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New evaluated data on ^{206,207,208}Pb photodisintegration

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Abstract New cross sections of the partial $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ and total (γ, Sn), and (γ, tot) photoneutron reactions for ^{206,207}Pb were evaluated using the experimental-theoretical method. The evaluation procedure was based on the comparison in detail of ^{206,207}Pb data obtained only at Livermore (USA) with ^{208}Pb data obtained at Livermore, Saclay (France) and also in other experiments. It was found that in the cases of all ^{206,207,208}Pb isotopes clear disagreements between Livermore data and new evaluated data can be explained by the assumption of loss of many neutrons in experimental $(\gamma, 1n)$ reaction cross sections. It was shown that Livermore experimental data for ^{206,207,208}Pb as well as for ^{75}As, ^{127}I, and ^{181}Ta investigated before are not reliable.

1 Introduction

Data for total and partial photoneutron reactions are widely used in both basic and applied photonuclear research. Such kind data for magic (Z=82) ^{208}Pb are very useful in comparisons of experimental reaction cross sections with those calculated by various models. Therefore, many experiments were carried out for ^{208}Pb using various methods and incident γ-quanta beams including bremsstrahlung [1–3], quasimonoenergetic photons obtained by annihilation in flight of relativistic positrons [4,5], monoenergetic tagged photons [6], and quasi-monochromatic laser-Compton scattering γ rays [7]. The procedures for extracting cross-section data from the experimentally measured quantities were noticeably different in the different experiments. There are significant disagreements between cross sections data obtained not only for partial photoneutron reactions $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ but also for total photoneutron neutron reaction cross-section,

$$\sigma(\gamma, \text{tot}) = \sigma(\gamma, 1n) + \sigma(\gamma, 2n) + \sigma(\gamma, 3n) + \cdots, \quad (1)$$

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and for neutron yield cross-section,

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

Those cross sections $\sigma(\gamma, Sn)$ were measured directly in experiments using bremsstrahlung beams. The comparisons of those with the results of experiments carried out using quasimonoenergetic and monoenergetic photons in which $\sigma(\gamma, Sn)$ were obtained as the sums (2) of directly measured $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions cross sections are of large interest.

Data for neutron yield cross sections $\sigma(\gamma, Sn)$ obtained for ^{206,207,208}Pb in various experiments are presented in Fig. 1. In the case of ^{208}Pb the $\sigma(\gamma, Sn)$ obtained at Livermore [4] and Saclay [5] are compared with the results of other available experimental data [6,7] as well as with the results of previous evaluation used the method of reduction [8]. This method is the special treatment for converting data obtained with various instrumental functions (effective initial photon spectra) into the form which they would have if the instrumental function has the form of the monochromatic function. It gives one the opportunity to jointly evaluate the data obtained using different photon beams. All experimental data are compared with the results of calculations in the frame of the Combined PhotoNucleon Reaction Model (CPNRM) [9] used in the experimental-theoretical evaluation method [10,11].

It is very important to point out that all $\sigma(\gamma, Sn)$ cross sections for ^{208}Pb under discussion, with the exception of Livermore data [4], are very close to each other. The results of above-mentioned comparisons confirm that the choice of Saclay [5] cross-section $\sigma^{\text{exp}}(\gamma, Sn)$ data as initial evaluation data (3) for for ^{208}Pb, instead of Livermore [4], data was completely justified [12].

In the experimental-theoretical method evaluated partial reaction cross sections $\sigma^{\text{eval}}(\gamma, in)$ for $i = 1, 2, 3, \ldots$ were obtained in the form,

$$\sigma^{\text{eval}}(\gamma, in) = F_i^{\text{theor}} \sigma^{\text{exp}}(\gamma, Sn) = \left[\sigma^{\text{theor}}(\gamma\ , in)/\sigma^{\text{theor}}(\gamma, Sn)\right] \sigma^{\text{exp}}(\gamma, Sn), \quad (3)$$

where $\sigma^{\text{exp}}(\gamma, Sn)$ is the experimental neutron yield cross-section,

$$\sigma^{\text{exp}}(\gamma, Sn) = \sigma^{\text{exp}}(\gamma, 1n) + 2\sigma^{\text{exp}}(\gamma, 2n) + 3\sigma^{\text{exp}}(\gamma, 3n) + \cdots , \quad (4)$$

defined in analogy to (2) and,

$$F_i^{\text{theor}} = \sigma^{\text{theor}}(\gamma, in)/\sigma^{\text{theor}}(\gamma, Sn), \quad (5)$$

are the ratios of specific partial reaction cross sections $\sigma^{\text{theor}}(\gamma, in)$ to neutron yield cross-section $\sigma^{\text{theor}}(\gamma, Sn)$ calculated in the frame of the CPNRM [9]. The experimental-theoretical method evaluation procedure (3) means that experimental cross-section $\sigma^{\text{exp}}(\gamma, Sn)$, rather independent on the problems of experimental neutron multiplicity sorting because all outgoing neutrons are included, is divided into partial reaction cross-section contributions using the ratios F_i^{theor} calculated in the CPNRM, also independent on those problems.

The CPNRM is based on the statistical approach and uses a combination of pre-equilibrium exciton model and particle evaporation process to calculate probabilities of formation of specific final nuclei after absorption of a photon. The global parameters (Z, N, level-density and quadrupole deformation parameters) were used. Additionally nucleus deformation and, the parameters of isospin splitting of nucleus Giant Dipole Resonance were considered. The uncertainty of 10% was introduced for each calculated F_i^{theor} after variation of such parameters with the aim of description of experimental neutron yield cross sections for many nuclei.

In the frame of the IAEA Coordinated Research Project the F_i^{theor} values calculated for ^{181}Ta [12] in the CPNRM [9] were in detail compared with the relevant F_i^{theor} values calculated using several other models (TALYS, CCONE, CoH$_3$, EMIRE, and MEND-G) [13].

It was shown that there are large discrepancies among the results obtained using different model codes in the high photon energy region, where pre-equilibrium emission is the dominant process. But at the energies of Giant Dipole Resonance, up to about 25–30 MeV, with our level of uncertainty for F-functions (10%), the agreements between $F_{1,2}$ calculated in the frames of various models are satisfactory. At the same time, the reliability of ratios Fi calculated in the CPNRM was confirmed using the comparisons of partial reaction cross sections evaluated using experimental-theoretical method with the experimental data obtained using activation method, in which partial reactions are separated reliably because the final nuclei in those reactions are different. Detailed comparisons were carried out for ^{181}Ta [14], ^{196}Au [15], and ^{209}Bi [16].

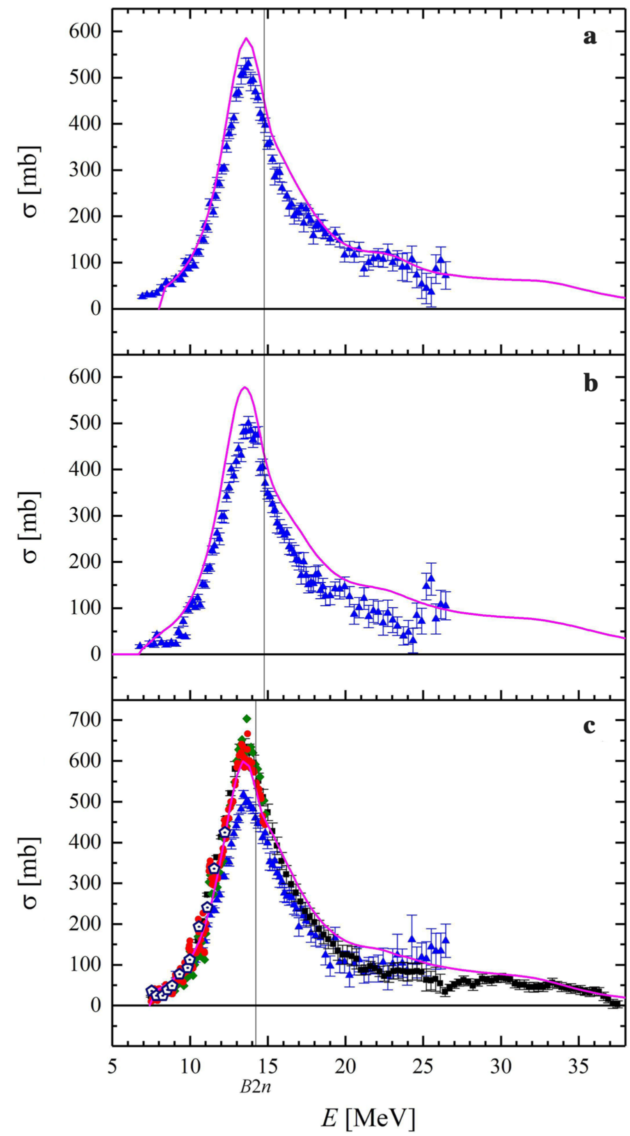

Fig. 1 The comparison of the experimental data (Livermore [4] – triangles, Saclay [5] – squares, tagged photons [6] – diamonds, laser-Compton scattering γ rays [7] - pentagons) with data evaluated using the method of reduction ([8] – circles) and the results of calculations in the frame of the CPNRM ([9] – lines): **a** ^{206}Pb, **b** ^{207}Pb, **c** ^{208}Pb.

