flux determination or in the neutron detection efficiency or in both".

2.2. Disagreements of partial photoneutron reaction cross sections (γ,n) and (γ,2n) obtained at Saclay and Livermore using QMA-photons

Beside discrepancies in the total photoneutron reaction (γ,xn) = [(γ,n) + (γ,np) + 2(γ,2n)] cross sections there are also certain discrepancies for the same partial reaction cross section data obtained at various laboratories. This was revealed /25/ for 12 nuclei (^{89}Y, ^{115}In, ^{117,118,120,124}Sn, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb) in analysis of (γ,n) and (γ,2n) reaction cross section data /1/ obtained at Livermore and Saclay (Table 3). These data were accurately recalculated /26/ (more precisely calculated needed energy shift and normalization, some initial data substitutions) and added by analogous data for another 7 nuclei (^{51}V, ^{75}As, ^{90}Zr, ^{116}Sn, ^{127}I, ^{232}Th, ^{238}U).

Table 3.

Comparison of QMA-experiment integrated partial σ^{int}(γ,n) and σ^{int}(γ,2n) reaction cross section data /1/ (Saclay/Livermore) ratios and R^{int}(γ,xn) = σ^{int}_S(γ,xn)/σ^{int}_L(γ,xn).

Nucleus	σ^{int}_S(γ,n)/ σ^{int}_L(γ,n), /1, 25/ (= arb. units)	σ^{int}_S(γ,2n)/ σ^{int}_S(γ,2n), /1, 25/ (= arb. units)	R^{int}(γ,xn) /25/ (arb. units)	σ^{int}_S(γ,n)/ σ^{int}_L(γ,n), /26/ (arb. units)	σ^{int}_S(γ,2n)/ σ^{int}_S(γ,2n), /26/ (arb. units)	R^{int}(γ,xn) /26/ (arb. units)
^{51}V				1.07	0.79	1.07
^{75}As				1.21	1.22	1.21
^{89}Y	1279/960 = 1.33	74/99 = 0.75	1.26	1.25	0.87	1.25
^{90}Zr				1.26	0.73	1.26
^{115}In	1470/1354 = 1.09	278/508 = 0.55	0.94	0.97	0.76	0.97
^{116}Sn				1.10	0.92	1.10
^{117}Sn	1334/1380 = 0.97	220/476 = 0.46	1.01	1.02	0.93	1.02
^{118}Sn	1377/1302 = 1.06	258/531 = 0.59	1.06	1.07	0.86	1.07
^{120}Sn	1371/1389= 0.98	399/673 = 0.75	0.99	1.00	0.86	1.00
^{124}Sn	1056/1285 = 0.82	502/670 = 0.75	0.93	0.93	0.94	0.93
^{127}I				1.34	1.07	1.34
^{133}Cs	1828/1475 = 1.24	328/503 = 0.65	1.11	1.10	0.88	1.10
^{159}Tb	1936/1413 = 1.37	605/887 = 0.68	1.06	1.07	0.71	1.07
^{165}Ho	2090/1735 = 1.20	766/744 = 1.03	1.14	1.20	1.05	1.20
^{181}Ta	2180/1300 = 1.68	790/881 = 0.90	1.22	1.25	0.89	1.25
^{197}Au	2588/2190 = 1.18	479/777 = 0.62	1.00	1.00	0.69	1.00
^{208}Pb	2731/1776 = 1.54	328/860 = 0.38	1.30	1.21	0.77	1.21
^{232}Th				0.84	0.69	0.84
^{238}U				0.76	0.79	0.76

It must be pointed out, that more correct designation for reaction with emission of one neutron must be (γ,1n): for each target nucleus this define exactly one final product. Unfortunately traditionally used designation (γ,n) in reality presents the sum of two reactions [(γ,n) + (γ,np)] leading to different final nuclei. This is because almost for all investigated nuclei the (γ,np) reaction energy threshold B(np) is not too high and this reaction contributes in the energy range under discussion. Further in this paper we will use designation (γ,n) for [(γ,n) +(γ,np)] reactions.

One can see (Table 3) very easily that in majority of presented cases while the integrated (γ,n) reaction cross section from Saclay is more higher than that from Livermore, the integrated (γ,2n) reaction cross section is, vise versa, more lower. For example, in case of ^{159}Tb up to the (γ,2n) reaction threshold the (γ,xn) reaction cross sections from Livermore and Saclay differ only at 6 % (R^{int}_{part}(γ,xn) = 1.062). At the same time while the integrated up to 28 MeV (γ,n) reaction cross section from Saclay is /25/ at 37% higher than from Livermore (1936/1413 = 1.37), its integrated (γ,2n) reaction cross section is at 47% lower (887/605 = 1.47).

