# Comment on photoneutron cross sections

E. Wolynec, A. R. V. Martinez, P. Gouffon, Y. Miyao,
V. A. Serrão, and M. N. Martins
*Instituto de Física, Universidade de São Paulo,
São Paulo, São Paulo, Brazil*
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The differences between the Saclay and Livermore photoneutron cross sections are discussed. It is shown that the differences between Saclay and Livermore $(\gamma,n)$ and $(\gamma,2n)$ cross sections arise from the neutron multiplicity sorting.

[ NUCLEAR REACTIONS Photoneutron cross sections analyzed. ]

In the last 20 years, photoneutron cross sections have been measured for many nuclei using monoenergetic photons. Most of this work was carried out at two laboratories: Saclay and Livermore. The available results are compiled in the *Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons.*[1] There are also in the literature a few review articles on the subject, but none of these publications has addressed the problem of the differences between the measurements performed at Saclay and Livermore. In this paper we compare the Saclay and Livermore measurements for the nuclei listed in Table I.

The typical differences between Saclay and Livermore data are illustrated in Fig. 1, where the $(\gamma,n)$ measurements from Saclay and Livermore are shown. The results from Livermore are multiplied by 1.06 in order to show both cross sections in the same absolute scale. The cross sections are in good agreement up to the $(\gamma,2n)$ threshold. Above this energy there is an important difference: The

TABLE I. Nuclei measured by Saclay (S) and Livermore (L).

| Nucleus | $\int \sigma_{\gamma,n}(E_\gamma)\,dE_\gamma$ [a] (MeV mb) | $\int \sigma_{\gamma,2n}(E_\gamma)\,dE_\gamma$ [a] (MeV mb) | Reference | $r$ |
|---|---|---|---|---|
| $^{89}$Y | 1279 S | 74 S | 2 | 1.255 ±0.005 |
| | 960 L | 99 L | 3 | |
| $^{115}$I | 1470 S | 278 S | 4 | 0.942 ±0.004 |
| | 1354 L | 508 L | 5 | |
| $^{117}$Sn | 1334 S | 220 S | 4 | 1.012 ±0.007 |
| | 1380 L | 476 L | 5 | |
| $^{118}$Sn | 1377 S | 258 S | 4 | |
| | 1302 L | 531 L | 5 | |
| $^{120}$Sn | 1371 S | 399 S | 4 | 0.987 ±0.004 |
| | 1389 L | 673 L | 5 | |
| $^{124}$Sn | 1056 S | 502 S | 4 | 0.929 ±0.006 |
| | 1285 L | 670 L | 5 | |
| $^{133}$Cs | 1828 S | 328 S | 4 | 1.106 ±0.007 |
| | 1475 L | 503 L | 6 | |
| $^{159}$Tb | 1936 S | 605 S | 7 | 1.062 ±0.001 |
| | 1413 L | 887 L | 8 | |
| $^{165}$Ho | 2090 S | 7665 | 7 | 1.136 ±0.007 |
| | 1735 L | 744 L | 9 | |
| $^{181}$Ta | 2180 S | 790 S | 7 | 1.218 ±0.018 |
| | 1300 L | 881 L | 10 | |
| $^{197}$Au | 2588 S | 479 S | 11 | 1.004 ±0.013 |
| | 2190 L | 777 L | 12 | |
| $^{208}$Pb | 2731 S | 328 S | 11 | 1.296 ±0.011 |
| | 1776 L | 860 L | 13 | |

[a]From Ref. 1.

 

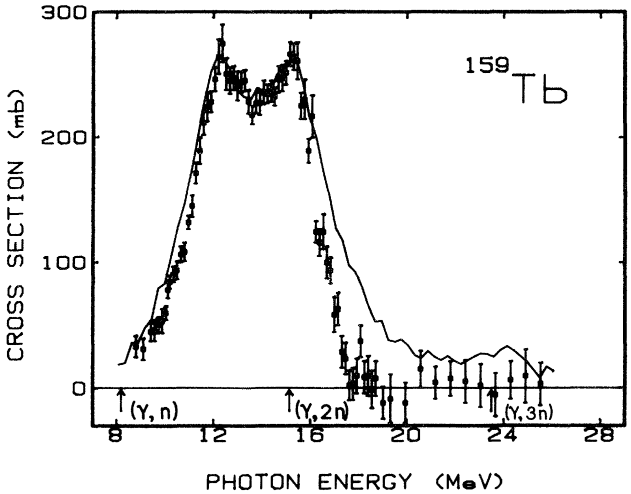


FIG. 1. $(\gamma,n)$ cross sections from Saclay (solid line) and Livermore (experimental points) for $^{159}Tb$. The Livermore data are multiplied by 1.06 in order to show both measurements at the same absolute scale.

