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EVALUATION OF (γ,xn), (γ,sn), (γ,n), (γ,2n), AND (γ,f) REACTIONS CROSS SECTIONS FOR ACTINIDES NUCLEI ^{232}Th, ^{238}U, ^{237}Np, AND ^{239}Pu: CONSISTENCY BETWEEN DATA OBTAINED USING QUASIMONOENERGETIC ANNIHILATION AND BREMSSTRAHLUNG PHOTONS

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Abstract

The detailed systematical analysis of the (γ,xn), (γ,sn), (γ,n), (γ,2n) and ((γ,f) reaction cross section data obtained by using quasimonoenergetic annihilation photon beams at Livermore (USA) and Saclay (France) was carried out for 4 actinides nuclei ^{232}Th, ^{238}U, ^{237}Np and ^{239}Pu. For overcoming of significant disagreements between the data and moving them into consistence the special method proposed before for taking into account both laboratories neutron multiplicity sorting procedure features was applied. The results of experiments used bremsstrahlung were also used. For all 4 nuclei the jointly corrected reaction cross sections were evaluated.

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В.В.Варламов, Н.Н.Песков

ОЦЕНКА СЕЧЕНИЙ РЕАКЦИЙ (γ,xn), (γ,sn), (γ,n), (γ,2n) И (γ,f) ДЛЯ ЯДЕР АКТИНИДОВ ^{232}Th, ^{238}U, ^{237}Np И ^{239}Pu: СОГЛАСОВАНИЕ ДАННЫХ, ПОЛУЧЕННЫХ С ПОМОЩЬЮ КВАЗИМОНОЭНЕРГЕТИЧЕСКИХ АННИГИЛЯЦИОННЫХ ФОТОНОВ И ТОРМОЗНОГО γ-ИЗЛУЧЕНИЯ

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Аннотация

Для 4 ядер актинидов ^{232}Th, ^{238}U, ^{237}Np и ^{239}Pu выполнен детальный систематический анализ данных по сечениям реакций (γ,xn), (γ,sn), (γ,n), (γ,2n) и (γ,f), полученных с помощью пучков квазимоноэнергетических аннигиляционных фотонов в Ливерморе (США) и Саклэ (Франция). Для преодоления имеющихся между данными обеих лабораторий существенных расхождений и приведения их к согласованию был использован предложенный ранее специальный метод, учитывающий особенности использованных в обеих лабораториях процедур сортировки фотонейтронов по множественности. Использовались также результаты экспериментов с тормозным γ–излучением. Для всех 4 ядер оценены взаимно скорректированные сечения реакций.

Работа выполнена в Отделе электромагнитных процессов и взаимодействий атомных ядер НИИЯФ МГУ и частично поддержана грантом Президента РФ № НШ-1619.2003.2 для поддержки ведущих научных школ РФ.

Introduction

As is well-known photonuclear data are widely used in both basic and applied research and in variety of applications. At the last time there is a renewed interest in photonuclear reactions especially for heavy fission nuclei, first of all to actinides. The importance of those data is reflecting by the existence of specific IAEA coordinated research program [1]. It is evident that the most accurate and reliable data are needed. The very nice evaluations for four actinides ^{232}Th, ^{235,238}U, and ^{239}Pu carried out using Giant Dipole Resonance (GDR) and quasideutron mechanisms were presented [2] on the 2007 International Conference on Nuclear Data for Science and Technology. The data for both total and partial photoneutron reaction cross section and photofission reaction data obtained using various photon beams have been used.

There are many data published but unfortunately, at the same time, there are many significant disagreements between data obtained using different methods and/or at different laboratories. The absence of intensive beams of monoenergetic photons is one of the main problems of experimental investigations of the γ-quanta interactions with atomic nuclei. This demands using of various methods for creation special conditions in which the effective photon energy spectrum in any approach can be interpreted as similar to the monoenergetic one (as whole looks like monoenergetic). In general there are many ways for this, which could be separated into two main groups: “mathematical” and “apparatus” ones.

The “mathematical” way means that at first step measurements could be carried out using bremsstrahlung with continuous energy spectrum and after that at second step one of many procedures (method of inverse matrix, method of photon difference, Penfold-Leiss's method, Cook’s method of least structure, Tikhonov’s method of regularization, and others) could be used for reaction cross section unfolding from experimental reaction yield.

The idea of “apparatus” way is to avoid unfolding procedure and measure not the reaction yield but cross section “directly”. This way means obtaining the photon energy spectrum that looks like spectrum of quasimonoenergetic photons in the experiment directly. The main method for this is the using of the annihilation in flight of relativistic positrons. The majority of such kind experiments were carried out at USA National Lawrence Livermore Laboratory and at Centre d’Etudes Nucleaires de Saclay (France).

Because the experiment conditions of measurements with bremsstrahlung and quasimonoenergetic photons, first of all the shapes of effective photon spectra, are quite different, this leads to the definite systematic disagreements of their results also in both, the amplitude (absolute value), and the shape (intermediate structure). Moreover the certain discrepancies exist between the same total and partial reaction cross section data obtained using the same method (both bremsstrahlung and annihilation photon beam) but at various laboratories in absolute values also because the presence of definite additional energy dependent systematical errors in energy calibration and data normalization. Therefore for obtaining of accurate and reliable data one need overview and analyze all available systematics of data for both total and partial photoneutron reaction cross sections and evaluate the most reliable reaction cross sections.