The complete joint systematic of these data for all 19 nuclei investigated is presented on Fig. 7.

As a rule ratios for (γ,n) reaction cross sections are more than 1, but those for (γ,2n) – vise versa are smaller than 1.

In comparison with data for total photoneutron reaction (γ,xn) cross section data obtained without separation for neutron multiplicity and presented on Fig 6 one can see dramatic disagreements (more higher and of opposite direction) between data obtained using the procedure of multiplicity sorting. The balance of one-neutron (γ,n) and two-neutron (γ,2n) reaction cross sections obtained at Livermore and Saclay for 12 nuclei mentioned above (Table 3) was analyzed /25/ in details using the results of (e,n) and (e,2n) reaction cross section measurements including that obtained by both neutron multiplicity sorting and residual activity measurement methods for one nucleus – ^{181}Ta /27 – 29/. It was shown that (e,2n) reaction cross section is in good agreement with (γ,2n) Livermore data but excludes the result obtained at Saclay. It was concluded /25/ that the discrepancies under discussion arise from the neutron multiplicity sorting caused by difference in the analysis that separates the total (γ,xn) counts into (γ,n) and (γ,2n) events. Livermore detector (large array of ^{10}BF$_3$ tubes and "ring-ratio" method additionally) efficiency was enough for correct neutron multiplicity sorting, but Saclay neutron detector (large liquid scintillator) efficiency was not. Therefore Saclay data for (γ,2n) reaction were underestimated (some of those data were interpreted as (γ,n) events) and correspondingly that for (γ,n) reaction – vise versa overestimated. Certainly both of them must be corrected.

The method for such correction proposed /25/ is very simple and clear.

Because total photoneutron reaction cross section generally consists of two parts

$$(\gamma,xn) = (\gamma,n) + 2(\gamma,2n) \qquad (16)$$

the ratio R discussed before (Fig. 7) has the following meaning

$$R = \sigma^{xn}{}_S/\sigma^{xn}{}_L = (\sigma^n{}_S + 2\sigma^{2n}{}_S)/(\sigma^n{}_L + 2\sigma^{2n}{}_L). \qquad (17)$$

Using that ratio one can easily obtain the main expression for Saclay corrected (γ,2n) reaction cross section data $\sigma^{2n}{}_S{}^*$

$$R\sigma^{2n}{}_L = \sigma^{2n}{}_S{}^* = \sigma^{2n}{}_S + \tfrac{1}{2}(\sigma^n{}_S - R\sigma^n{}_L). \qquad (18)$$

The right part of expression (18) reflects the main idea described above: Saclay (γ,n) reaction cross section part is added ("transmitted back") to Saclay (γ,2n) reaction cross section $\sigma^{2n}{}_S$. This part is obtained as correspondent difference $\tfrac{1}{2}(\sigma^n{}_S - R\sigma^n{}_L)$ between (γ,n) reaction cross section data obtained at Saclay and Livermore (additionally normalized). At the same time it is important to point out that if the reason of Saclay-Livermore disagreements is the Saclay neutron multiplicity sorting procedure mistake really, the left part of expression (18) also must be correct: $\sigma^{2n}{}_S{}^* = R\sigma^{2n}{}_L$ (recalculated Saclay (γ,2n) reaction cross section must be in agreement with Livermore (γ,2n) reaction cross section multiplied by R).

Corrected data obtained /25/ for 12 nuclei (^{89}Y, ^{115}In, ^{117,118,120,124}Sn, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb) were /26/ also accurately recalculated and added by analogous data for another 7 nuclei (^{51}V, ^{75}As, ^{90}Zr, ^{116}Sn, ^{127}I, ^{232}Th, ^{238}U). All corrected cross sections together with integrated cross section data are presented in /26/. Two examples of data obtained are presented on Figs. 8, 9.

Fig. 8 represents the results of joint correction of Saclay and Livermore data for ^{208}Pb including (γ,xn), (γ,n) and (γ,2n) reaction data. Fig 8a shows how appropriate (γ,xn) reaction cross section data were put into consistency to each other using slight energy shift and absolute value normalization. The criteria was maximum of consistency in the energy region till the (γ,2n) reaction cross section threshold B(2n) where both cross sections must be identical. Fig. 9 shows Saclay and Livermore data for (γ,n) and (γ,2n) reaction cross sections for ^{159}Tb before and after joint correction described.

