INTERNATIONAL ATOMIC ENERGY AGENCY

INDC(CCP)-433
Distr.: GN/EL

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Study of Consistency Between (γ,xn), [(γ,n) + (γ,np)] and (γ,2n) Reaction Cross Sections Using Data Systematics

V.V.Varlamov, B.S.Ishkhanov

Skobeltsyn Institute of Nuclear Physics,
Lomonosov Moscow State University
119992 Moscow, Russia

August 2002

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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Nuclear Data Section
International Atomic Energy Agency
PO Box 100
Wagramer Strasse 5
A-1400 Vienna
Austria

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Abstract

The majority of published data for photoneutron reaction both total and partial cross section data obtained using both bremsstrahlung and quasimonoenergetic photon beams has been analyzed systematically. The last kind data were treated separately for results obtained at USA National Lawrence Livermore Laboratory and at Centre d'Etudes Nucleaires de Saclay (France). It was found out that as a rule total photoneutron reaction cross sections obtained at Livermore differ (being smaller in amplitude) from that of other laboratories. The Saclay-Livermore data discrepancies were analyzed in details. Combined the result of this analysis with that of analysis of partial photoneutron reactions [(γ,n) + (γ,np)] and (γ,2n) cross sections balance between Livermore and Saclay data published before the following recommendation was formulated: for reliable balance of total photoneutron (γ,xn) and partial [(γ,n) + [(γ,np)] and (γ,2n) reactions cross section absolute values the Livermore (not Saclay) data must be used but multiplied to the parameter 1.122. Saclay total reaction data could be used directly but partial reaction data must be recalculated via complex procedure.

August 2002

I. Introduction

The absence of intensive beams of monoenergetic photons is one of 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.

Mathematical. This way means that at first step measurements could be carried out using bremsstrahlung with continuous energy spectrum. 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. Some methods without unfolding, for example method of reduction, could be used also. The methods of data processing are constructed by such a manner that the needed result – reaction cross section – could be obtained for effective photon spectrum (experiment apparatus function) and looks like quasimonoenergetic.

Apparatus. The idea of this way is to avoid unfolding procedure and measure directly reaction cross section and not the yield. This way means obtaining at first step of the experiment the photon energy spectrum that looks like spectrum of quasimonoenergetic photons. The main method for this is the using of the annihilation in flight of relativistic positrons. The tagging of bremsstrahlung or some other special methods could be used also.

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). As well known, the same total photonuclear (primarily photoneutron) reaction cross sections have shape significantly smoother (less structure) when it is being obtained using quasimonoenergetic photons than bremsstrahlung. 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.

The aim of this work is to overview and analyze several available systematics of data for both total and partial photoneutron reaction cross sections and prepare the recommendations for reliable reaction cross section absolute value estimation.

II. The Photoneutron Reaction Cross Section Data Discrepancies

1. Total Photoneutron Reaction Cross Section Data Obtained Using Bremsstrahlung and Quasimonoenergetic Photons

The absolute majority of photonuclear reaction cross sections has been obtained using bremsstrahlung and quasimonoenergetic photons, produced by in flight annihilation of relativistic positrons at several laboratories, primarily at USA National Lawrence Livermore Laboratory and at Centre d'Etudes Nucleaires de Saclay (France).

The typical example of discrepancies concerned could be obtained from the detailed comparison[1)] (**Table 1 –** authors data) of (γ,xn) = [(γ,n) + (γ,np) + 2(γ,2n)] reaction cross sections for ^{18}O obtained using bremsstrahlung[1)] (BR, University of Melbourne, Australia) and quasimonoenergetic photons[2)] (QM, Lawrence Livermore Laboratory, USA).

Despite authors[1)] say about good agreement between experimental data, it is clear that almost all resonances have larger amplitudes in BR- than in QM-photon cross sections. Moreover the integrated cross section values for incident photons energies 8 – 28 MeV are different also: σ^{int}_{BR} = 187 MeV×mb and σ^{int}_{QM} = 177 MeV×mb (corresponding ratio is equal to 1.06).