At the same time one can see from Fig. 1c that in the case of ^{208}Pb theoretically calculated cross-section $\sigma^{\text{theor}}(\gamma, Sn)$ is in agreement with the modern data for $(\gamma, 1n)$ reaction cross-section obtained using laser-Compton scattering γ rays [7]. This cross-section $\sigma^{\text{exp}}(\gamma, 1n)$ [7] was measured up to photon energy 12.2 MeV and is identical to the neutron yield cross section $\sigma^{\text{exp}}(\gamma, Sn)$ because the threshold $B2n$ of the reaction $(\gamma, 2n)$ is equal to 14.1 MeV.

Many new data were recommended for use in basic research and applications as a result of discussions and new evaluations of available data in the frame of the IAEA Coordinated Research Project [13]. The above-mentioned evaluated data were recommended in the case of ^{208}Pb, however, in the cases of ^{206,207}Pb, the Livermore experimental data [4] were adopted in the absence of experimental-theoretical evaluations for these isotopes. The new evaluated data on photodisintegration of ^{206,207}Pb obtained in this paper using the physical criteria of data reliability and experimental-theoretical method for evaluation fill this gap.

The ratios F_i^{exp} defined in analogy to F_i^{theor} (5) were proposed [10,11] as the objective physical criteria of experimental partial photoneutron reaction cross-section data reliability. According to the definitions, F_i^{exp} should have definitely positive values and at the same time values $F_1 > 1.00$, $F_2 > 0.50$, $F_3 > 0.33$, etc never can be. F_i^{exp} values larger than those upper limits mean that partial reaction cross sections were obtained with large systematic uncertainties and are not reliable.

In Fig. 1 one can see that in the cases of Pb isotopes:

- the experimental cross-section $\sigma^{exp}(\gamma, Sn)$ for ^{208}Pb obtained at Saclay [5] agree with the relevant results obtained using tagged photons [6], the results of joint evaluation of many cross sections obtained in various experiments using the method of reduction [8], as well as the results of calculations in the CPNRM [9];
- the experimental $\sigma^{exp}(\gamma, Sn)$ for ^{208}Pb [5] agree with modern results obtained using laser-Compton γ scattering rays [7] for reaction $(\gamma, 1n)$ obtained in the photon energy range up to 12.2 MeV; this $\sigma^{exp}(\gamma, 1n)$ must be identical to $\sigma^{exp}(\gamma, Sn)$ because the threshold $B2n$ of the reaction $(\gamma, 1n)$ is equal to 14.1 MeV;
- the experimental cross-section obtained at Livermore [4] for ^{208}Pb differs significantly from all data from refs. [5–9] even in the field of energies below the threshold $B2n$ of the reaction $(\gamma, 2n)$ where one has no neutron multiplicity sorting problems and the neutron yield cross sections should be identical;
- the $\sigma^{exp}(\gamma, Sn)$ for ^{208}Pb obtained at Livermore [4] is significantly underestimated in comparison with other experimental [5–7] and evaluated before [8] ones;
- the neutron yield cross sections $\sigma^{exp}(\gamma, Sn)$ for ^{206,207}Pb obtained at Livermore [4] across the peak of the Giant Dipole Resonance are significantly underestimated in comparison with those calculated in the CPNRM [9].

One is forced to conclude that experimental cross sections $\sigma^{exp}(\gamma, Sn)$ obtained at Livermore [4] for both isotopes ^{206,207}Pb can be used in the evaluation procedure (3) only after the appropriate re-normalization. In connection with the above, the unique way for reliable re-normalization is the increasing of both cross sections in accordance with theoretically calculated [9] ones because the cross sections $\sigma^{exp}(\gamma, Sn)$ for ^{206,207}Pb were obtained only at Livermore [4].

Such recommendation agrees in general with those from the previous special investigations of the reasons of disagreements between Livermore and Saclay data [17,18]. The problem of disagreements between $\sigma^{exp}(\gamma, Sn)$ for ^{208}Pb, as well as those for several other nuclei obtained at Livermore and Saclay, was the subject of special research carried out at Livermore [17]. Absolute photoneutron cross sections $\sigma^{exp}(\gamma, Sn)$ for Zr, I, Pr, Au, and Pb were specially re-measured at Livermore across the peak of the Giant Dipole Resonance to solve the problem of significant data disagreements under discussion. It was concluded [17] that “noticeable disagreements exist”. Basing on the comparison of experimental data for ^{nat}Pb with calculated Lorentz curve concern isotopes ^{206,207,208}Pb, the explanations of the possible reasons of those the following sentences were written [17] as following: “Therefore, this comparison implies an error either in the photon flux determination or in the neutron detection efficiency or in both” and “... it is clear that the cross sections of Ref. 11 (this paper reference [4]) are far too low”. It was recommended to put those data for several nuclei obtained at Livermore and Saclay into consistency to each other using the re-normalization procedure: “... the old Livermore cross sections for ^{206}Pb, ^{207}Pb, ^{208}Pb, and also Bi (all from Ref. 11 (this paper reference [4])) be increased by 22%”. The general recommendations [17] for re-normalization factors are presented in Table 1.

In the cases of ^{127}I and ^{197}Au it was recommended do not use the data obtained at Livermore before, maybe because the errors mentioned above were too large.

From those data one can see the definite ambiguity of proposed recommendations because those were definitely individual and significantly different for different nuclei, in several cases opposite to each other. The proposed normalization factors are in the range of 0.80–0.93 in the cases of data for ^{nat}Rb, ^{89}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{127}I, ^{197}Au, and ^{208}Pb obtained at Saclay. Those factors mean the recommendation to decrease the Saclay data. But at the same time normalization factors are equal to 1.22 in the cases of data for ^{206,207,208}Pb (and data for ^{209}Bi, by the way obtained in the same experiment [4]). Those factors mean the opposite recommendation of increasing the Livermore data.

The recommendations given in [17] contradict those based on the complete systematic of integrated cross sections R^{int} for more than 500 $\sigma^{exp}(\gamma, Sn)$ cross-section data for nuclei from ^{3}H to ^{238}U obtained in various experiments carried out using both quasimonoenergetic photons and bremsstrahlung [18]. The results of that systematic research have shown clearly that in general Livermore data are lower in comparison with others data obtained in various other laboratories with the average value of ratio $< R^{int}_{syst} >= 1.12 \pm 0.24$. It forces one to conclude that in agreement with what has been

Table 1 The re-normalization factors recommended for put the Livermore and Saclay data into the consistency to each other [17]

Nucleus	Laboratory	Re-normalization factor
^{nat}Rb	Saclay	0.85 ± 0.03
^{89}Sr	Saclay	0.85 ± 0.03
^{89}Y	Saclay	0.82
^{89}Y	Livermore	1.0
^{90}Zr	Saclay	0.88
^{90}Zr	Livermore	1.0
^{91}Zr	Livermore	1.0
^{92}Zr	Livermore	1.0
^{93}Nb	Saclay	0.85 ± 0.03
^{94}Zr	Livermore	1.0
^{127}I	Saclay	0.80
^{127}I	Livermore	Do not use
^{197}Au	Saclay	0.93
^{197}Au	Livermore	Do not use
^{206}Pb	**Livermore**	**1.22**
^{207}Pb	**Livermore**	**1.22**
^{208}Pb	**Livermore**	**1.22**
^{208}Pb	Saclay	0.93
^{209}Bi	Livermore	1.22

observed for many other nuclei, to make the Livermore and Saclay cross sections for ^{206,207}Pb, as well as for ^{208}Pb [12], consistent with each other one should increase the first ones rather than to reduce the second ones.