Photoneutron reactions (γ,n) и (γ,2n) integrated cross section data (S – Saclay, L – Livermore) before [6] and after correction are presented in the Table 4.

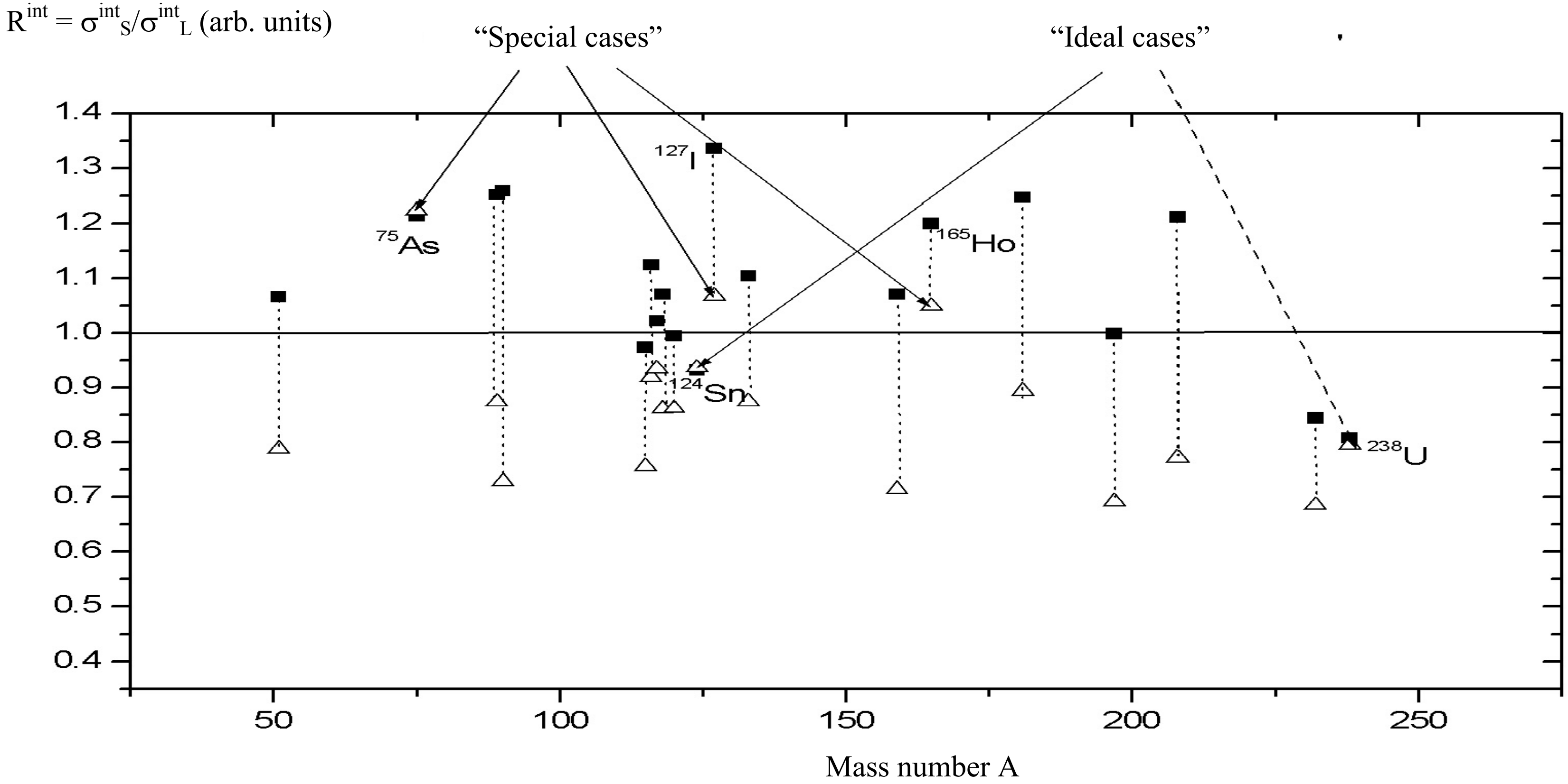

Рис. 7. Systematics /26/of values $R^{int}(n) = \sigma^{int}_{Saclay}(\gamma,n)/\sigma^{int}_{Livermore}(\gamma,n)$ – squares and $R^{int}(2n) = \sigma^{int}_{Saclay}(\gamma,2n)/\sigma^{int}_{Livermore}(\gamma,2n)$ – triangles, obtained for the same ranges of integration using data of QMA-experiments of Saclay and Livermore.