Table 1

Comparison of QM- and BR-photon cross section resonance amplitudes

BR-experiment[1)]		QM-experiment[2)]		A_{BR}/A_{QM} [arbitrary units]
E [MeV]	A [mb]	E [MeV]	A [mb]	
9.1	1.4	9.1	1.1	1.27
10.4	6.5	10.3	5.3	1.27
11.6	11.5	11.5	9.0	1.28
13.2	8.5	13.1	8.6	1.00
14.0	8.5	13.8	6.9	1.23
14.8	14.0	14.8	13.1	1.07
15.8	13.0	15.8	10.9	1.19
17.6	10.5	17.2	10.1	1.04
19.3	12.0	19.1	10.0	1.20
23.6	21.0	23.7	17.7	1.19

2. The Total Photoneutron Reaction Cross Section Data Obtained Using Quasimonoenergetic Photons at Various Laboratories

2.1. 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 bremsstrahlung and quasimonoenergetic photons. The comparison of the integrated cross section data[3)] for QM-total photoneutron (γ,xn) reaction cross sections obtained at Livermore (USA) and Saclay (France) is shown in **Table 2**.

The only 5 cases[3] for very close integration energy limits E_γ^{max} or vise versa integrated cross section values σ^{int} are presented. 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.

Table 2

Comparison of QM-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_γ^{max} [MeV]	27.8 27.8	26.2 29.5	25.9 27.6	24.2 29.5	26.8 28.9
σ^{int} [MeV×mb]	689 654	1306 1130	1309 1158	2484 2505	3667 3385

Many other similar discrepancies exist[3] but they are not so evident because of large differences in the integration energy limits.

2.2. Reaction Cross Section Absolute Value

The photoneutron reaction cross sections for nuclei ^{nat}Zr, ^{127}I, ^{141}Pr, ^{197}Au, and ^{nat}Pb obtained earlier at Livermore were specially remeasuared[4] 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 3**.

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 %. It was mentioned[4] that "…this comparison implies an Livermore experiments error either in the photon flux determination or in the neutron detection efficiency or in both".

3. The Partial Photoneutron Reaction Cross Section Data Obtained Using Quasimonoenergetic Photons at Various Laboratories

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[5] for 12 nuclei in (γ,n) and (γ,2n) reaction cross section data obtained[3] at Livermore and Saclay as shown in **Table 4**.

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 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.

Table 3

Recommended[4)] normalization factors to improve Saclay and Livermore data agreement

Nucleus	Laboratory	Normalization factor F [arb. units]	Factor 1/F [arb. units]
^{nat}Rb	S	0.85 ± 0.03	
^{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	

Table 4

Comparison of QM-experiment integrated partial σ^{int}(γ,n) and σ^{int}(γ,2n) reaction cross section data (**Saclay**/Livermore) and R^{int}_{part}(γ,xn) = $\boldsymbol{\sigma^{int}_{S}}$**(γ,xn)**/$\sigma^{int}_{L}$(γ,xn).

Nucleus	(γ,np) reaction threshold [MeV]	σ^{int}(γ,n) [MeV×mb]	σ^{int}(γ,2n) [MeV×mb]	R^{int}_{part}(γ,xn) [arbitrary units]
^{89}Y	18.2	**1279**/960	**74**/99	1.255 ± 0.005
^{115}I	15.3	**1470**/1354	**278**/508	0.942 ± 0.004
^{117}Sn	16.2	**1334**/1380	**220**/476	1.012 ± 0.007
^{118}Sn	18.8	**1377**/1302	**258**/531	1.056 ± 0.005
^{120}Sn	19.0	**1371**/1389	**399**/673	0.987 ± 0.004
^{124}Sn	20.0	**1056**/1285	**502**/670	0.929 ± 0.006
^{133}Cs	15.0	**1828**/1475	**328**/503	1.106 ± 0.007
^{159}Tb	14.0	**1936**/1413	**605**/887	1.062 ± 0.001
^{165}Ho	13.5	**2090**/1735	**766**/744	1.136 ± 0.007
^{181}Ta	13.3	**2180**/1300	**790**/881	1.218 ± 0.018
^{197}Au	13.7	**2588**/2190	**479**/777	1.004 ± 0.013
^{208}Pb	14.9	**2731**/1776	**328**/860	1.296 ± 0.011

One can see very easily that in all presented cases while the integrated (γ,n) reaction cross section from Saclay is higher than that from Livermore, the integrated (γ,2n) reaction cross section is lower.

For example, in case of ^{159}Tb (**Table 4**) even though up to the (γ,2n) reaction threshold the (γ,n) reaction cross sections from Livermore and Saclay differ only at 6 %, their integrated cross sections up to 28 MeV are 2413 and 1936 MeV×mb, respectively. While the integrated (γ,n) reaction cross section from Saclay is at 37% higher than from Livermore, its integrated (γ,2n) reaction cross section is at 47% lower[5)].