In accordance with those recommendations, similar to the data for ^{206,207,208}Pb and ^{209}Bi, those for ^{89}Y and ^{90,91,92,94}Zr obtained at Livermore should be multiplied by the factors equal to 1/0.93–1/0.8 = 1.08–1.25 (Table 1), on average (≈ 1.16) being in general close to 1.22 recommended [17] to put Livermore data into the consistency with relevant Saclay data.

Therefore based on the data in Fig. 1c it could be pointed out once more that the recommendation [18] to enlarge Livermore experimental ^{208}Pb(γ, Sn) reaction cross-section is in agreement with the results of comparison of those with the $\sigma^{\mathrm{theor}}(\gamma, Sn)$ calculated in the CPNRM [9] and other data [5–8].

In connection with the above, one is forced to conclude that the evaluations of partial photoneutron reaction cross sections for ^{206,207}Pb using the procedure (3) of the experimental-theoretical method [10,11] must be carried out only by using the new re-normalized cross sections $\sigma^{\mathrm{exp}}_{\mathrm{corr}}(\gamma, Sn)$ and not the original ones [4],

$$\sigma^{\mathrm{exp}}_{\mathrm{corr}}(\gamma, Sn) = \sigma^{\mathrm{exp}}(\gamma, Sn)_{[4]} \text{ x } K_{\mathrm{corr}}, \quad (6)$$

where

$$K_{\mathrm{corr}} = \sigma^{int-\mathrm{theor}}(\gamma, Sn)/\sigma^{int-\mathrm{exp}}(\gamma, Sn) \quad (7)$$

is the ratio of the relevant integrated calculated cross sections [9] and experimental ones [4].

2 Evaluation of partial photoneutron reaction cross sections for ^{207}Pb

At first the ratios F_i^{exp} were obtained using experimental data [4] and compared with the F_i^{theor} [9]. Both of F_i^{exp} and F_i^{theor} are presented in Fig. 2.

One can see that there are serious doubts in experimental data reliability because in the energy range $E > 17$ MeV there are many unreliable $F_1^{\mathrm{exp}} < 0$ values, many $F_2^{\mathrm{exp}} > 0.50$ values, and noticeable differences between F_1^{exp} and F_i^{theor} values.

In accordance with all said above, concerning the underestimation of the experimental neutron yield cross-section $\sigma^{\mathrm{exp}}(\gamma, Sn)$ that was normalized to the $\sigma^{\mathrm{theor}}(\gamma, Sn)$ [9] using the relevant calculated and experimental integrated cross-section data. The initial $\sigma^{\mathrm{exp}}(\gamma, Sn)$ and new $\sigma^{\mathrm{exp}}_{\mathrm{corr}}(\gamma, Sn)$ corrected in accordance with (7) are presented in Fig. 3.

The relevant integrated cross-section and center of gravity values for compared cross sections calculated for energy range up to threshold $B2n = 14.82$ MeV of the reaction (γ, 2n) are presented in Table 2. The energy range 10.00–14.82 MeV was used for the re-normalization procedure because one can see in Fig. 3 some strange irregularities of experimental cross-section at the energies lower than 10 MeV.

The corrected cross-section $\sigma^{\mathrm{exp}}_{\mathrm{corr}}(\gamma, Sn)$ was obtained (7) as X K_{corr} $\sigma^{\mathrm{exp}}(\gamma, Sn)$ where re-normalization factor $K_{\mathrm{corr}} = \sigma^{\mathrm{theor}}(\gamma, Sn)/\sigma^{\mathrm{exp}}(\gamma, Sn) = 1846.6/1529.8 = 1.21$ is the ratio of the correspondent integrated cross-section values of calculated and experimental cross sections (Table 2) because the centers of gravity $E^{\mathrm{c.g.}}$ of all compared cross sections are very close to each other. The value $K_{\mathrm{corr}} = 1.21$ is close to the re-normalization factor 1.22 (Table 1) recommended before [17] on the base of comparison Livermore and Saclay data across the peak of the giant dipole resonance.

The procedure (3) of the experimental-theoretical method [10,11] described above was used for evaluating the new partial photoneutron reaction cross sections for ^{207}Pb. The new corrected neutron yield cross-section $\sigma^{\mathrm{exp}}_{\mathrm{corr}}(\gamma, Sn)$ was used in the evaluation procedure (3) for obtaining new partial reaction cross sections satisfied physical criteria of data reliability. All new evaluated cross sections are presented in Fig. 4 in comparison with the relevant experimental data [4] and the corrected ones. The relevant integrated cross-section values σ^{int} obtained for evaluated data are presented in Table 3 in comparison with data obtained for Livermore experimental data [4] and corrected ones.

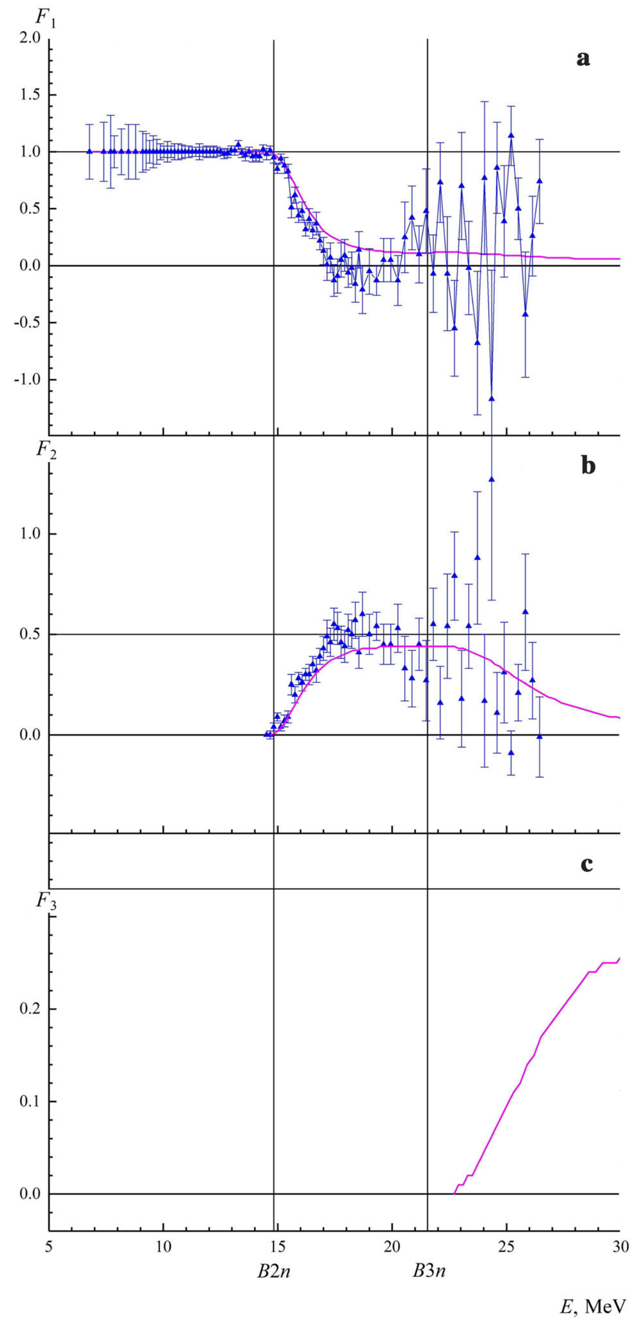

Fig. 2 The comparison of the ratios F_i^{exp} ([4] – triangles,) and F_i^{theor} ([9] – lines) for ^{207}Pb.