A detailed systematic analysis [3] of the (γ,xn), (γ,n) and (γ,2n) reaction cross-section data obtained using quasimonoenergetic annihilation photon beams at Livermore and Saclay was carried out for 19 nuclei (7 initially): ^{51}V, ^{75}As, ^{89}Y, $_{90}$Zr, ^{115}In, ^{116,117,118,120,124}Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, ^{238}U. It was found out that the (γ,xn) reaction cross-section data obtained at both laboratories without using a neutron multiplicity determination procedure disagreed by ~ 10 - 15%, but the disagreement of the (γ,n) and (γ,2n) partial reaction cross-sections obtained at both laboratories using neutron multiplicity determination procedure was significantly greater (up to 30 - 40%), and as a rule in different directions. These disagreements were interpreted as being the result of differences in the neutron multiplicity determination procedures used in both laboratories: the procedure at Saclay was incorrect, resulting in the incorrect attribution of part of the (γ,2n) reaction cross- section to the (γ,n) reaction: 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. A special method was used to make the data consistent. This involved recalculating the part of the (γ,n) reaction cross-section determined to be ”false‘ and moving it back to the (γ,2n) reaction cross-section. For all 19 nuclei listed above, the jointly corrected (γ,xn), (γ,n) and (γ,2n) reaction cross-sections were evaluated and prepared for inclusion in the EXFOR nuclear reaction database.

Unfortunately for heaviest fission nuclei ^{232}Th and ^{238}U the possible contributions of photofission reaction (γ,f) cross sections which play important role in all energy region investigated because of very low threshold have not been taken into account [3]. In this connection the aim of this work is once more to overview and analyze actinides nuclei ^{232}Th and ^{238}U photonuclear reaction cross sections (γ,xn), (γ,sn), (γ,n), (γ,2n) and (γ,f) data obtained in both laboratories, to add to this group of fission nuclei ^{237}Np for which also data were obtained in both laboratories and after that use the obtained evaluation recommendations for ^{239}Pu investigated only at Livermore.

1. Systematic overview of total photoneutron reaction cross sections

For the complete systematic of integrated cross sections date were used obtained [4] for number (more than 500) of (γ,xn) reaction cross section data for nuclei from ^{3}H to ^{238}U. To avoid additional errors connected with taking into account photoneutron multiplicity, the integrated cross sections for each nucleus were calculated for incident photon energy ranges between the (γ,n) and (γ,2n) reaction thresholds. The systematic of ratios of total photoneutron raction integration cross section values $R^{int}_{syst} = \sigma^{int}_{various}(\gamma,xn)/\sigma^{int}_{Livermore}(\gamma,xn)$ of the data from various laboratories to that from Livermore laboratory, is presented on Fig. 1.

The result shown on figure confirms clearly that systematical disagreements exist definitely: one can see that Livermore data are lower than others - the average value of ratio $<R^{int}_{syst}> \neq 1$. In spite of some spread of the R^{int}_{syst} values obtained in various laboratories they are clearly concentrated near the value $<R^{int}_{syst}> = 1.12 \pm 0.24$. It was specially underlined that (γ,xn) reaction cross section data obtained at Saclay in absolute values are more consistent with data of other laboratories obtained using both quasiumonoenergetic photons (at General Atomic, Pennsylvania, Illinois, and Giessen) and bremsstrahlung (primarily at Moscow State University (Russia) and University of Melbourne (Australia)) than with Livermore data. Such divergences in the absolute values of the reaction cross-sections could be caused by "… an Livermore experiments error either in the photon flux determination or in the neutron detection efficiency or in both" [5].

It must be pointed out that for actinides nuclei (A > 230) ratios R^{int}_{syst} are close not to 1.12 and more not to 1.0, but to ~ 0.8. That means that for all four nuclei under discussion (γ,xn) cross sections obtained at Livermore are not smaller but larger than those obtained at Saclay and other laboratories (one can see on Fig. 1 many cases of such kind disagreements also). By the way for 17 nuclei (without ^{232}Th and ^{238}U) systematically investigated before [3] the averaged individual ratio $<R^{int}_{Th,U}>$ is equal to 1.118 that is very close to the $<R^{int}_{syst}>$ value, but for all 19 nuclei that is clearly smaller – 1.074. So the situation is not typical and demands the special investigation.

2. Comparison of ^{232}Th, ^{238}U and ^{237}Np photoneutron and photofission reaction cross sections obtained both at Saclay and Livermore

All published initial data under discussion obtained at Livermore and Saclay for ^{232}Th [6,7], ^{238}U [6,7] and ^{237}Np [7,8] are presented on the left sides ("Before") of Figs. 2 - 4 correspondingly. One can see that almost all cross sections under discussion obtained at Saclay have absolute values clearly smaller than those obtained at Livermore.

It is very important that though all reaction cross sections must be in consistency to each other the correspondent ratios S/L are differing individually for each reaction. That is very clearly seen from correspondent integrated cross sections and ratios data (Tables 1 – 3, columns "Before"): 0.62 - 1.02 for ^{232}Th, 0.80 - 0.88 for ^{238}U and 0.41 – 0.93 for ^{237}Np.

It must be pointed out that for each of three nuclei under investigation the situations are individual: for ^{238}U Saclay and Livermore data are near consistency, for ^{232}Th the most inconsistency exists for (γ,f) reaction, but for ^{237}Np – for (γ,2n) reaction. For all three nuclei the σ(γ,n) and σ(γ,2n) reactions cross section data confirm the conclusions [3] that at Saclay compare to Livermore σ(γ,n) are overestimated and σ(γ,2n) underestimated. From the point of view of [3] it is resulted from the different procedures of neutron multiplicity sorting.

