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Experimental and evaluated photoneutron cross sections for ^{197}Au

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There is a serious well-known problem of noticeable disagreements between the partial photoneutron cross sections obtained in various experiments. Such data were mainly determined using quasimonoenergetic annihilation photon beams and the method of neutron multiplicity sorting at Lawrence Livermore National Laboratory (USA) and Centre d'Etudes Nucleaires of Saclay (France). The analysis of experimental cross sections employing new objective physical data reliability criteria has shown that many of those are not reliable. The IAEA Coordinated Research Project (CRP) on photonuclear data evaluation was approved. The experimental and previously evaluated cross sections of the partial photoneutron reactions $(\gamma,1n)$ and $(\gamma,2n)$ on ^{197}Au were analyzed using the new data reliability criteria. The data evaluated using the new experimental-theoretical method noticeably differ from both experimental data and data previously evaluated using nuclear modeling codes GNASH, GUNF, ALICE-F, and others. These discrepancies needed to be resolved.

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I. INTRODUCTION

Data on cross sections for partial photoneutron reactions with different numbers of outgoing particles, primarily $(\gamma,1n)$, $(\gamma,2n)$, and $(\gamma,3n)$, are important for both basic research [mainly for energies of giant dipole resonance (GDR)] and many applications for safety, geology, chemistry, medicine, etc. Those data are included in the international nuclear reaction database [1–3] and the Atlases [4,5]. The partial and total photoneutron cross-section data were mainly determined using quasimonoenergetic annihilation photon beams [4,6] at Lawrence Livermore National Laboratory (California) and Centre d'Etudes Nucleaires of Saclay (France).

The well-known significant data discrepancies were obtained for 19 nuclei from ^{51}V to ^{232}Th [7–10] investigated in both laboratories. Those are definitely systematic. Though the averaged disagreement among cross sections,

$$\sigma(\gamma,Sn) = \sigma(\gamma,1n) + 2\sigma(\gamma,2n) + 3\sigma(\gamma,3n), \tag{1}$$

of neutron yield reactions is about 10%, as a rule the $(\gamma,1n)$ reaction cross sections are larger at Saclay, but the $(\gamma,2n)$ cross sections are larger at Livermore (up to 60–100%). It was shown [10–12] that for those nuclei mentioned above the average ratio of integrated cross sections for Saclay data to those for Livermore data, $\sigma^{\mathrm{int}}_{\mathrm{S}}/\sigma^{\mathrm{int}}_{\mathrm{L}}$, is equal to 1.08 in the case of the $(\gamma,1n)$ reaction but 0.83 in the case of the $(\gamma,2n)$ reaction. For ^{197}Au under discussion the corresponding values are equal to 1.00 and 0.69 [1–3].

In experiments under discussion the neutrons were detected directly. In this case the neutron from the $(\gamma,1n)$ reaction is detected once, each neutron from the $(\gamma,2n)$ reaction twice, and so on. To identify a reaction with definite multiplicity one has to know what multiplicity should be assigned to the detected neutron. In both laboratories mentioned, the method use to separate reactions with different numbers of neutrons was the same: neutron multiplicity sorting. This method was based on the assumption that the energies of neutrons from partial photoneutron reactions $(\gamma,1n)$, $(\gamma,2n)$, and $(\gamma,3n)$ are radically different. Because the thresholds ($B1n, B2n$, and $B3n$, respectively, for the reactions mentioned) are relatively close to each other, in wide ranges of the incident photon energy there is a competition of two or three open partial reaction channels. The multiplicity of a detected neutron was determined on the basis of its kinetic energy measurement. Quite different methods were used to measure kinetic energy of neutrons for many cross-section determinations. Those are so called "ring-ratio" method at Livermore and the specifically calibrated large Gd-loaded liquid scintillator at Saclay. It was shown [7–10] that noticeable systematic uncertainties of the photoneutron multiplicity sorting were the reasons for the disagreements under discussion.

Those disagreements between Livermore and Saclay data were investigated in many special studies (for example, [7–12]). It has been shown that the main reason for the noticeable differences of the partial reaction cross sections is the difference of procedures used to separate counts into $1n$ and $2n$ events. The main result of that was unreliable transmission of many neutrons from one partial reaction to another. It was concluded that the some $(\gamma,2n)$ events were mistakenly interpreted as two $(\gamma,1n)$ events at Saclay. Therefore the Saclay data, which overestimated for the $(\gamma,1n)$ and underestimated for the $(\gamma,2n)$ reaction, were declared unreliable. At the same time Livermore data were declared reliable.

Despite those efforts, there has been a lack of evaluated photonuclear data. Users rely on raw data, primarily those from different (and often discrepant) measurements. It is difficult to develop a complete photonuclear data file on the basis of measured cross sections alone. These data were often obtained from different kinds of photon sources, causing significant systematic discrepancies. Nevertheless, recent developments both in methods to resolve experimental discrepancies and in nuclear theory are promising for use in the generation of evaluated photonuclear data. The evaluated cross sections for various photoneutron reactions and for many nuclei were produced using nuclear modeling codes GNASH, GUNF,

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GLANF, SLICE-F, and MCPHOTO by the IAEA Coordinated Research Project on Photonuclear Data and included into the IAEA Photonuclear Data Library (PDL) [13]. The IAEA PDL includes various evaluated photoneutron reaction cross sections, and neutron energy spectra for 164 isotopes of 48 elements (from ^{2}H to ^{241}Pu).