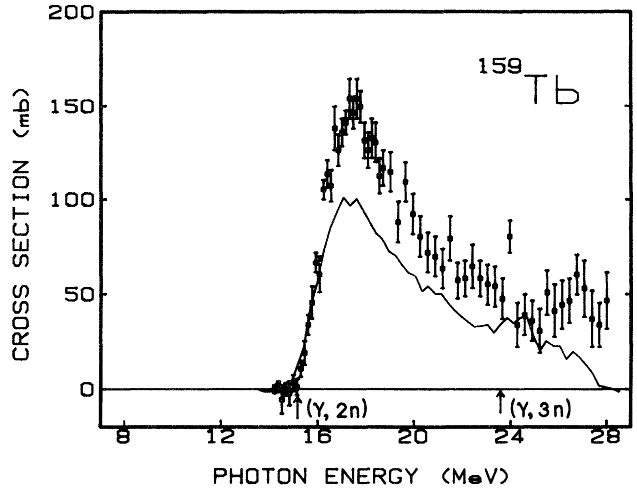


FIG. 2. $(\gamma,2n)$ cross sections from Saclay (solid line) and Livermore (experimental points) for $^{159}Tb$. The Livermore data are multiplied by 1.06 in order to show both measurements at the same absolute scale.

Livermore cross section vanishes a few MeV above the $(\gamma,2n)$ threshold, in good agreement with the predictions of the statistical model, while the Saclay cross section has a tail. In Ref. 7, the observed tail of the Saclay cross section is interpreted as arising from fast neutrons that would have escaped detection in the Livermore measurements, leading to the conclusion that for $^{159}Tb$ the contribution of the "direct effect" in the photoneutron cross section is $n_d = 23 \pm 4\%$. In Table II the percentages of direct neutrons inferred by Saclay are given for several nuclei.

Figure 2 shows the $(\gamma,2n)$ cross sections from Saclay and Livermore. The $(\gamma,2n)$ cross sections differ in shape and magnitude, the Livermore one being much bigger. Even though up to the $(\gamma,2n)$ threshold the $(\gamma,n)$ cross section from Livermore, $\sigma^L_{\gamma,n}$, and that from Saclay, $\sigma^S_{\gamma,n}$, differ by only 6% in the absolute scale, their integrated cross sections up to 28 MeV are 1413 and 1936 MeV mb, respectively. While the integrated $(\gamma,n)$ cross section from Saclay is 37% bigger than the Livermore result, their integrated $(\gamma,2n)$ cross section is 47% smaller.

In order to understand these differences we reconstructed the total neutron measurements from Saclay and Livermore:

$$\sigma_{\gamma,\mathrm{tn}} = \sigma_{\gamma,\mathrm{n}} + 2\sigma_{\gamma,2\mathrm{n}} + 3\sigma_{\gamma,3\mathrm{n}} \quad . \qquad (1)$$

Since $\sigma_{\gamma,\mathrm{tn}}$ is the cross section measured and the $(\gamma,n)$ and $(\gamma,2n)$ cross sections are obtained by neutron multiplicity sorting, it is important to compare $\sigma^S_{\gamma,\mathrm{tn}}$ and $\sigma^L_{\gamma,\mathrm{tn}}$. This comparison has not been discussed in the literature. Figure 3 shows $\sigma_{\gamma,\mathrm{tn}}$ from Saclay and Livermore for $^{159}Tb$. In Fig. 4 the ratio $r = \sigma^S_{\gamma,\mathrm{tn}}/\sigma^L_{\gamma,\mathrm{tn}}$ is shown. The ratio is reasonably constant and the least-squares fit of a constant yields the

TABLE II. Percentage of direct neutrons obtained by Saclay.