In this connection the special attention must be paid to the multiplicity of prompt photofission neutrons. As was mentioned above because of very low thresholds of (γ,f) reaction instead of equation

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

has been used in [3] the following one

$$\sigma(\gamma,xn) = \sigma(\gamma,n) + 2\sigma(\gamma,2n) + \nu\sigma(\gamma,f), \quad (2)$$

must be used for joint evaluation where ν is the averaged prompt photofission neutron multiplicity. Using equation (2) one can obtain real values for ν from the experimental photoneutron and photofission reaction cross sections

$$\nu = [\sigma(\gamma,xn) - \sigma(\gamma,n) - 2\sigma(\gamma,2n)]/\sigma(\gamma,f). \quad (3)$$

The data for ν obtained using experimental data for photoneutron and photofission cross sections are presented on Figs. 2f, 3f and 4f. It must be pointed out that for all three nuclei under discussion ν data have been obtained using equation (3) for Livermore cross sections are in good agreement with those Livermore data specially investigated before [8, 10]. Data for ν obtained using equation (3) for Saclay cross sections are very close to Livermore data for ^{238}U (Fig. 3f), close but slightly systematically higher in comparison with Livermore data for ^{232}Th (Fig. 2f) and have clear differ energy dependence for ^{237}Np (Fig. 4f).

Because of new doubts concern the Saclay neutron multiplicity sorting procedure later on the Livermore ν data will be used for correction of Saclay reaction cross sections.

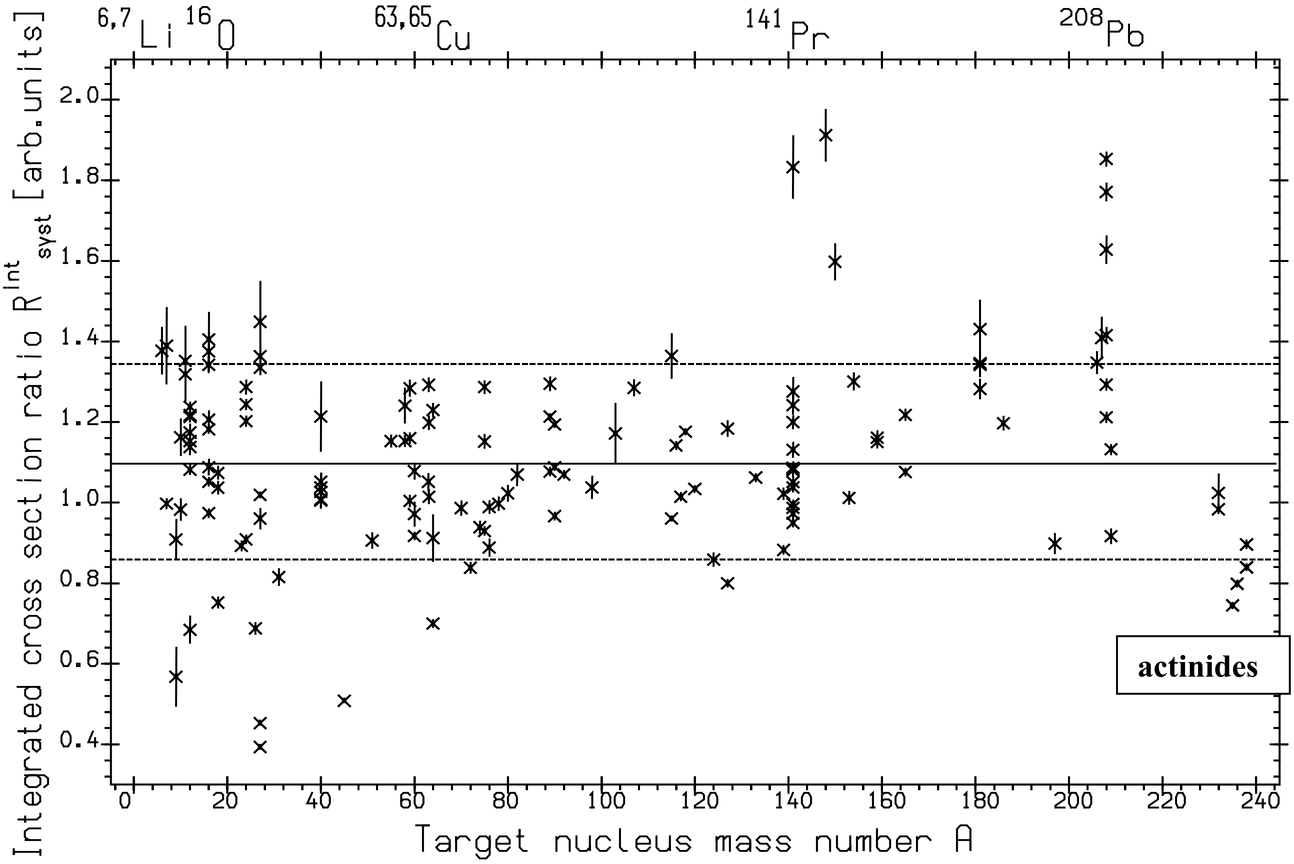

Fig.1. Complete R^{int}_{syst} systematic up to the (γ,2n) reaction threshold for various nuclei, obtained using various photon beams in various laboratories and using quasimonoenergetic annihilation photons at Livermore. Continuous line – mean value $<R^{int}_{syst}> = 1.12$, dotted lines – boundaries of the standard deviation range.