III. Systematical Overview of Total Photoneutron Reaction Cross Section Values

1. Experimental Data

The complete systematic of integrated cross sections was obtained[6)] 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 (for details see part IV), 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^{int}_{syst} 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 $\langle R^{int}_{syst} \rangle \neq 1$. In spite of some spread of the R^{int}_{syst} values obtained in various laboratories they are concentrated near the value $\langle R^{int}_{syst} \rangle = 1.122 \pm 0.243$.

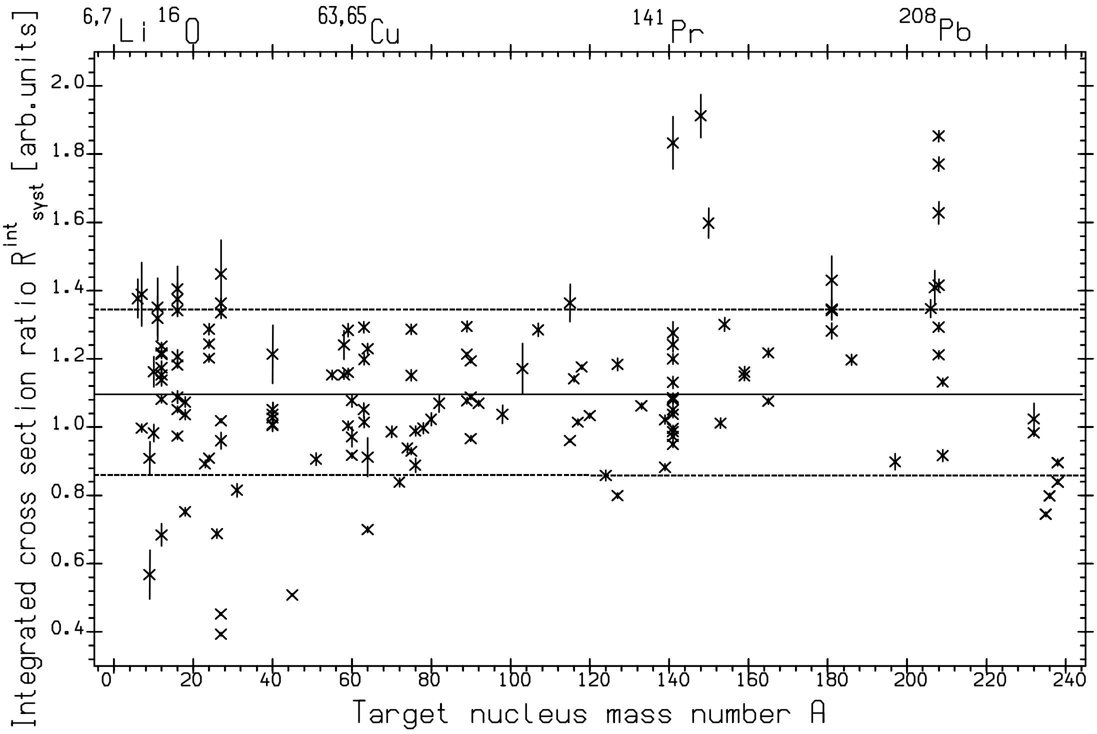

Fig.1. Complete R^{int}_{syst} systematic.

It is very important to underline 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.

2. Evaluated Data

The method of reduction[6,8,9].was proposed to exclude various systematical uncertainties in photonuclear experiments. Very shortly, this method gives a possibility to transform the data obtained with some effective photon spectrum (experimental apparatus function) to the form as they could be measured with other effective photon spectrum. Using more "better" apparatus function, for example having a shape of gaussian, one has a possibility to find reasonable monoenergetic representation for the cross section. It was found out also that there are additional energy dependent systematic errors in experiment calibration and normalization that essentially complicate the use of traditional methods of data evaluation. The method of reduction proposed[6,8,9] makes it possible to take into account all three types of systematic discrepancies under discussion and to obtain the evaluated reaction cross section with reliable shape and amplitude.

Using this method for reduction and subsequent evaluation of (γ,n) cross sections obtained in different laboratories (including the Livermore data) for ^{16}O, ^{28}Si, ^{63}Cu, ^{141}Pr, and ^{208}Pb nuclei, the ratios R^{int}_{eval} have been obtained[6] as ratios of evaluated energy-integrated cross sections to those of Livermore laboratory. The ratio averaged on five nuclei is equal $<R^{int}_{eval}> = 1.139 \pm 0.016$.