“Special cases” – both (γ,n) and (γ,2n) cross section ratios are more than 1.

“Ideal cases” - (γ,n) and (γ,2n) cross section ratios are near.

“Special cases” and “Ideal cases” were processed by special procedures /26/.

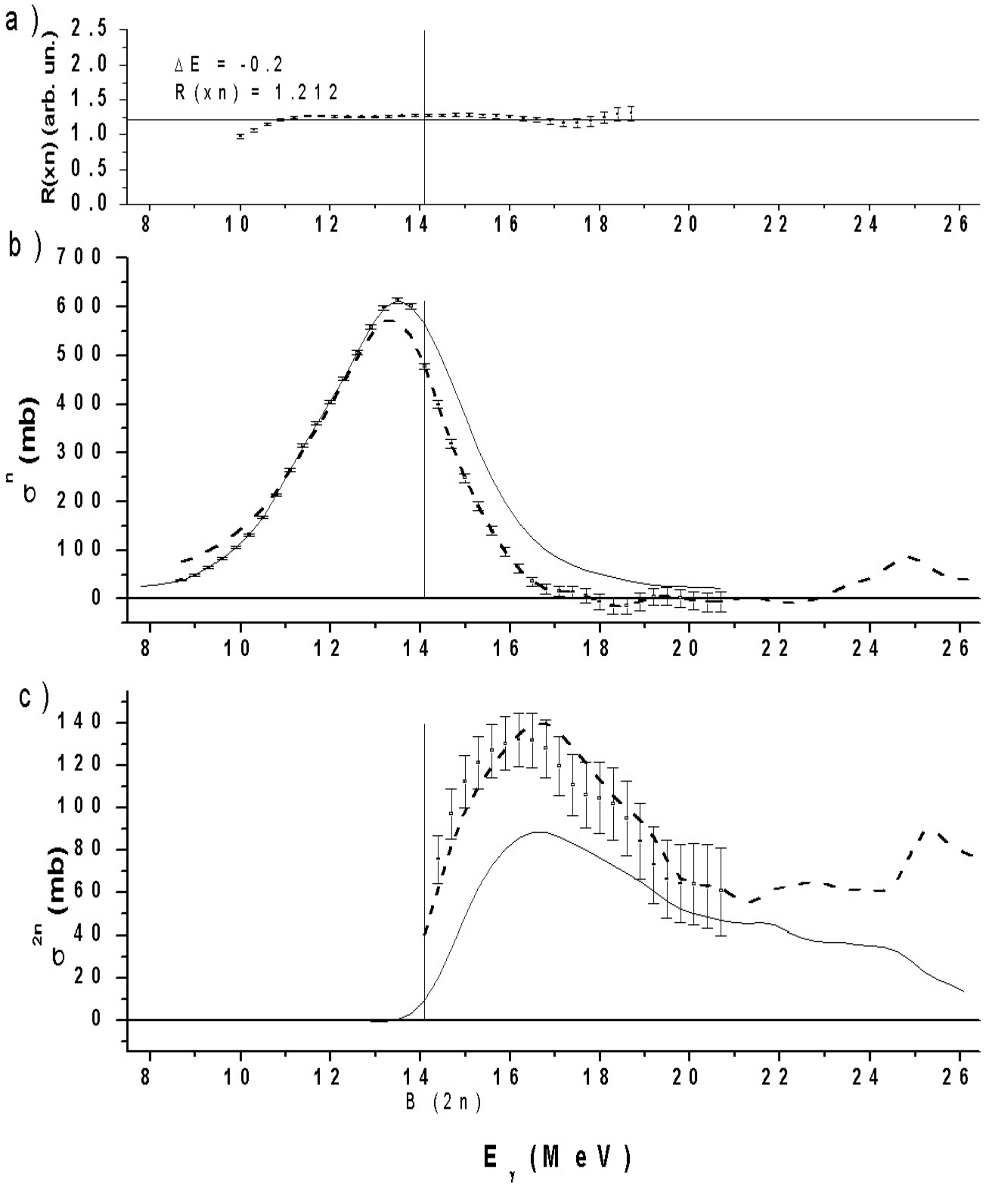

Fig. 8. The results of joint correction /26/ of total and partial photoneutron reaction cross sections for ^{208}Pb obtained at Saclay and Livermore:

a) ratios R(E) for (γ,xn) reaction cross sections; ΔE and R(xn) are presented;

b) (γ,n) reaction cross section data:
  - solid line– initial Saclay data $\sigma^{n}{}_{S}$;
  - dots with error bars – evaluated (18) Saclay data $\sigma^{n}{}_{S}{}^{*}$;
  - dotted line – Livermore evaluated data $R\sigma^{n}{}_{L}$;

c) (γ,2n) reaction cross section data:
  - solid line – initial Saclay data $\sigma^{2n}{}_{S}$;
  - dots with error bars – evaluated Saclay data $\sigma^{2n}{}_{S}{}^{*}$;
  - dotted line – Livermore evaluated data $R\sigma^{2n}{}_{L}$.

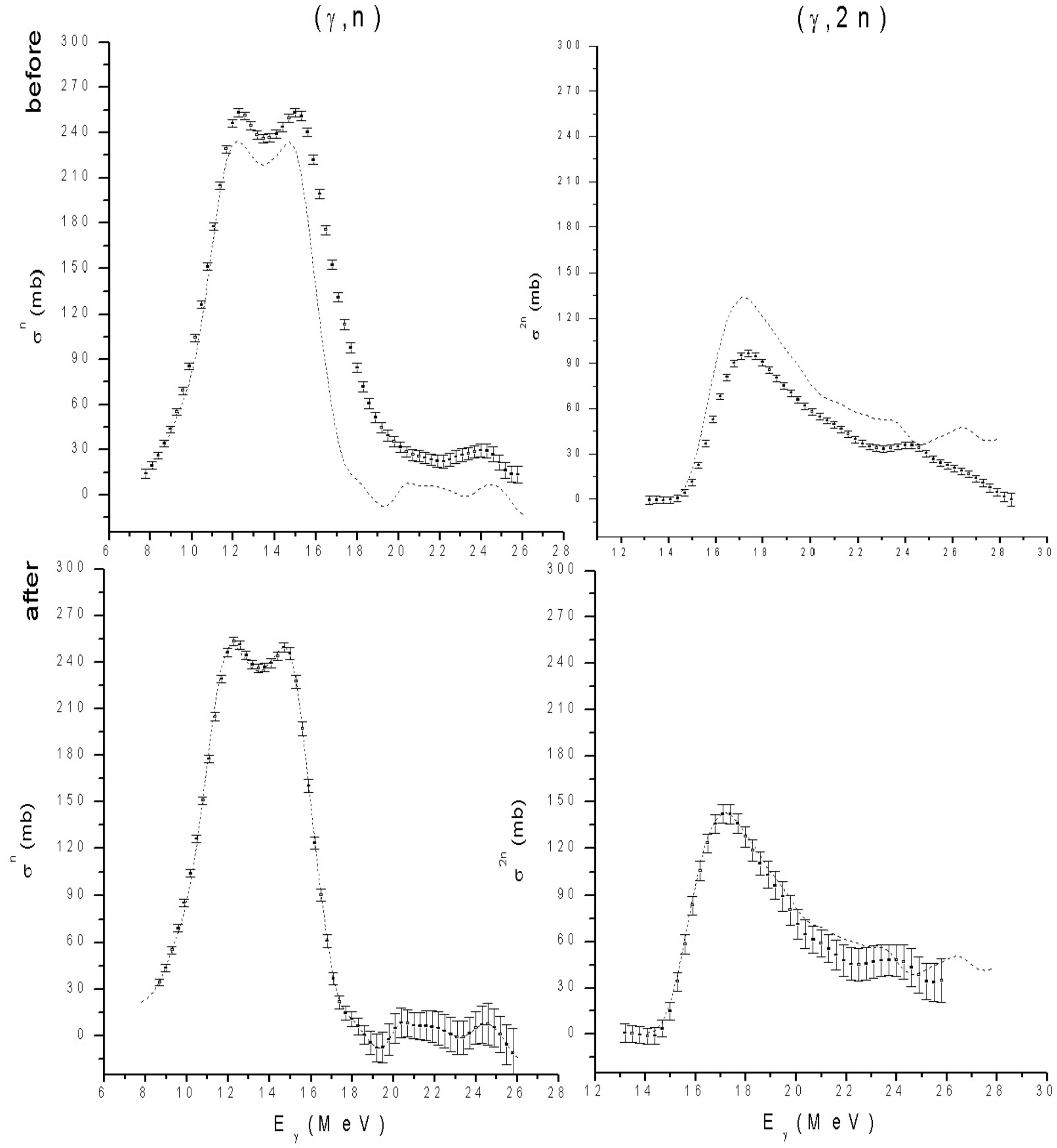

Fig. 9. Comparison of ^{159}Tb Saclay (dots with error bars) and Livermore (dash) data for (γ,n) and (γ,2n) reaction cross sections before and after joint correction described.