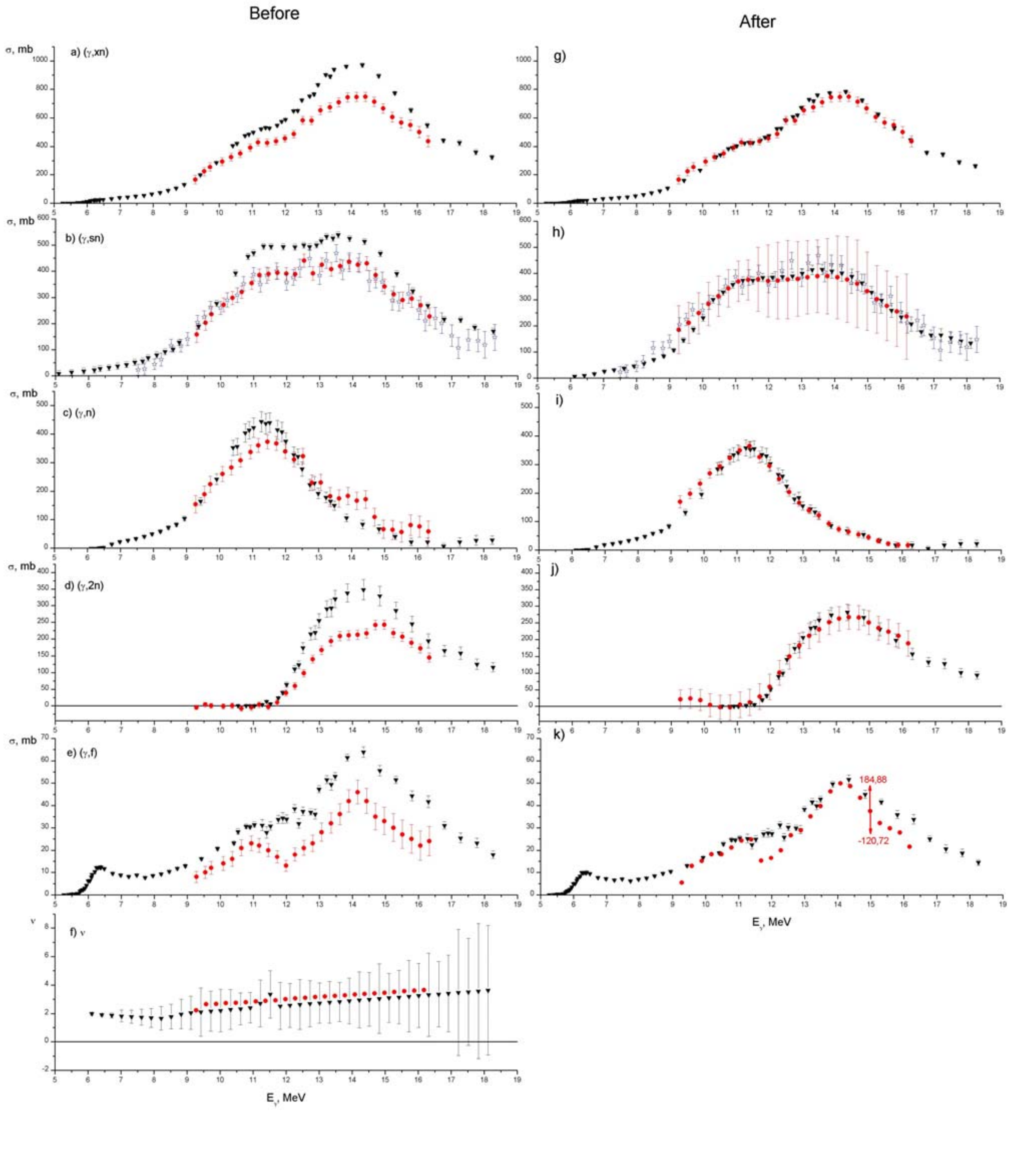

Fig 2. All published initial ("Before", left) and evaluated ("After", right) data for ^{232}Th under discussion (Livermore [6] – triangles, Saclay [7] – circles) data:

a), g) - total photonuclear reaction (γ,xn) cross section;

b), h) - (γ,sn) reaction cross section; stars – (γ,abs) cross section [9];

c), i) - (γ,n) reaction cross section;

d), j) - (γ,2n) reaction cross section;

e), k) - (γ,f) cross section;

f) – neutron multiplicity.