| Nucleus | $n_d$ (%) | References |
|---|---|---|
| $^{94}Mo$ | 25 ±7 | 14 |
| $^{96}Mo$ | 15 ±7 | 14 |
| $^{98}Mo$ | 10 ±7 | 14 |
| $^{100}Mo$ | 11 ±7 | 14 |
| $^{139}La$ | 28 ±5 | 7 |
| $^{140}Ce$ | 12 ±3 | 15 |
| $^{142}Ce$ | 10 ±3 | 15 |
| $^{nat}Sm$ | 10 ±3 | 15 |
| $^{159}Tb$ | 23 ±4 | 7 |
| $^{165}Ho$ | 23 ±4 | 7 |
| $^{nat}Er$ | 11 ±3 | 15 |
| $^{175}Lu$ | 15 ±3 | 15 |
| $^{181}Ta$ | 22 ±2 | 7 |
| $^{197}Au$ | 20 ±4 | 11 |
| $^{208}Pb$ | 15 ±4 | 11 |
| $^{238}U$ | 14 ±2 | 16 |

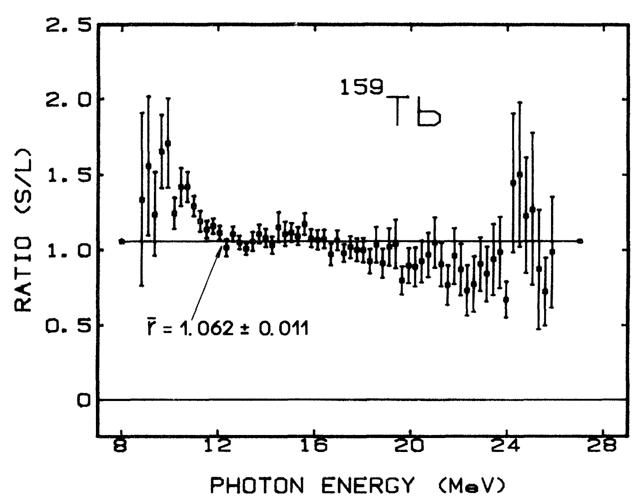


FIG. 3. $\sigma_{\gamma,\mathrm{tn}}$ from Saclay divided by $\sigma_{\gamma,\mathrm{tn}}$ from Livermore. $\sigma_{\gamma,\mathrm{tn}} = \sigma_{\gamma,\mathrm{n}} + 2\sigma_{\gamma,2\mathrm{n}} + 3\sigma_{\gamma,3\mathrm{n}}$.

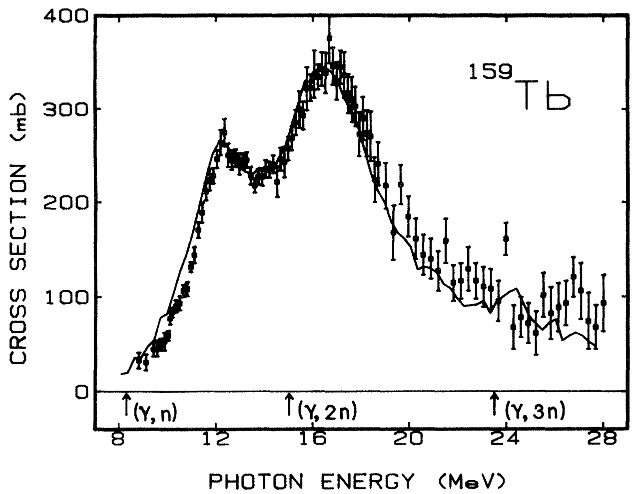


FIG. 4. $\sigma_{\gamma,\mathrm{tn}}$ from Livermore multiplied by 1.06 (experimental points) and $\sigma_{\gamma,\mathrm{tn}}$ from Saclay (solid line). $\sigma_{\gamma,\mathrm{tn}}=\sigma_{\gamma,\mathrm{n}}+2\sigma_{\gamma,2\mathrm{n}}+3\sigma_{\sigma,3\mathrm{n}}$.