Table 5.

Photoneutron reactions (γ,n) и (γ,2n) integrated cross section data (S – Saclay, L – Livermore)
before [6] and after correction

Nucleus	$\sigma^{int}_{S}(\gamma,n)/\sigma^{int}_{L}(\gamma,n)$, both – MeV∗mb		$\sigma^{int}_{S}(\gamma,2n)/\sigma^{int}_{L}(\gamma,2n)$, both – MeV∗mb	
	Before [6]	After	Before [6]	After
^{89}Y	1279/960 = 1.33	1205.3/1206.1 = 1.00	74/99 = 0.75	112.6/107.3 = 1.05
^{115}In	1470/1354 = 1.09	1298.0/1298.2 = 1.00	278/508 = 0.55	364.6/358.3 = 1.02
^{117}Sn	1334/1380 = 0.97	1261.6/1261.4 = 1.00	220/476 = 0.46	234.1/243.6 = 0.96
^{118}Sn	1377/1302 = 1.06	1281.3/1281.4 = 1.00	258/531 = 0.49	298.9/320.4 = 0.93
^{120}Sn	1371/1389 = 0.99	1282.7/1282.6 = 1.00	399/673 = 0.59	444.5/460.2 = 0.97
^{124}Sn	1056/1285 = 0.82	1042.5/1042.4 = 1.00	502/670 = 0.75	511.5/502.6 = 1.02
^{133}Cs	1828/1475 = 1.24	1619.5/1618.5 = 1.00	328/503 = 0.65	431.8/413.7 = 1.04
^{159}Tb	1936/1413 = 1.37	1485.3/1485.4 = 1.00	605/887 = 0.68	633.9/675.7 = 0.94
^{165}Ho	2090/1735 = 1.20	2040.7/2040.7 = 1.00	766/744 = 1.03	825.6/803.4 = 1.03
^{181}Ta	2180/1300 = 1.68	1616.4/1615.7 = 1.00	790/881 = 0.90	520.1/559.9 = 0.93
^{197}Au	2588/2190 = 1.18	2144.6/2142.4 = 1.00	479/777 = 0.62	367.0/345.0 = 1.06
^{208}Pb	2731/1776 = 1.54	2274.5/2273.8 = 1.00	328/860 = 0.38	611.0/626.0 = 0.98

incorrect initial data used

3. Summary: Modern status of well-known data

Some important conclusions. All things described explain well what is known and what is unknown now. The “modern” status of well-known published photonuclear data must be taken into account. It means the following: value, accuracy and reliability of each data obtained could be understandable only after analysis of evident systematical disagreements depended on experimental method used (photon beam, detector, normalization, calibration, neutron multiplicity sorting, etc.).

Complete systematic of data from big databases /5/ and results of analysis have been carried out give to one possibility to do several evident general conclusions concern “modern” status of data under discussion:

- clear various data discrepancies force one to use data existed strongly individually: one must pay attention to experimental method and data processing procedure used in each laboratory;
- QMA-data are strongly over-smoothed (real energy resolution is several (3 – 4) times worse than declared one) in comparison with BR-data and must be additionally reprocessed using the method of reduction ((12 – (15)) or similar one to take into account real (not enough local) shape of apparatus function (effective photon spectrum);
- the total photoneutron reaction (γ,xn) cross sections obtained using QMA-photons at Livermore have in general absolute values smaller then that obtained using both BR- and QMA-photons at various laboratories; the reason can be “… an Livermore experiments error either in the photon flux determination or in the neutron detection efficiency or in both” /24/; therefore (γ,xn) cross sections data of Livermore for 19 nuclei studied /25, 26/ must be multiplied by appropriate coefficients R^{int}(γ,xn) (Table 3) and for others – by $<R^{int}_{syst}>$ = 1.12 /15/ at least;
- the partial photoneutron reactions (γ,n) and (γ,2n) cross sections obtained at Saclay are not correct and consistent each other because of incorrect neutron multiplicity sorting procedure used and must be recalculated using expression (18);
- Livermore neutron multiplicity sorting procedure at the same time is correct and therefore Livermore (γ,n) and (γ,2n) cross sections are in consistence with each other and with (γ,xn) cross sections and both can be used but again only multiplied by coefficients R^{int}(γ,xn) or $<R^{int}_{syst}>$.