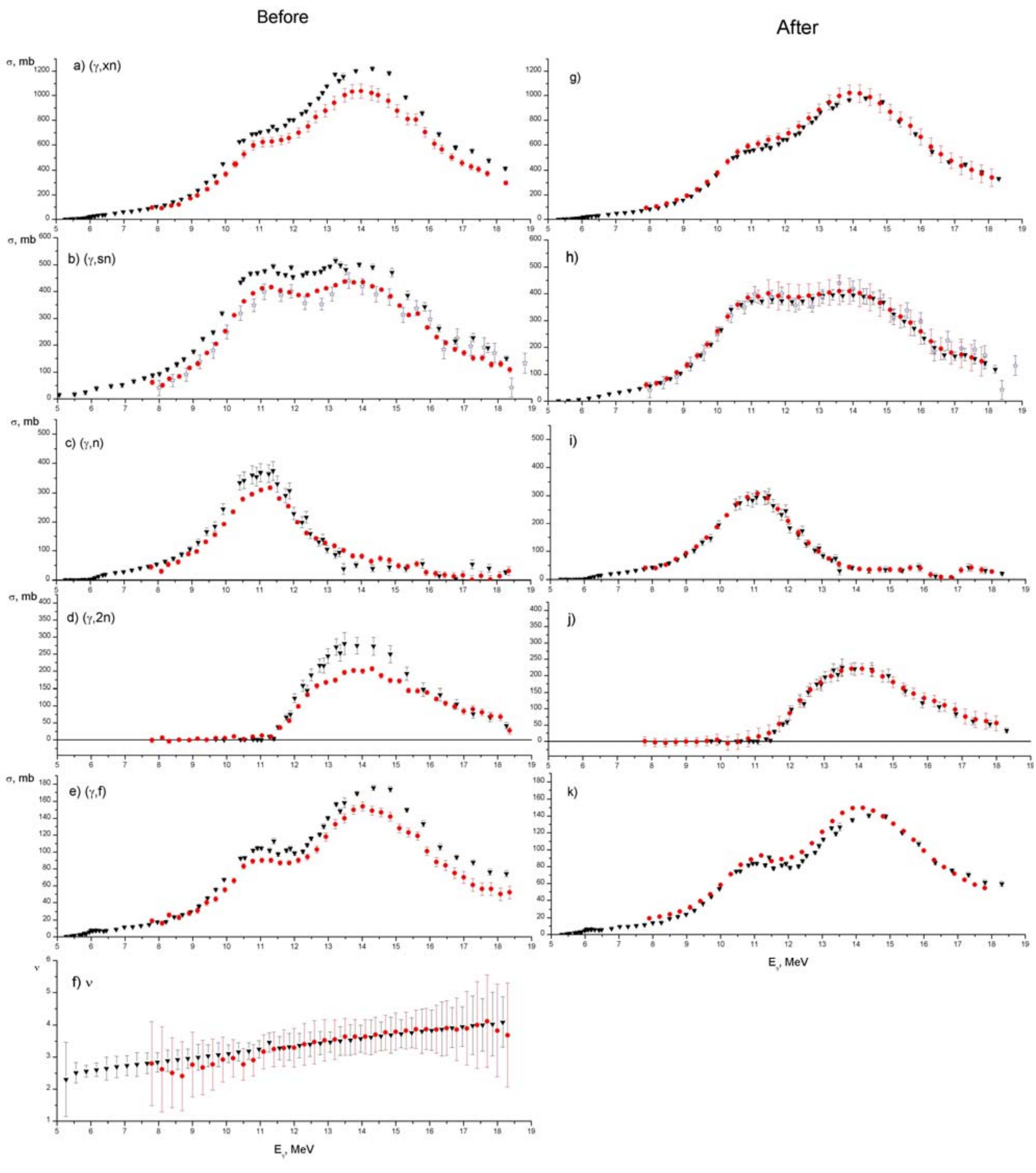

Fig 3. All published initial ("Before", left) and evaluated ("After", right) data for ^{238}U under discussion (Livermore [6] – triangles, Saclay [7] – circles) data:

a), g) – total photonuclear reaction (γ,xn) cross section;

b), h) - (γ,sn) reaction cross section; stars – (γ,abs) cross section [9];

c), i) - (γ,n) reaction cross section;

d), j) - (γ,2n) reaction cross section;

e), k) - (γ,f) cross section;

f) – neutron multiplicity.

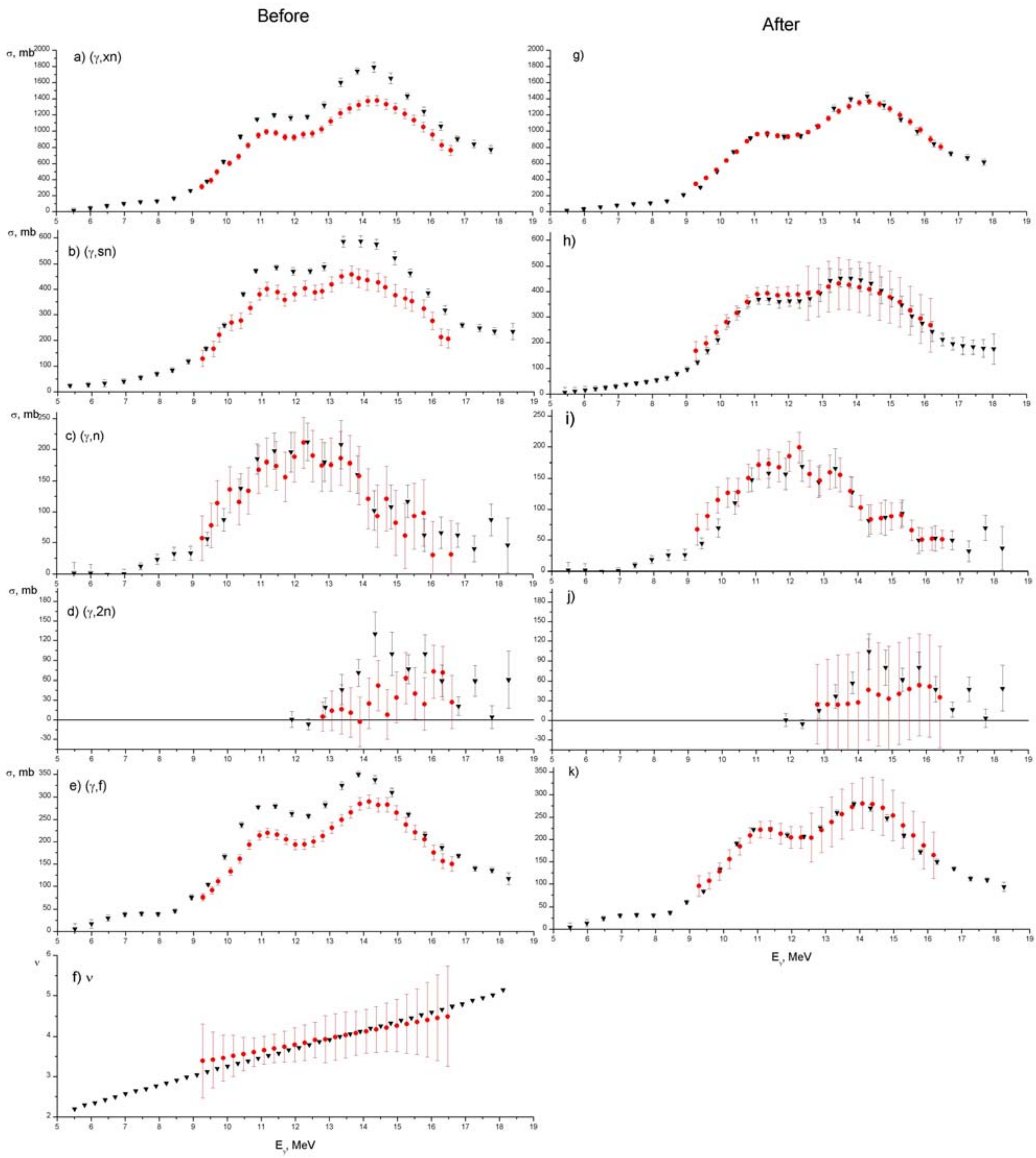

Fig 4. All published initial ("Before", left) and evaluated ("After", right) data for ^{237}Np under discussion (Livermore [8] – triangles, Saclay [7] – circles) data:

a), g) – total photonuclear reaction (γ,xn) cross section;

b), h) - (γ,sn) reaction cross section;

c), i) - (γ,n) reaction cross section;

d), j) - (γ,2n) reaction cross section;

e), k) - (γ,f) cross section;

f) – neutron multiplicity.