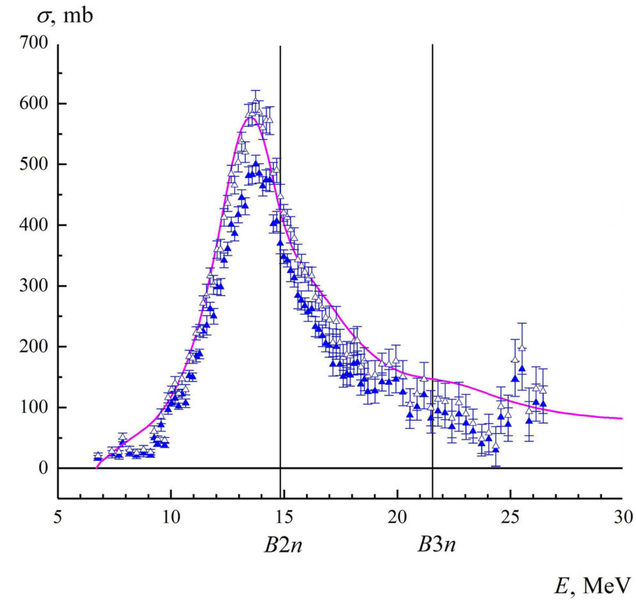

Fig. 3 The comparison of ^{207}Pb experimental [4] cross-section $\sigma^{\text{exp}}(\gamma, Sn)$ (full triangles), corrected cross-section $\sigma_{\text{corr}}^{\text{exp}}(\gamma, Sn)$ (empty triangles) and theoretical [9] cross-section $\sigma^{\text{theor}}(\gamma, Sn)$ (line).

Table 2 The experimental [4], calculated [9] and corrected integrated (for energy range E^{int} from 10 MeV to $B2n = 14.8$ MeV) cross sections σ^{int} (in MeV mb) and centers of gravity $E^{\text{c.g.}}$ (in MeV) for ^{207}Pb neutron yield cross-section.

	σ^{int}	$E^{\text{c.g}}$
Calculated data $\sigma^{\text{theor}}(\gamma, Sn)$ [9]	1846.6 (28.78)	12.94 (0.85)
Experimental data $\sigma^{\text{exp}}(\gamma, Sn)$ [4]	1529.8 (7.81)	12.95 (0.28)
Corrected $\sigma_{\text{corr}}^{\text{exp}}(\gamma, Sn)$ data [4]	1847.6 (9.44)	12.97 (0.28)

From the data of Fig. 4 and Table 3 one can see that:

- all experimental Livermore [4] cross sections of partial and total reactions are noticeably underestimated in comparison with the evaluated ones;
- the evaluated cross section of $(\gamma, 1n)$ reaction is in agreement with the modern results obtained using laser-Compton γ scattering rays [7];
- the simple re-normalization (multiplication of all experimental data for ^{207}Pb using factor 1.21) of experimental data [4] does not give the solution of discussed systematic disagreements problem because in the energy range up to $E^{\text{int}} = B3n = 21.6$ MeV moving up into the consistency data for $(\gamma, 1n)$ reaction (2598.9/2416.9 = 1.08 (8% difference) instead of 2598.9/2002.1 = 1.30) naturally leads to significant increasing of the disagreement between the data for $(\gamma, 2n)$ reaction (423.4/498.7 = 0.85(18% difference) instead of 1.02).

It is important to point out that the evaluation procedure (3) of the experimental-theoretical method based on using the neutron yield cross-section $\sigma^{\text{exp}}(\gamma, Sn)$, experimental ones in many cases, or corrected once as in the case of ^{207}Pb under discussion, gives to one an opportunity to evaluate the unknown before (in this case not obtained in experiment [4]) reaction cross-section for the reaction ^{207}Pb$(\gamma, 3n)$. New cross section of the reaction ^{207}Pb$(\gamma, 3n)$ was evaluated in the photon energy range up to 26.4 MeV.

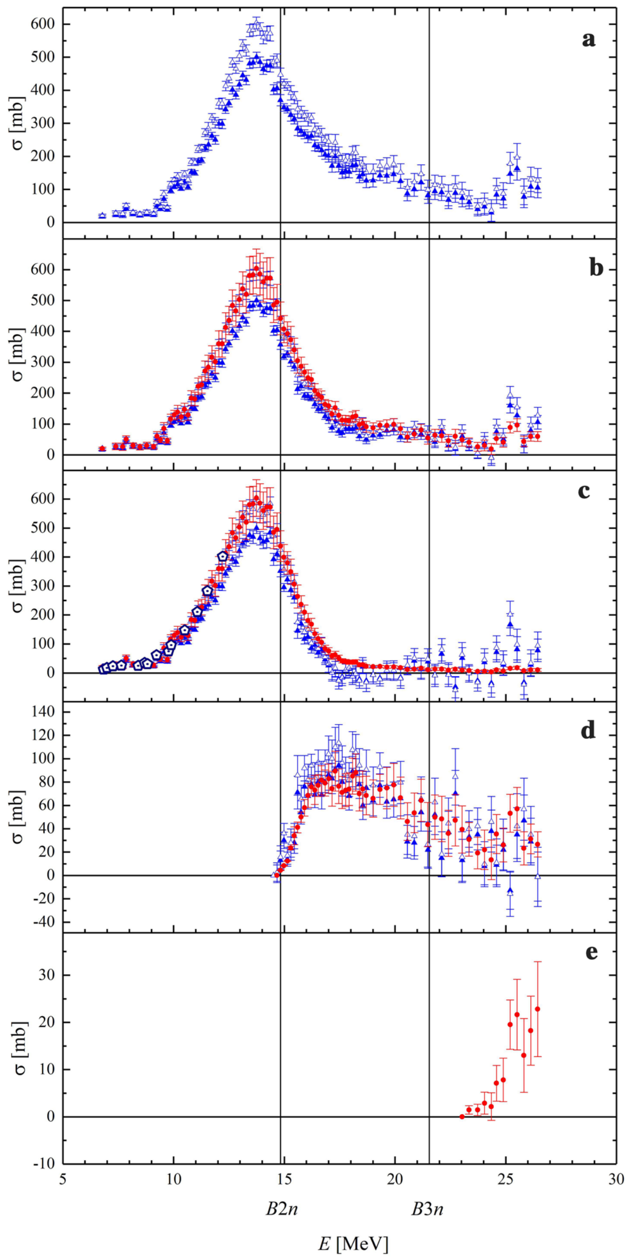

Fig. 4 The comparison of the evaluated (circles), the experimental ([4] – full triangles, [7] – pentagons) cross sections and the corrected ones (open triangles) of the reactions on ^{207}Pb: **a** $\sigma(\gamma, Sn)$, **b** $\sigma(\gamma, \text{tot})$, **c** $\sigma(\gamma, 1n)$, **d** $\sigma(\gamma, 2n)$, **e** $\sigma(\gamma, 3n)$.

3 Evaluation of partial photoneutron reaction cross sections for ^{206}Pb

The completely analogous treatment was used in the case of ^{206}Pb. The ratios F_i^{exp} obtained using experimental data [4] are presented in Fig. 5 in comparison with the F_i^{theor} [9]. One can see that in the case of ^{206}Pb there are no noticeable unreliable $F_1^{\text{exp}} < 0$ values or $F_2^{\text{exp}} > 0.50$ values at the energies up to $B3n = 23.2$ MeV, but at the same time there are noticeable differences between F_i^{exp} and F_i^{theor} at energies higher ∼21 MeV. Additionally, it must be pointed out that dependences on photon energies of both F_1^{exp} and F_2^{exp} are very strange at energies higher ∼24 MeV.

The results of correction (re-normalization) of the neutron yield cross-section carried out for energy range from 8.4 MeV to $B2n = 14.8$ MeV are presented in Fig. 6.

The correspondent integrated cross-section and center of gravity values are presented in Table 4. Experimental cross-section $\sigma^{\text{exp}}(\gamma, Sn)$ for ^{206}Pb was multiplied by 1.13 (1927.4/1705.9). So in the case of ^{206}Pb the re-normalization factor is slightly different from that for ^{207}Pb (1.21) and ^{208}Pb (1.22) recommended before [17] and is near to that recommended in [18].

The new corrected neutron yield cross-section $\sigma^{\text{exp}}_{\text{corr}}(\gamma, Sn)$ was used in the evaluation procedure (3) for obtaining new partial reaction cross sections satisfied physical criteria of data reliability similar to that in the case of ^{207}Pb. All new evaluated cross sections are presented in Fig. 7 in comparison with experimental data [4] and those corrected also. The relative integrated cross-section values σ^{int} obtained for the evaluated, experimental and corrected data are presented in table 5.