Some important physical consequences. The are several important physical conclusions:

- problem of GDR structure existence, especially for medium and heavy nuclei, must be treated as open; BR-data look like more preferable for GDR structure detailed study because QMA-data are strongly over-smoothed; the real energy resolution (~ 1.3 - 1.6 MeV) of majority of QMA-data give not to one possibility to investigate physical effects produced structures with smaller width; the additional processing of QMA-data reveals the GDR structure very close to that obtained in BR-data;
- it looks like that E1 GDR decays dominantly statistically; Saclay interpretation /30 - 33/ of high-energy tails of (γ,n) reaction cross sections as contributions of high-energy neutrons from GDR nonstatictical direct decay processes (those contributions evaluated to be about 17 - 30 %) because of small decreasing of (γ,n) reaction cross sections for energies higher than (γ,2n) reaction threshold B(2n) looks like as very doubtful; Saclay (γ,n) reaction cross sections corrections described decrease those and put them into accordance with Livermore data: direct decay contributions are not more than 10 % (being multiplied to 1.12 – not more about 12 %);
- big extra integrated cross section σ^{int}(γ,abs) ≈ 1.28 60NZ/A (MeV•mb) became doubtfully being all due to effective mass of nucleon changing because of the effect of exchange forces /30- - 33/; the errors in Saclay procedure of neutron multiplicity sorting seriously affect their results for total photoabsorption cross section evaluation using the following reaction cross section data combinations (γ,abs) = (γ,sn) + (γ,p) and (γ,sn) = (γ,xn) - (γ,2n); it is very clear that mistake in (γ,2n) reaction data produces the mistakes in both (γ,sn) and (γ,abs) reaction data; correction described do them more smaller;
- further investigations using new intensive really monoenergetic photon beams in combination with effective methods for neutron multiplicity sorting are needed to establish the correct shapes and magnitudes of total and partial photoneutron reaction and photoabsorption cross sections especially for medium and heavy nuclei.