Table 1.

^{232}Th various reactions integrated cross section data
and Saclay [7]/Livermore [6] ratios calculated for joint energy ranges

Reaction	Before			After		
	Saclay	Livermore	Ratio S/L	Saclay	Livermore	Ratio S/L
(γ,xn)	3637 ± 82	4594 ± 27	0.79	3636 ± 82	3711 ± 22	0.98
(γ,sn)	2468 ± 72	3046 ± 31	0.81	2304 ± 334	2322 ± 53	0.99
(γ,n)	1510 ± 78	1482 ± 59	1.02	1205 ± 37	1194 ± 48	1.00
(γ,2n)	784 ± 29	1160 ± 51	0.68	912 ± 88	913 ± 40	1.00
(γ,f)	175 ± 12	284 ± 5	0.62	194 ± 413	225 ± 4	0.86

Table 2.

^{238}U various reactions integrated cross section data
and Saclay [7]/Livermore [6] ratios calculated for joint energy ranges

Reaction	Before			After		
	Saclay	Livermore	Ratio S/L	Saclay	Livermore	Ratio S/L
(γ,xn)	6054 ± 165	7283 ± 40	0.83	6054 ± 165	5823 ± 32	1.04
(γ,sn)	2945 ± 22	3806 ± 37	0.77	2837 ± 157	2740 ± 54	1.04
(γ,n)	1161 ± 30	1320 ± 55	0.88	1070 ± 30	1052 ± 44	1.02
(γ,2n)	906 ± 20	1129 ± 51	0.80	929 ± 57	892 ± 40	1.04
(γ,f)	895 ± 16	1065 ± 8	0.84	869 ± 120	822 ± 6	1.06

Table 3.

^{237}Np various reactions integrated cross section data
and Saclay [7]/Livermore[8] ratios calculated for joint energy ranges

Reaction	Before			After		
	Saclay	Livermore	Ratio S/L	Saclay	Livermore	Ratio S/L
(γ,xn)	7242 ± 133	9056 ± 109	0.80	7242 ± 133	7104 ± 86	1.02
(γ,sn)	2529 ± 86	3159 ± 110	0.80	2462 ± 203	2404 ± 84	1.02
(γ,n)	937 ± 121	1016 ± 77	0.93	876 ± 62	788 ± 60	1.11
(γ,2n)	120 ± 73	291 ± 50	0.41	134 ± 144	222 ± 38	0.60
(γ,f)	1520 ± 35	1890 ± 18	0.81	1467 ± 119	1420 ± 13	1.03

3. ^{232}Th and ^{238}U photoneutron and photofission reaction cross sections joint evaluation

Because of unusual (differ from complete systematic of integrated cross section ratios) balance of total photonuclear reaction (γ,xn) cross sections – those from Livermore are not smaller but larger that those from Saclay – it is very important to compare both of them with another kind data, first of all obtained using bremsstrahlung.

Unfortunately there are not such kind data. But for both nuclei the total photoabsorption cross sections

$$\sigma(\gamma,abs) = \sigma(\gamma,n) + \sigma(\gamma,2n) + \sigma(\gamma,p) + \sigma(\gamma,f) \quad (4)$$

obtained using bremsstrahlung have been published [9]. It is well known that σ(γ,p) for heavy nuclei is very small in comparison of others mentioned. For example for ^{208}Pb the amplitude of σ(γ,p) is equal to ~ 2 mb, σ(γ,2n) - ~ 140 mb, σ(γ,n) - ~ 700 mb. Therefore one can describe the total photoabsorption reaction cross section by the equation

$$\sigma(\gamma,abs) \approx \sigma(\gamma,n) + \sigma(\gamma,2n) + \sigma(\gamma,f) = \sigma(\gamma,sn). \quad (5)$$

In this connection the experimental total photoabsorption reaction cross sections [9] are presented on Figs. 2b and 3b. One can see that for both nuclei under discussion the shapes of σ(γ,abs) [9] are in very good agreement with the shapes of both Saclay σ(γ,sn) [7] and Livermore σ(γ,sn) [6]. At the same time absolute values of σ(γ,abs) [9] are in agreement to those of Saclay σ(γ,sn) [7] and contradict to those of Livermore σ(γ,sn) [6]. That confirms again the conclusions [3, 4] about reliability of total photoneutron reaction cross section data obtained at Saclay and about many doubts in reliability of those obtained at Livermore.

Livermore data evaluation.

Therefore the way to evaluate the most reliable data for all σ(γ,xn), σ(γ,sn), σ(γ,n), σ(γ,2n) and σ(γ,f) reaction cross sections is normalization of Livermore experimental cross sections using ratio

$$K = \sigma^{int}_{[9]}(\gamma,abs)/\sigma^{int}_{[6]}(\gamma,sn). \quad (6)$$

For ^{232}Th (Fig. 2b) K(Th) = 0.84, for ^{238}U (Fig. 3b) K(U) = 0.83. The data obtained for all reaction cross sections by this way – normalization of Livermore data using K(Th) and K(U) calculated values are presented on Figs. 2g-k and 3g-k (triangles).

Saclay data evaluation.