One can see from the data of Fig. 7 and Table 5 that Livermore experimental data [4] for all reactions obtained for ^{206}Pb are noticeably underestimated in comparison with the relevant evaluated ones, in complete analogy to those in the case of ^{207}Pb. Those disagreements also could not be excluded using the simple re-normalization of experimental cross sections.

Similar to the case of ^{207}Pb, in the incident photon energy range up to 12.2 MeV the new cross-section of partial reaction $(\gamma, 1n)$ evaluated using the experimental-theoretical method is in agreement with the modern results obtained using laser-Compton γ scattering rays [7].

The unknown before (not obtained in experiment [4]) the reaction cross-section for the reaction $(\gamma, 3n)$ was evaluated using the known experimental data for neutron yield cross-section $\sigma^{\text{exp}}(\gamma, Sn)$ obtained for ^{206}Pb in the photon energy range up to 26.4 MeV, in analogy to that for ^{207}Pb.

4 Comparison of the experimental and evaluated reaction cross-section data for ^{206,207,208}Pb with ones for ^{75}As, ^{127}I, and ^{181}Ta

From the data obtained now for ^{207}Pb (Fig. 4 and Table 3) and for ^{206}Pb (Fig. 7 and Table 5), as well as for ^{208}Pb (Table 6, data obtained before [12]), one can see that for all three nuclei under discussion in the photon energies ranges up to $B3n$ values of the $(\gamma, 3n)$ reaction thresholds there are similar and very specific competitions between the cross sections of the reactions (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$.

Table 3 The integrated cross sections σ^{int} (in MeV mb) of the evaluated, experimental, and corrected photoneutron reaction cross sections for ^{207}Pb. For evaluated cross sections the uncertainties of model-dependent experimental-theoretical method are presented.

Reaction	Livermore [4]	Evaluation	Livermore-corrected
$E^{int} = B2n = 14.8$ MeV			
(γ, Sn)	1641.6 (8.8)	1982.9 (10.6)	1982.9 (10.6)
(γ, tot)	1640.3 (8.7)	1983.2 (29.6)	1981.3 (10.5)
$(\gamma, 1n)$	1633.1 (10.3)	1982.9 (29.6)	1972.6 (12.4)
$E^{int} = B3n = 21.6$ MeV			
(γ, Sn)	2853.7 (18.8)	3444.3 (22.7)	3444.3 (22.7)
(γ, tot)	2440.3 (15.2)	3022.4 (34.85)	2945.6 (18.3)
$(\gamma, 1n)$	2002.1 (23.5)	2598.9 (32.5)	2416.9 (28.3)
$(\gamma, 2n)$	413.4 (11.2)	423.4 (12.8)	498.7 (13.4)
$E^{int} = 26.4$ MeV			
(γ, Sn)	3268.1 (30.3)	3945.0 (36.6)	3945.0 (36.6)
(γ, tot)	2717.5 (23.5)	3281.4 (38.4)	3280.3 (28.3)
$(\gamma, 1n)$	2133.6 (38.4)	2648.9 (32.7)	2575.4 (46.3)
$(\gamma, 2n)$	550.6 (19.2)	599.6 (19.7)	664.7 (23.2)
$(\gamma, 3n)$		32.8 (3.8)	

The reactions mentioned differ fundamentally by the contributions of the reaction $(\gamma, 1n)$:

- the contribution of $\sigma(\gamma, 1n)$ into the neutron yield cross-section $\sigma(\gamma, Sn)$ has some definite value because it is summed (2) with $2\sigma(\gamma, 2n)$;
- the contribution of $\sigma(\gamma, 1n)$ into the total neutron reaction cross-section $\sigma(\gamma, \text{tot})$ has larger value in comparison with the previous once because in this case $\sigma(\gamma, 1n)$ is summed (1) with the only $1\sigma(\gamma, 2n)$;
- the contribution of $\sigma(\gamma, 1n)$ into the $\sigma(\gamma, 1n)$ is naturally maximal and equal to 100%;
- the contribution of $\sigma(\gamma, 1n)$ into the $\sigma(\gamma, 2n)$ is naturally equal to zero.

From the data of Table 3 one can see that in the case of ^{207}Pb the values of the integrated cross sections ratios $\sigma^{int}{}_{eval}/\sigma^{int}{}_{L}$ [4] corresponding to the (γ, Sn), (γ, tot), $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions and obtained for photon energies up to the threshold $B3n = 21.6$ MeV of reaction $(\gamma, 3n)$ are equal to 1.21 (3444.3/2853.7), 1.24 (3022.4/2440.3), 1.30 (2598.9/2002.1), and 1.02 (423.4/413.4), relatively. It means that the larger the fraction of the $(\gamma, 1n)$ reaction in the experimental cross-sections of the reactions (γ, Sn), (γ, tot), and $(\gamma, 1n)$, the higher the degree to which the latter is underestimated. At the same time the experimental $\sigma(\gamma, 2n)$ is practically equal to the evaluated once (the difference is equal only to 2%).

From Table 5 one can see that in the case of ^{206}Pb the ratios $\sigma^{int}{}_{eval}/\sigma^{int}{}_{L}$ [4] values corresponding to the (γ, Sn), (γ, tot), $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions and calculated for photo energies up to the threshold $B3n = 23.2$ MeV of reaction $(\gamma, 3n)$ are in general analogous for those for ^{207}Pb and equal relatively to 1.13 (3643.9/3224.6), 1.15 (3201.4/2799.1), 1.19 (2758.3/2322.1), and 1.02 (442.7/426.4). Those ratios are naturally slightly smaller in comparison with the relevant ones for ^{207}Pb because the re-normalization factor K_{corr} (7) used in the case of ^{206}Pb is equal to 1.13 (smaller in comparison with 1.21 for ^{207}Pb).

From Table 6 one can see that in the case of ^{208}Pb [12] the ratios $\sigma^{int}{}_{eval}/\sigma^{int}{}_{L}$ [4] values corresponding to the (γ, Sn), (γ, tot), $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions and calculated for photon energies up to the threshold $B3n = 23.2$ MeV of reaction $(\gamma, 3n)$ are also analogous to those for ^{206,207}Pb and equal relatively to 1.20 (3820.8/3186.7), 1.30 (3270.9/2508.2), 1.40 (2699.6/1922.0.1), and 0.85 (571.2/670.9). By the way, it may be pointed out that the ratio of integrated cross sections for (γ, Sn) reaction $\sigma^{int}{}_{eval}/\sigma^{int}{}_{L}$ [4] values in this case is equal to 1.20 (is close to 1.22 (Table 1) recommended before [17]).

At the same time one can see from Table 6 that $\sigma^{int}{}_{eval}/\sigma^{int}{}_{exp}$ [5] values obtained for ^{208}Pb at Saclay [5] for energies up to $B3n$ values are quite different from those obtained using Livermore [4] data. At Saclay $\sigma^{int}_{eval}/\sigma^{int}_{S}$ values for all reactions under discussion, (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$, are about unity and near to each other (disagreements are about only several percents). This means that in Saclay experiment partial photoneutron reaction cross sections contain only the relatively small systematic uncertainties the reason of which is the shortcoming of procedure used to separate counts into $1n$ and $2n$ events.