3. Data Obtained by Summation of Partial Reaction Cross Sections

It was mentioned above that there are clear discrepancies (**Table 4**) between the cross sections of (γ,n) and (γ,2n) reaction cross sections obtained at Saclay and Livermore. To avoid difficulties connected with neutron multiplicity measurement these data have been summed up[5] for common energy ranges to obtain the total photoneutron reaction cross sections (γ,xn) = (γ,n) + (γ,np) + 2(γ,2n). Its comparison reveals the evident disagreements between (γ,xn) reaction cross obtained at these laboratories: the averaged ratio of the total photoneutron integrated reaction cross sections $R^{int}_{part}(\gamma,xn) = \sigma^{int}_{S}(\gamma,xn)/\sigma^{int}_{L}(\gamma,xn)$ obtained at Saclay and Livermore is equal to $<R^{int}_{par}> = 1.084 \pm 0.082$ (authors[5] used the value r = 1.06 obtained for 12 nuclei given in Table 4).

IV. Partial [(γ,n) and (γ,2n)] Reaction Cross Section Data

The integrated cross section data presented in the **Table 4** confirm clearly the definite discrepancies between the cross sections of (γ,n) and (γ,2n) reaction cross sections obtained at Saclay and Livermore.

The balance of one-neutron (γ,n) and two-neutron (γ,2n) reaction cross sections obtained at Livermore and Saclay for nuclei from **Table 4** was analyzed[5] in details using the results of (e,n) and (e,2n) reaction cross section measurements for one nucleus – ^{181}Ta [10-12]. 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[5)] 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. Because Saclay neutron detector (large liquid scintillator) efficiency was not enough for correct neutron multiplicity sorting and Livermore detector (large array of $^{10}BF_3$ tubes) efficiency was enough, Saclay data for (γ,2n) reaction were underestimated but that for (γ,n) reaction – vise versa overestimated and must be corrected.

The following equation was proposed[5)]

$$\sigma^{S*}_{(\gamma,2n)} = \sigma^{S}_{(\gamma,2n)} + ½(\sigma^{S}_{(\gamma,n)} - <r = 1.06>\sigma^{L}_{(\gamma,n)}), \qquad (1)$$

to recalculate Saclay (γ,2n) reaction data – to transmit the “lost” part from (γ,n) to (γ,2n) channel. It was shown that recalculated cross sections $\sigma^{S*}_{(\gamma,2n)}$ from Saclay agree well with (γ,2n) reaction cross sections from Livermore multiplied by r = 1.06.

One can easily get convinced that using of value $<R^{int}_{par}> = 1.122$ ($<R^{int}_{par}> = 1.084$ at least) proposed above instead of r = 1.06

$$\sigma^{S*}_{(\gamma,2n)} = \sigma^{S}_{(\gamma,2n)} + ½(\sigma^{S}_{(\gamma,n)} - <r = 1.122>\sigma^{L}_{(\gamma,n)}), \qquad (2)$$

leads to better agreement of the data.

V. Conclusion

The following assertions could be done[13,14)] on the basis of presented data:

- some systematical discrepancies in photonuclear reaction cross sections exist between data obtained using different experimental methods or the same method but at different laboratories; the reasons for that are different effective photon spectra used and additionally energy dependent systematical errors in experiment calibration and normalization;
- the total photoneutron reaction cross sections obtained at Livermore using quasimonoenergetical photon beam have as a rule the absolute values smaller than that obtained by the same method at Saclay or with bremsstrahlung beam at various laboratories: different approaches gave the data disagreement factor equal to 1.06 – 1.17 (**Tables 1, 2**), 1.08 – 1.25 (**Table 3**), 1.122 (**Fig. 1**), 1.139[6)];
- Saclay data for (γ,2n) reaction are substantially underestimated but for (γ,n) reaction – overestimated in comparison with Livermore data and both must be corrected using proposed[5)] equation (1).

Therefore the reliability for total photoneutron reaction (γ,xn) and partial (γ,n) and (γ,2n) reactions cross sections and balance of the cross sections between channels will be improved if data obtained at Livermore are used but only after their normalization using discrepancy factor R. In spite of spread of R value discussed above (from 1.06 to 1.25), the value obtained for the complete set of data, which are not influenced by the uncertainty in measurements of neutron multiplicity – $R = <R^{int}_{syst}> = 1.122$ is a most reliable. At the same time the total photoneutron reaction cross sections obtained at Saclay can be used directly (without any additional normalization) but recalculation of partial reaction cross sections according equation (2) is needed.

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Nuclear Data Section	e-mail: services@iaeand.iaea.org
International Atomic Energy Agency	fax: (43-1) 26007
P.O. Box 100	cable: INATOM VIENNA
A-1400 Vienna	telex: 1-12645
Austria	telephone: (43-1) 2600-21710

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