Because of Saclay incorrect procedure of neutron multiplicity sorting [3] the reciprocal correction method proposed for joint Saclay and Livermore data evaluation must be used:

$$R = \sigma(\gamma,xn)_S/\sigma(\gamma,xn)_L = (\sigma(\gamma,n)_S + 2\sigma(\gamma,2n)_S)/(\sigma(\gamma,n)_L + 2\sigma(\gamma,2n)\sigma_L), \quad (7)$$

$$\sigma(\gamma,xn)_S = (\sigma(\gamma,n)_S + 2\sigma(\gamma,2n)_S) = R\sigma(\gamma,xn)_L = R(\sigma(\gamma,n)_L + 2\sigma(\gamma,2n)\sigma_L) \quad (8)$$

$$R\sigma(\gamma,2n)_L = \sigma(\gamma,2n)_S^{eval} = \sigma(\gamma,2n)\sigma_S + 1/2(\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L). \quad (9)$$

$$R\sigma(\gamma,n)\sigma_L = \sigma(\gamma,n)_S^{eval} = \sigma(\gamma,n)\sigma_S - (\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L). \quad (10)$$

The right-hand side of expression (9) has the same meaning as discussed above: part of the (γ,n) reaction cross-section $(1/2(\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L))$, determined by taking into account the coefficient R and using the data on the (γ,xn) reaction cross-sections, is added to the (γ,2n) reaction cross-section value determined at Saclay $\sigma(\gamma,2n)_S$.

Here it is important to note that, if the disagreement between the Livermore and Saclay data is caused only by the Saclay photoneutron multiplicity error, the left-hand side of expression (9) should also apply: the evaluated Saclay cross-section $\sigma(\gamma,2n)_S^{eval}$ should agree with the Livermore cross-section $\sigma(\gamma,2n)_L$, multiplied by the coefficient R. The evaluated Saclay cross section $\sigma(\gamma,n)_S^{eval}$ can be obtained using (10) where difference $(\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L)$ is calculated in the energy region above B(2n) threshold.

In accordance with the method described the way for Saclay data evaluation is the following:

- after appropriate correction of the energy scales of the cross sections to be compared [3] the ratio $R = \sigma^{int}(\gamma,xn)_{[8]}/\sigma^{int}(\gamma,xn)_{[6]}$ is calculated; R(Th) = 0.93, R(U) = 1.00;
- in the energy region below the reaction (γ,2n) threshold $\sigma^{eval}(\gamma,n)_S = \sigma^{exp}(\gamma,n)_S$;
- in the energy region behind $\sigma^{eval}(\gamma,n)_S = R\,\sigma^{exp}(\gamma,n)_S$;
- $\sigma^{eval}(\gamma,2n)_S = \sigma^{exp}(\gamma,2n)_S + 1/2\,[\sigma^{exp}(\gamma,n)_S – R\,\sigma^{exp}(\gamma,n)_L]$;
- $\sigma^{eval}(\gamma,f)_S = [\sigma^{exp}(\gamma,xn)_S - \sigma^{exp}(\gamma,n)_S – 2\,\sigma^{eval}(\gamma,2n)_S]/\nu_L$, where ν is the averaged prompt photofission neutron multiplicity obtained for correspondent Livermore data (Figs. 2f, 3f).

The Saclay data evaluated by the way described are also presented on Figs. 2g-k and 3g-k (circles). From both figures and Tables 1, 2 one can see that on the whole these data are in good agreement with correspondent evaluated Livermore data. Arbitrarily poor agreement is achieved for reaction ^{232}Th(γ,f), very large uncertainties must be pointed out. The possible reason could be that the shapes of initial Livermore and Saclay cross sections differ significantly.

4. ^{237}Np photoneutron and photofission reaction cross sections joint evaluation

Unfortunately there are no appropriate data for extra normalization of data for ^{237}Np. But all mentioned above confirms that as a rule total photoneutron reaction (γ,xn) cross sections obtained at Saclay unlike to those obtained at Livermore are in consistency with many data obtained at various other laboratories using various photon beams. Therefore to obtain more reliable evaluated data one can use normalization of Livermore (γ,xn) reaction cross sections data to Saclay ones. All other ideas described can be used for joint evaluatuion of the all σ(γ,xn), σ(γ,sn), σ(γ,n), σ(γ,2n) and σ(γ,f) reaction cross sections obtained at Livermore [8] and Saclay [7].

Livermore data evaluation.

Therefore the way to evaluate the most reliable data for all σ(γ,xn), σ(γ,sn), σ(γ,n), σ(γ,2n) and σ(γ,f) reaction cross sections is normalization of Livermore experimental cross sections using coefficient $R = \sigma(\gamma,xn)_S/\sigma(\gamma,xn)_L = \sigma^{int}(\gamma,xn)_{[7]}/\sigma^{int}(\gamma,xn)_{[6]} = 0.78$. The data obtained for all reaction cross sections by this way – normalization of Livermore data using R calculated values are presented on Figs. 4g-k (triangles).

Saclay data evaluation.

For Saclay data the method described above ((7) – (10)) must be applied. The data evaluated by this way are also presented on Figs. 4g-k (circles). From that figure and Table 3 one can see that similar to two other nuclei under discussion on the whole evaluated Saclay data are in good agreement with correspondent evaluated Livermore data. Arbitrarily poor agreement is achieved for reaction ^{237}Np(γ,2n). The possible reason could be that data obtained at both laboratories have very different shapes and at the same time very poor accuracy.

5. Evaluation of ^{239}Pu photoneutron and photofission reaction cross sections

The situation with data published for ^{239}Pu (Fig. 5) can be treated as intermediate between two situations studied before – there are only Livermore data [8] and no Saclay data. But there are photoabsorption reaction data obtained bremsstrahlung [9].

One can see that unfortunately for ^{239}Pu in difference to ^{232}Th and ^{238}U discussed above the σ(γ,abs) [9] and Livermore σ(γ,sn) [6] are in contradiction not only in absolute value but in shape also. Moreover the very strange shapes of (γ,sn), (γ,n), (γ,2n) reactions cross sections in energy range near ~ 15 – 17 MeV are the reasons to suspect that in difference to all cases analyzed before in the case of ^{239}Pu there are some additional photoneutron multiplicity errors in Livermore data. At least the wide range of negative values of (γ,n) reaction cross section for energies near 15 – 17 MeV could be interpreted as result of some failure of neutron multiplicity sorting procedure in that case. Therefore the evaluation of reliable data in such case is quite a challenget.