In accordance with all said above the main result obtained in our research is that in the cases of ^{206,207,208}Pb investigated in the same Livermore experiment [4] the relations between the cross sections of total and partial reactions are in general analogous: the larger the fraction of the $(\gamma, 1n)$ reaction

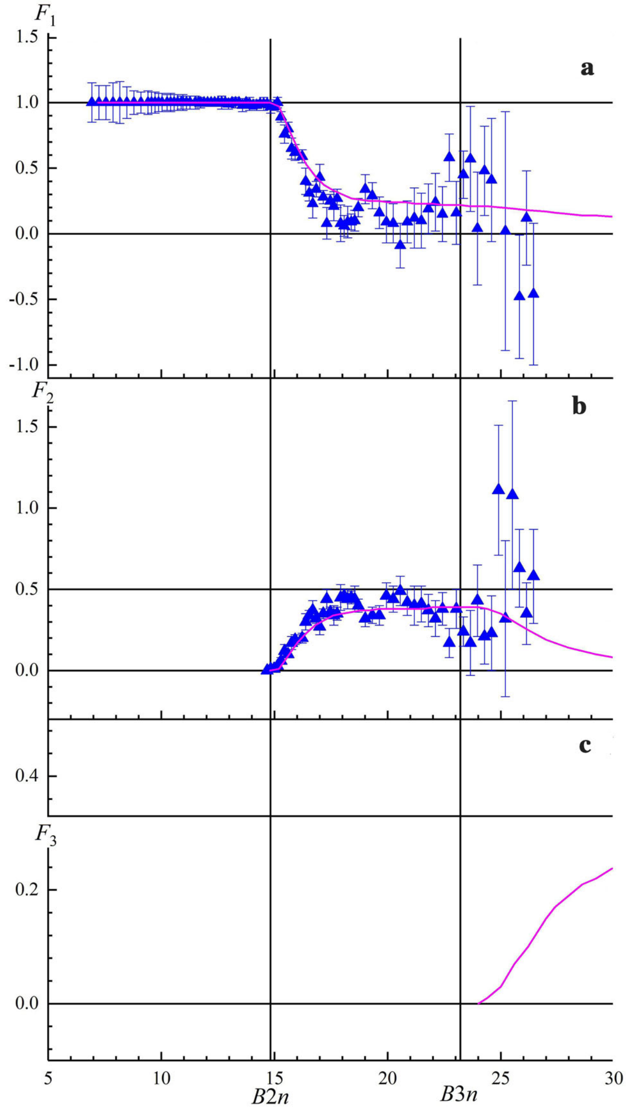

Fig. 5 The comparison of F_i^{exp} ([4] – triangles) and F_i^{theor} ([9] – lines) for ^{206}Pb.

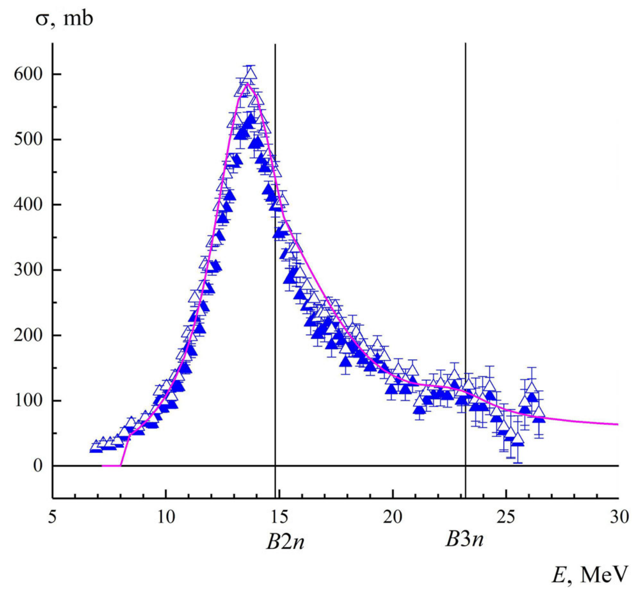

Fig. 6 The comparison of ^{206}Pb experimental $\sigma^{exp}(\gamma, Sn)$ ([4] – full triangles), theoretical $\sigma^{theor}(\gamma, Sn)$ ([9] – line) neutron yield cross sections. $\sigma^{exp}_{corr}(\gamma, Sn)$ (empty triangles)

Table 4 The experimental [4], calculated [9], and corrected integrated cross sections σ^{int} (in MeV mb) and centers of gravity $E^{c.g.}$ (in MeV) for ^{206}Pb neutron yield cross-section obtained for energy range E^{int} from 8.4 MeV to $B2n = 14.8$ MeV

	σ^{int}	$E^{c.g}$
Calculated data $\sigma^{theor}(\gamma, Sn)$ [9]	1927.4 (40.7)	12.74 (1.15)
Experimental data $\sigma^{exp}(\gamma, Sn)$ [4]	1705.9 (7.8)	12.74 (0.24)
Corrected $\sigma^{exp}_{corr}(\gamma, Sn)$ data [4]	1928.8 (8.8)	12.74 (0.24)

cross-section in the experimental cross sections of other reactions with the exception of $(\gamma, 2n)$ reaction cross-section, the higher the degree to which all of those are underestimated. This is not in case of $(\gamma, 2n)$ reaction cross section in which fraction of the $(\gamma, 1n)$ reaction cross-section is equal to zero.

Moreover, the relations between experimental and evaluated reaction cross sections found for ^{206,207,208}Pb are completely analogous to those obtained before [12,19,20] for ^{75}As [21], ^{127}I [22], and ^{181}Ta [23] Livermore data. All relevant data are presented in Table 7. It is very important to point out that in the cases of all six nuclei under discussion, ^{75}As, ^{127}I, ^{181}Ta, and ^{206,207,208}Pb, in contradiction to the cases of many other nuclei investigated before there are significant (up to tens of percents) disagreements between neutron yield cross sections $\sigma(\gamma, Sn)$ in the energy ranges $E_\gamma < B2n$ where one has no neutron multiplicity sorting problems and where $\sigma(\gamma, Sn)$, $\sigma(\gamma, \text{tot})$, and $\sigma(\gamma, 1n)$ should be identical.

It is very important to point out that such disagreements between neutron yield cross sections $\sigma(\gamma, Sn)$ (2) are not typical for many other nuclei investigated at both Livermore and Saclay, ^{89}Y, ^{90}Zr, ^{115}In, ^{116,117,118,120,124}Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{197}Au, [10,11,15,20,27]. In general for those cases cross sections $\sigma(\gamma, Sn)$ which are rather independent on the neutron multiplicity-sorting problems, are very close to each other at energies before the thresholds $B2n$ of the $(\gamma, 2n)$ reactions. It was shown using the experimental-theoretical method [12,14,16,19,28–40] that all disagreements under discussion exist at higher energies where one has the competition between $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions. The typical example of such disagreements in the case of ^{159}Tb data [26,41] is presented in Fig. 8.

In the case of ^{159}Tb the integrated cross sections for reaction (γ, Sn) calculated up to incident photon energy 30 MeV are equal to 3187 MeV mb [41] and 3194 MeV mb [26],

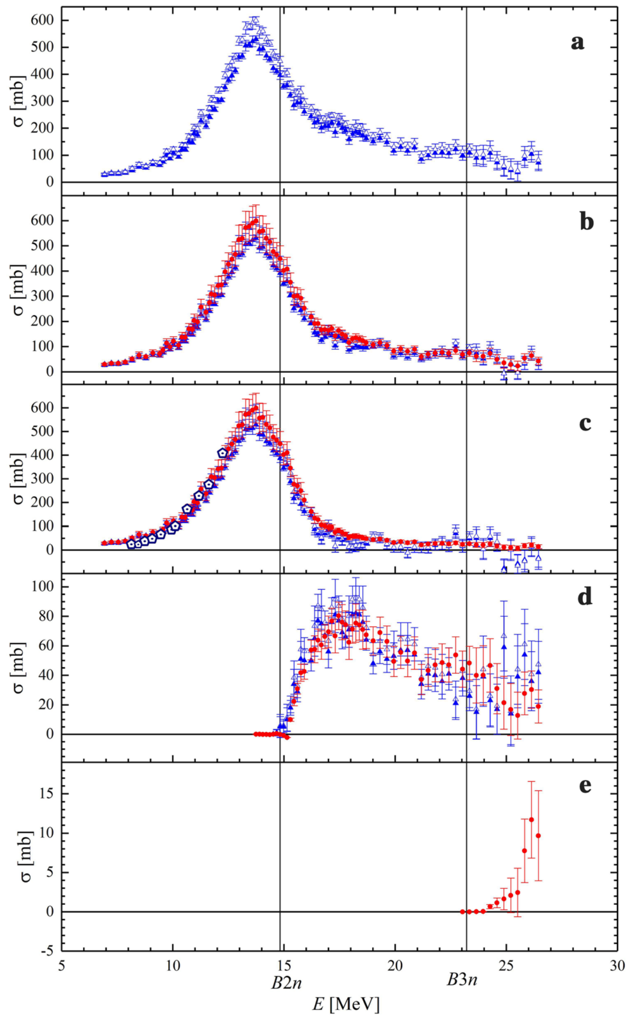

Fig. 7 The comparison of the evaluated (circles), the experimental ([4] – full triangles, [7] – pentagons), and the corrected (open triangles) cross sections of the reactions on ^{206}Pb: **a** $\sigma(\gamma, Sn)$, **b** $\sigma(\gamma, \text{tot})$, **c** $\sigma(\gamma, 1n)$, **d** $\sigma(\gamma, 2n)$, **e** $\sigma(\gamma, 3n)$

with the disagreement equal to ∼2%. At the same time for $(\gamma, 1n)$ reaction integrated cross sections are equal to 1936 MeV mb [26] and 1413 MeV mb [41] with the disagreement equal to ∼37%. For $(\gamma, 2n)$ reaction the relevant data are 605 MeV mb [41] and 887 MeV mb [26] with the opposite disagreement equal to ∼46%.