References

1. S.S.Dietrich, B.L.Berman. Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons. Atomic Data and Nuclear Data Tables, 38 (1988) 199.
2. A.V.Varlamov, V.V.Varlamov, D.S.Rudenko, M.E.Stepanov. Atlas of Giant Dipole Resonances. Parameters and Graphs of Photonuclear Reaction Cross Sections. INDC(NDS)-394, IAEA NDS, Vienna, Austria, 1999.
3. E.G.Fuller, H.Gerstenberg. Photonuclear Data - Abstracts Sheets 1955 - 1982. NBSIR 83-2742. U.S.A. National Bureau of Standards, 1986.
4. V.V.Varlamov, V.V.Sapunenko, M.E.Stepanov. Photonuclear Data 1976 - 1995. Index. Moscow State University. Moscow, 1996.
5. I.N.Boboshin, V.V.Varlamov, E.M.Ivanov, S.V.Ivanov, N.N.Peskov, M.E.Stepanov, V.V.Chesnokov. Relational Nuclear Databases Upon the MSU INP CDFE Web-site and Nuclear Data Centres Network CDFE Activities. Report on the IAEA Consultant's Meeting on the Co-ordination of Nuclear Reaction Data Centres (Technical Aspects), 28 – 30 May 2001, Vienna, Austria. INDC(NDS)-427, IAEA NDS, Vienna, Austria, 2001, p. 49.
   The CDFE Web-Site Nuclear Databases URL - http://depni.sinp.msu.ru/cdfe.
6. B.L.Berman, S.C.Fultz. Rev.Mod.Phys.. 47 (1975) 713.
7. B.S.Ishkhanov, I.M.Kapitonov, E.V.Lazutin, I.M.Piskarev, V.S.Sopov, V.G.Shevchenko. Yadernaya Fizika, 12 (1970) 892.
8. A.Veyssiere, H.Beil, R.Bergere, P.Carlos, A.Lepretre, A.De Miniac. Nucl.Phys., A227 (1974) 513.
9. R.L.Bramblett, J.T.Caldwell, R.R.Harvey, S.C.Fultz. Phys.Rev., 133 (1964) B869.
   J.T.Caldwell, R.L.Bramblett, B.L.Berman, R.R.Harvey. Phys.Rev.Lett., 15 (1965) 976.
10. R.E.Pywell, M.N.Thompson, B.L.Berman. Nucl.Instr. and Meth., 178 (1980) 149.
11. J.G.Woodworth, K.G.McNeill, J.W.Jury, R.A.Alvarez, B.L.Berman, D.D.Faul, P.Meyer. Phys.Rev., C19 (1979) 1667.
12. V.V.Varlamov, N.G.Efimkin, N.A.Lenskaja, A.P.Chernjaev. The Investigation of the Reasons for Discrepancies in Results of Photonuclear Experiments at the Beams of Bremsstrahlung and Quasimonoenergetic Gamma-Quanta. The Problem of Interpretation. MSU INP Preprint-89-66/143, -M., 1989.
13. V.V.Varlamov, B.S.Ishkhanov. Study of Consistency Between (γ,xn), [(γ,n) + (γ,np)] and (γ,2n) Reaction Cross Sections Using Data Systematics. Vienna, Austria. INDC(CCP)-433, IAEA NDS, Vienna, Austria, 2002.
14. N.G.Efimkin, B.S.Ishkhanov, Ju.P.Pyt'ev, V.V.Varlamov. The Energy Resolution Improvement by the Method of Reduction in Photonuclear Experiments. MSU INP Preprint-91-35/239, -M., 1991.
15. V.V.Varlamov, N.G.Efimkin, B.S.Ishkhanov, V.V.Sapunenko. Voprosy Atomnoj Nauki i Tekhniki. Seriya: Yadernye Konstanty,. 1 (1993) 52.
16. N.G.Efimkin, V.V.Varlamov. The Method of Reduction as Photonuclear Data Evaluation Tool. International Symposium on Nuclear Data Evaluation Methodology (USA BNL, 12 - 16 October 1992). World Scientific Press, ISBN 981-02-1285-2, 1993, p. 585.
17. Yu.P.Pyt'ev. Matematichesky Sbornik, 118 (1982) 19.
18. Yu.P.Pyt'ev. Vestnik Moskovskogo Universiteta. Fizika. Astronomiya. 25 (1984) 53.
19. Young L.M. Photoneutron Cross Sections and Spectra from Monoenergetic Photons on Yttrium, Praseodimium, Lead, and Bismuth in the Giant Resonance. Ph.D. Thesis, Univ. of Illinois, USA, 1972.
20. R.E.Sund, M.P.Baker, L.A.Kull, R.B.Walton. Phys. Rev., 176 (1968) 1366.
21. B.S.Ishkhanov, I.M.Kapitonov, E.M.Lazutin, I.M.Piskarev, V.G.Shevchenko. Vestnik Moskovskogo Universiteta. Fizika.Astronomiya. 6 (1970) 606.
22. V.V.Varlamov, B.S.Ishkhanov, D.S.Rudenko, M.E.Stepanov. Giant Dipole Resonance Structure in Experiments with Beams of Quasimonoenergetic Photons. MSU SINP Preprint-2002-19/703, Moscow, 2003.
23. S.C.Fultz, R.L.Bramblett, J.T.Caldwell, N.A.Kerr. Phys.Rev., 127 (1962) 1273.
24. B.L.Berman, R.E.Pywell, S.S.Dietrich, M.N.Thompson, K.G.McNeill, J.W.Jury. Phys.Rev., C36 (1987) 1286.
25. E.Wolynec, M.N.Martins. Revista Brasileira Fisica, 17 (1987) 56.
26. V.V.Varlamov, N.N.Peskov, D.S.Rudenko, M.E.Stepanov. Photoneutron Reaction Cross Sections in Experiments with Beams of Quasimonoenergetical Annihilation Photons. MSU SINP Preprint-2003-2/715, Moscow, 2003.
27. W.W.Gargaro, D.S.Onley. Phys.Rev., C4 (1971) 1032.
28. C.W.Soto Vargas, D.S.Onley, L.E.Wright. Nucl.Phys., A288 (1977) 45.
29. W.R.Dodge, E.Hayward, E.Wolinec. Phys.Rev., C28 (1983) 150.
30. R.L.Bergere, H.Beil, A.Veyssiere. Nucl.Phys., A121 (1968) 463.
31. R.L.Bramblett, J.T.Caldwell, G.F.Auchampaugh, S.C.Fultz. Phys.Rev., 129 (1963) 2723.
32. R.Bergere, H.Beil, P.Carlos, A.Veyssiere. Nucl.Phys., A133 (1969) 417.
33. H.Beil , R.Bergere , P.Carlos , A.Lepretre. Nucl.Phys., A227 (1974) 427.