But nevertheless formally all published before gives to one possibility to use very simple way for obtaining the evaluated (slightly improved) data – normalization of Livermore ^{239}Pu(γ,sn) data to bremsstrahlung photoabsorption data using coefficient K^*(Pu) = $\sigma^{int}_{[9]}(\gamma,abs)/\sigma^{int}_{[8]}(\gamma,sn)$ = 0.92, where * means that because of all things described before coefficient K was calculated for energy range up to B(2n) - threshold of (γ,2n) reaction.

Initial experimental data for ^{239}Pu are presented on Figs. 5 a-f and more evaluated data are presented on Figs. 5 g-k.

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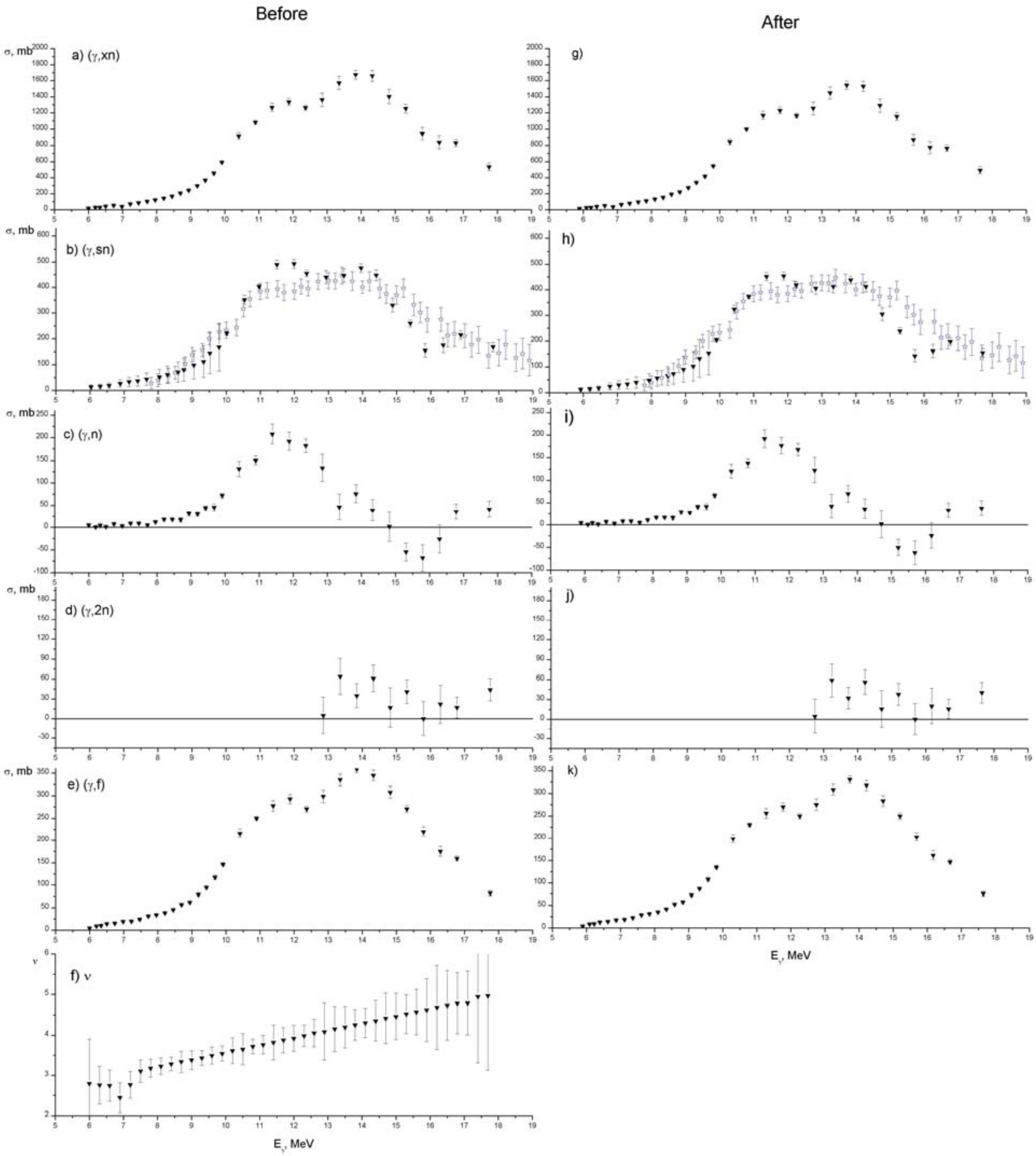

Fig 5. All published initial ("Before", left) and evaluated ("After", right) data for ^{239}Pu under discussion (Livermore [8] – triangles) data:

a), g) – total photonuclear reaction (γ,xn) cross section;
b), h) - (γ,sn) reaction cross section; stars – (γ,abs) cross section [9];
c), i) - (γ,n) reaction cross section;
d), j) - (γ,2n) reaction cross section;
e), k) - (γ,f) cross section;
f) – neutron multiplicity.

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ОЦЕНКА СЕЧЕНИЙ РЕАКЦИЙ (γ,xn), (γ,sn), (γ,n), (γ,2n) И (γ,f) ДЛЯ ЯДЕР АКТИНИДОВ ^{232}Th, ^{238}U, ^{237}Np И ^{239}Pu: СОГЛАСОВАНИЕ ДАННЫХ, ПОЛУЧЕННЫХ С ПОМОЩЬЮ КВАЗИМОНОЭНЕРГЕТИЧЕСКИХ АННИГИЛЯЦИОННЫХ ФОТОНОВ И ТОРМОЗНОГО γ-ИЗЛУЧЕНИЯ

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