The examples of disagreements between Livermore and Saclay data in the energy range $E < B2n$, typical for all six nuclei mentioned above, ^{75}As, ^{127}I, ^{181}Ta, and ^{206,207,208}Pb, are presented in Fig. 1c for the case of ^{208}Pb and in Fig. 9 for the case of ^{181}Ta.

The correspondent ratios of integrated cross sections $\sigma^{\text{int}}_{\text{eval}}/\sigma^{\text{int}}_{\text{L}}(\gamma, Sn)$ are 1.20 for ^{208}Pb (3820.8/3186.7, Table 6) and 1.24 for ^{181}Ta (Table 7). In the cases of ^{75}As [21,24] and ^{127}I [22,25], as well as of ^{206,207}Pb (Figs. 4 and 7), one can see the analogous disagreements between experimental [4] and evaluated reaction cross sections.

It was pointed out before [12] that in Livermore experiment for ^{181}Ta$(\gamma, 1n)$ reaction [20] the neutrons were not detected generally at incident photon energies higher than ∼17.5 MeV, though neutrons from this reaction are presented in the Saclay up to energies about 25 MeV [23] and the evaluated [12] cross sections in the photon energy ranges up to ∼30 MeV. Therefore, the very large (46%) underestimation of the $(\gamma, 1n)$ cross-section [23] is exactly responsible (Table 7) for a substantial (24%) underestimation of the (γ, Sn) cross section. This could be resulted not only from some problem of neutron detection efficiency at different neutron energies but from some technical problems. It was concluded [12] that in the Livermore experiment [23] for ^{181}Ta many neutrons from $(\gamma, 1n)$ reaction were lost and relevant experimental data are not reliable.

A complete analogy of the competitions between various reaction cross sections in the cases of ^{206,207,208}Pb [4] to that for ^{181}Ta [23], as well as for ^{75}As [21], and ^{127}I [22], forces one to conclude in Livermore experimental data obtained for all six nuclei mentioned many neutrons from $(\gamma, 1n)$ reaction were lost. Therefore, those experimental data for partial and total photoneutron reaction cross-section obtained are not reliable.

5 Summary and conclusions

The recommended data for ^{206,207,208}Pb were presented before as a result of discussions and new evaluations of available data in the frame of the IAEA Coordinated Research Project [13]. The previously evaluated data were recommended in the case of ^{208}Pb, but the Livermore experimental data [4] were recommended in the cases of ^{206,207}Pb, because for those isotopes the evaluations based on using of objective physical criteria of data reliability have not been carried out before. This paper fills this gap.

The reliability of experimental photoneutron reaction data for ^{206,207}Pb obtained using quasimonoenergetic annihilation photons only at Livermore [4] was investigated in detail using the physical criteria of data reliability [10,11]. It was found that the cross sections of the reactions $(\gamma, 1n)$ and $(\gamma, 2n)$ in the cases of both ^{206,207}Pb do not satisfy those criteria and because of that are not reliable.

In the cases of ^{206,207}Pb the experimental data for cross sections of (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$ reactions across the peak of the Giant Dipole Resonance were obtained using quasimonoenergetic annihilation photons with energies up to 26 MeV only at Livermore [4]. Because of that for both ^{206,207}Pb the new evaluations were based on the results of previous evaluations carried out for ^{208}Pb [12] using the experimental $\sigma(\gamma, Sn)$ obtained at Saclay [5], not that obtained at Livermore [4] in the evaluation procedure (3) of the experimental-theoretical method [10,11]. It was shown

Table 5 The integrated cross sections σ^{int} (in MeV mb) of the evaluated, experimental and corrected photoneutron reaction cross sections for ^{206}Pb. Uncertainties of evaluated cross sections are the same as in Table 3

Reaction	Livermore [4]	Evaluation	Livermore-corrected
$E^{int} = B2n = 14.8$ MeV			
(γ, Sn)	1761.9 (8.2)	1992.2 (9.3)	1992.2 (9.3)
(γ, tot)	1761.3 (8.2)	1992.2 (28.4)	1991.6 (9.3)
$(\gamma, 1n)$	1757.6 (9.2)	1992.2 (28.4)	1987.2 (10.4)
$E^{int} = B3n = 23.2$ MeV			
(γ, Sn)	3224.6 (17.5)	3643.9 (19.8)	3643.9 (19.8
(γ, tot)	2799.1 (14.6)	3201.0 (33.5)	3162.8 (16.4)
$(\gamma, 1n)$	2322.1 (21.4)	2758.3 (31.9)	2623.9 (24.2)
$(\gamma, 2n)$	426.4 (9.8)	442.7 (10.4)	481.8 (10.9)
$E^{int} = 26.4$ MeV			
(γ, Sn)	3478.5 (27.2)	3930.6 (30.8)	3930.6 (30.8)
(γ, tot)	2947.5 (21.5)	3368.4 (36.2)	3330.7 (24.3)
$(\gamma, 1n)$	2321.7 (33.8)	2816.6 (32.6)	2623.9 (38.2)
$(\gamma, 2n)$	532.6 (16.7)	541.8 (15.6)	601.6 (18.9)
$(\gamma, 3n)$		10.0 (1.9)	

Table 6 The integrated cross sections obtained for experimental [4,5] and evaluated [12] cross sections of various reactions for ^{208}Pb. Uncertainties of evaluated cross sections are the same as in Table 3

Reaction	Livermore [4]	Saclay [5]	Evaluation [12]
$E^{int} = B2n = 14.1$ MeV			
(γ, Sn)	1432.9 (11.8)	1811.1 (15.4)	1811.1 (15.4)
(γ, tot)	1431.0 (12.1)	1811.1 (11.3)	1791.8 (11.1)
$(\gamma, 1n)$	1432.3 (9.2)	1810.7 (12.0)	1791.4 (11.2)
$E^{int} = B3n = 23.2$ MeV			
(γ, Sn)	3186.7 (47.5)	3820.8 (41.6)	3820.8 (41.6)
(γ, tot)	2508.2 (36.9)	3299.4 (29.3)	3270.9 (16.4)
$(\gamma, 1n)$	1922.0 (57.9)	2817.1 (41.6)	2699.6 (13.2)
$(\gamma, 2n)$	670.9 (32.0)	530.0 (18.2)	571.2 (7.7)
$E^{int} = 40.20$ MeV			
(γ, Sn)	3581.6 (74.9)	4592.9 (55.0)	4592.9 (55.0)
(γ, tot)	2671.8 (55.0)	3587.8 (32.5)	3663.1 (25.8)
$(\gamma, 1n)$	1960.5 (89.6)	2875.6 (55.9)	2774.7 (13.2)
$(\gamma, 2n)$	860.9 (49.3)	615.7 (33.0)	714.5 (10.8)
$(\gamma, 3n)$		197.2 (13.8)	165.5 (13.9)

that in the case of ^{208}Pb cross-section $\sigma(\gamma, Sn)$ obtained at Livermore [4] is significantly underestimated in comparison with the results obtained using tagged photons beam [6], laser-Compton scattering γ rays [7], the results of the joint evaluation [8] carried out using the method of reduction for various published cross sections $\sigma(\gamma, Sn)$ [1–6], as well as the results of the relevant calculations carried out in the CPNRM [9]. The calculated cross sections are very close to all data mentioned with the exception of Livermore data [4].