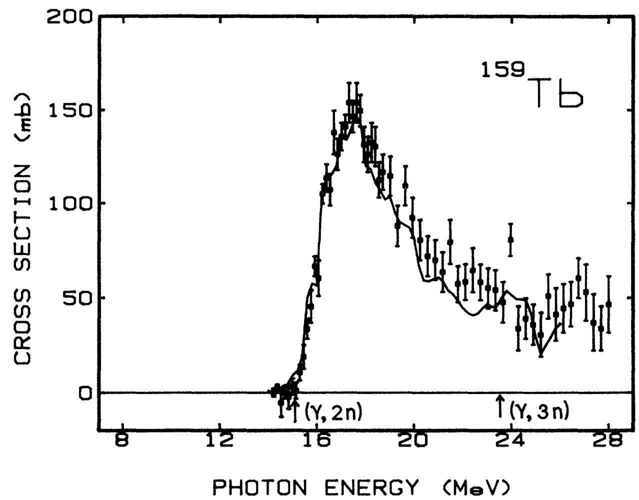


FIG. 5. $\sigma_{\gamma,2\mathrm{n}}$ from Livermore (experimental points) and the modified (see text) $\sigma_{\gamma,2\mathrm{n}}$ from Saclay (solid line).

value $r=1.062\pm0.011$. In order to compute $r$ we interpolated $\sigma^S_{\gamma,\mathrm{tn}}$ and $\sigma^L_{\gamma,\mathrm{tn}}$, since their data points are not at the same photon energies. One important conclusion can be derived from Fig. 3: Both laboratories are detecting the same number of neutrons for all photon energies. If there were fast neutrons escaping detection in the Livermore measurements above 20 MeV, $r$ should increase above this energy. The value of the constant $r$ is the difference in the absolute scale of both measurements. Figure 4 shows $\sigma^L_{\gamma,\mathrm{tn}}$ multiplied by 1.06 and $\sigma^S_{\gamma,\mathrm{tn}}$, just to illustrate the good agreement between them, when they are plotted at the same absolute scale.

Since both laboratories agree as to the total number of neutrons detected, the differences in their $(\gamma,\mathrm{n})$ and $(\gamma,2\mathrm{n})$ cross sections arise from the separation of the total counts into $(\gamma,\mathrm{n})$ and $(\gamma,2\mathrm{n})$ events (neutron multiplicity sorting).

If we assume that the excess $(\gamma,\mathrm{n})$ cross section in the Saclay measurement is due to $(\gamma,2\mathrm{n})$ events interpreted as two $(\gamma,\mathrm{n})$ events, that is, if we compute

$$\sigma^{S*}_{\gamma,2\mathrm{n}}=\sigma^S_{\gamma,2\mathrm{n}}+\tfrac{1}{2}(\sigma^S_{\gamma,\mathrm{n}}-1.06\sigma^L_{\gamma,n}) \ , \quad (2)$$

we obtain for $\sigma^{S*}_{\gamma,2\mathrm{n}}$ the solid line shown in Fig. 5. The modified $\sigma_{\gamma,2\mathrm{n}}$ cross section from Saclay agrees well with the $(\gamma,2\mathrm{n})$ cross section from Livermore multiplied by 1.06 (data points).

The same analysis carried out for $^{159}$Tb was repeated for all nuclei listed in Table I. The results obtained for these nuclei are presented in detail in a report from our Institute, available upon request.[17] Here we show only the results obtained by fitting a constant $r$ to the ratio $\sigma^S_{\gamma,\mathrm{tn}}/\sigma^L_{\gamma,\mathrm{tn}}$. The values of $r$ and the standard deviation of the mean are listed in Table I. For all these nuclei we obtained results similar to $^{159}$Tb:

(a) Both laboratories are detecting the same number of neutrons versus the incident photon energy.

(b) $\sigma^S_{\gamma,\mathrm{n}}$ is bigger than $r\sigma_{\gamma,\mathrm{n}}$ above the $(\gamma,2\mathrm{n})$ threshold.

(c) $\sigma^S_{\gamma,2\mathrm{n}}$ is smaller than $r\sigma^L_{\gamma,2\mathrm{n}}$.

(d) If $\sigma^S_{\gamma,2\mathrm{n}}$ is modified using Eq. (2), then $\sigma^S_{\gamma,2\mathrm{n}}$ and $\sigma^S_{\gamma,\mathrm{n}}$ are in agreement with $r\sigma^L_{\gamma,2\mathrm{n}}$, respectively.

The analysis performed here shows that the differences in shape and magnitude in the $(\gamma,\mathrm{n})$ and $(\gamma,2\mathrm{n})$ cross sections measured by Saclay and Livermore arise from the neutron multiplicity sorting.

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