In the cases of ^{206,207}Pb, similar to that for ^{208}Pb, experimental cross sections $\sigma(\gamma, Sn)$ are significantly underestimated in comparison with relevant cross sections calculated in the CPNRM. In connection with the above, the experimental cross sections $\sigma(\gamma, Sn)$ for ^{206,207}Pb normalized to the relevant calculated cross sections were used in the evaluation procedures (3) of the experimental-theoretical method of evaluation [10,11]. The experimental cross section $\sigma^{exp}(\gamma, Sn)$ [4] was multiplied by the factor 1.21 in the case of ^{207}Pb and 1.13 in the case of ^{206}Pb.

The new evaluated cross sections were obtained in the cases of ^{206,207}Pb for reactions (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$. Additionally the cross sections for $(\gamma, 3n)$ reaction, not measured before, were evaluated in the energy ranges where $\sigma^{exp}(\gamma, Sn)$ [4] were obtained.

The competitions between the new evaluated and experimental cross sections of the reactions (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$ for ^{206,207,208}Pb were analyzed in detail. It was obtained that:

- Livermore data [4] for reaction (γ, Sn) disagree substantially (20% in the case of ^{208}Pb, 21% in the case of ^{207}Pb, and 13% in the case of ^{206}Pb) from the evaluated data in the range $E_\gamma < B2n$ where one has no neutron multiplicity sorting problems and where $\sigma(\gamma, Sn)$, $\sigma(\gamma, \mathrm{tot})$, and $\sigma(\gamma, 1n)$ cross sections must be identical;
- the larger the fraction of the $(\gamma, 1n)$ reaction in the experimental [4] cross sections of the reactions (γ, Sn), (γ, tot), and $(\gamma, 1n)$, the higher the degree to which the latter is underestimated ;
- many neutrons from the reaction $(\gamma, 1n)$ were lost in Livermore experiment [4]; the very large (40% in the case of ^{208}Pb, 30% in the case of ^{207}Pb, and 19% in the case of ^{206}Pb) underestimations of the $(\gamma, 1n)$ cross sections are

Table 7 The ratios $\sigma^{int}_{eval}/\sigma^{int}_{S}$ and $\sigma^{int}_{eval}/\sigma^{int}_{L}$ obtained for evaluated and experimental cross sections of various reactions for ^{75}As, ^{127}I, and ^{181}Ta

	^{75}As [19]		^{127}I [20]		^{181}Ta [12]	
	$\sigma^{int}_{eval}/\sigma^{int}_{S}$ [24]	$\sigma^{int}_{eval}/\sigma^{int}_{L}$ [21]	$\sigma^{int}_{eval}/\sigma^{int}_{S}$ [25]	$\sigma^{int}_{eval}/\sigma^{int}_{L}$ [22]	$\sigma^{int}_{eval}/\sigma^{int}_{S}$ [26]	$\sigma^{int}_{eval}/\sigma^{int}_{L}$ [23]
(γ, Sn)	0.99	1.27	0.99	1.20	1.00	1.24
(γ, tot)	1.00	1.30	1.00	1.25	0.96	1.30
$(\gamma, 1n)$	1.02	1.34	1.01	1.33	0.88	1.46
$(\gamma, 2n)$	0.92	1.14	0.94	0.98	1.16	1.05

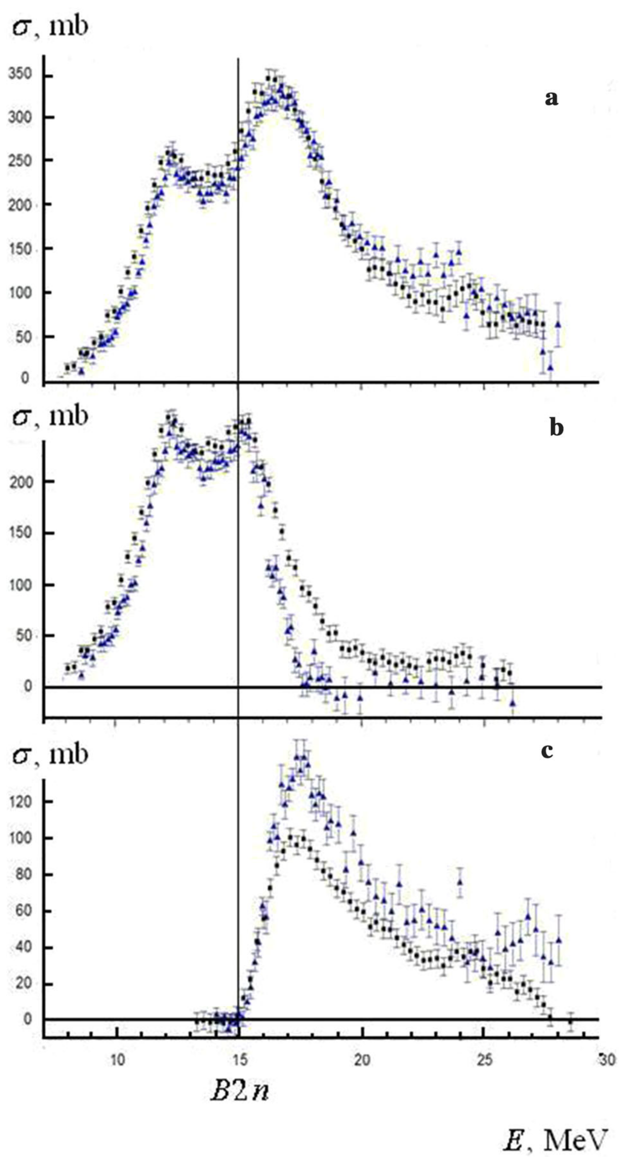

Fig. 8 The comparison of the experimental ([41], triangles, and [26], squares) neutron yield cross sections for ^{159}Tb: **a** $\sigma(\gamma, Sn)$, **b** $\sigma(\gamma, 1n)$, **c** $\sigma(\gamma, 2n)$.

exactly responsible for a substantial underestimations of the (γ, Sn) cross sections;

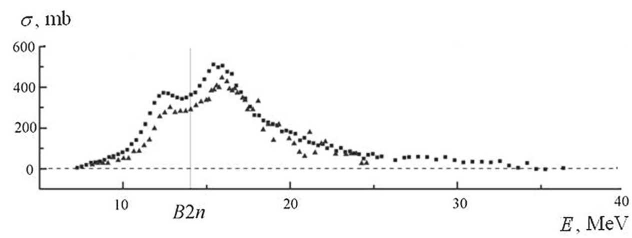

Fig. 9 The comparison of the experimental ([23], triangles, and [26], squares) neutron yield cross sections $\sigma(\gamma, Sn)$ for ^{181}Ta

– the experimental [4] cross sections $\sigma(\gamma, 2n)$ are nearer to the evaluated ones.

It was pointed out that found competitions between experimental and evaluated cross sections of the reactions (γ, Sn), (γ, tot), $(\gamma, 1n)$, and $(\gamma, 2n)$ in the cases of ^{206,207,208}Pb are completely analogous to those obtained before for ^{181}Ta [12], as well as for ^{75}As [19], and ^{127}I [20]. It was concluded that the Livermore experimental cross sections of reactions (γ, Sn), (γ, tot), $(\gamma, 1n)$ obtained for ^{206,207,208}Pb [4], as well as for ^{75}As [21], ^{127}I [22], and ^{181}Ta [23], are significantly and unreliably underestimated because of the loss of many neutrons from the reaction $(\gamma, 1n)$. Therefore, the experimental cross sections of those reactions for all six nuclei mentioned are not reliable and could not be recommended for using in estimation of Giant Dipole Resonance parameters and in various applications.

At the same time the new data for ^{206,207}Pb total and partial reaction cross sections evaluated using the experimental-theoretical method basing on the objective physical criteria of data reliability (Fig. 4, Table 3, Fig. 7, Table 5), as well as analogous data for ^{208}Pb [12] ^{75}As [19], ^{127}I [20], and ^{181}Ta [12] can be preferably recommended for using in basic research and various applications basing on all that has been said above.

New and reliable measurements of ^{206,207}Pb photonuclear reaction yields, total and partial reaction cross sections are welcome to confirm the results of evaluations.

This research was carried out at the Department of Electromagnetic Processes and Atomic Nuclei Interactions of the

Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics.

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