The IAEA PDL has been extremely useful to a broad community, but it is now evident that it needs to be revised and updated. The main reason for that is that objective physical criteria and the new theoretical method for reliable data evaluation were proposed. New partial and total photoneutron reaction cross sections for many nuclei (^{59}Co, ^{63,65}Cu, ^{91,94}Zr, ^{115}In, ^{133}Cs, ^{141}Pr, ^{159}Tb, ^{181}Ta, ^{186}W, $^{186-192}$Os, ^{197}Au, ^{208}Pb, ^{209}Bi) [9–12,14–17] were evaluated. Data satisfying the proposed physical reliability criteria in many cases differ noticeably from both the experimental data and the data evaluated before [13]. The IAEA Research Contract 20501 of the Coordinated Research Project F41032 on updating the photonuclear data library was adopted for period 2016–2019 [18].

The article is devoted to the description of the partial photoneutron reaction cross-section reliability problem, evaluation of reliable data for ^{197}Au, and comparison of the results of new and previous evaluations with corresponding experimental data.

II. PHYSICAL DATA RELIABILITY CRITERIA FOR PARTIAL PHOTONEUTRON REACTION CROSS SECTIONS

As mentioned above, for many nuclei it was shown that as a rule $\sigma(\gamma,1n)$ are unreliably overestimated in Saclay data and underestimated in Livermore data, and correspondingly $\sigma(\gamma,2n)$ are overestimated in Livermore data and underestimated in Saclay data [7–9]. The average ratio of integrated cross sections for Saclay data to those for Livermore data, $\sigma_{\mathrm{S}}^{\mathrm{int}}/\sigma_{\mathrm{L}}^{\mathrm{int}}$, is equal to 1.08 in the case of $(\gamma,1n)$ reaction but 0.83 in case of $(\gamma,2n)$ reaction [10–12]. For ^{197}Au specifically the corresponding values [19,20] are equal to 1.00 and 0.69 [1–3].

In order to clear up these outstanding discrepancies, the photoneutron cross sections for the nuclei Zr, I, Pr, Au, and Pb were remeasured across the peak of the giant dipole resonance [21]. For Au, $\sigma(\gamma,1n)$, $\sigma(\gamma,2n)$, and $\sigma(\gamma,\mathrm{tot})$ were measured in the energy range from 12.1 to 16.9 MeV. The results of mew measurements were compared with Saclay data. It was concluded that discrepancies exist. To put the data of the two laboratories into consistency it was recommended to use special normalization. But those normalizations were individual and quite different for each nucleus, and this looks strange. "In the case of ^{89}Y, the analysis of Sec. III indicates that the… the Saclay data should be multiplied by 0.82. For ^{197}Au, we recommend that the Saclay data be multiplied by 0.93 but that the Livermore data not be used at all. For ^{208}Pb, we recommend that the Livermore data be multiplied by 1.22 and the Saclay data by 0.93 [21]. The Livermore data for ^{89}Y were multiplied by 1.255 and for ^{208}Pb were multiplied by 1.255 in Ref. [21]. Before those phrases for $^{\mathrm{nat}}$Zr it was written [21] "Therefore, this comparison implies an error either in the photon flux determination or in the neutron detection efficiency or in both." In [22] it was written that "unfortunately this recommendation is based mainly on the data measured around the peak region of the GDR i.e. around about 14 MeV. In the region… close above the photoneutron reaction threshold, Berman et al. did not measure any data points at all. Therefore it is uncertain if their recommendation is also valid in this region." After accurate measurements of the ^{197}Au$(\gamma,1n)$ reaction cross section using the activation method in the energy range up to 9.9 MeV, a parametrization for the energy range up to 17 MeV noticeably different from experimental data [19,20] was obtained.

Moreover, because normalization factors are proposed for energies across the peak of the giant dipole resonance, they decrease the disagreements between Livermore and Saclay data for $\sigma(\gamma,1n)$ but correspondingly increase the disagreements between $\sigma(\gamma,2n)$ data. The concrete numerical data for such normalization coefficients also do not look as reliable because of some shortcomings of Saclay data. In [6] it was pointed out that the "Saclay detector suffers from a much higher background rate, made up largely of single-neutron events, which introduces larger uncertainties in the background subtractions and pile-up corrections." So nobody knows which data are reliable or not.

Therefore one needs to use not various normalizations for putting Livermore and Saclay data into consistency but objective physical criteria of data reliability. The ratios of definite partial reaction cross sections to that of the neutron yield reaction,

$$\begin{aligned} F_i &= \sigma(\gamma,in)/\sigma(\gamma,Sn) \\ &= \sigma(\gamma,in)/[\sigma(\gamma,1n)+2\sigma(\gamma,2n)+3\sigma(\gamma,3n)+\cdots], \end{aligned} \quad (2)$$

were proposed [14] as criteria of partial photoneutron reaction cross-section reliability. According to the definitions, $F_1 > 1.0, F_2 > 0.5, F_3 > 0.33$, etc., can never occur.

F_i^{exp} values larger than the upper limits mentioned mean that experimental sorting of neutrons between partial reactions was carried out with large systematic uncertainties. Therefore partial reaction cross sections obtained are not reliable.

Additionally it should be underlined that ratios F_i include only the cross-section terms and therefore should be definitely positive.

It is important to point out that, because of direct detection of neutrons in wide energy regions, $\sigma(\gamma,1n)$ is the sum $[\sigma(\gamma,1n)+\sigma(\gamma,1n1p)]$.

In [9–12,14–17], using the proposed physical criteria of data reliability, it was found that the experimental partial photoneutron reaction cross sections obtained using quasimonoenergetic annihilation photons for about 20 nuclei mentioned above (^{59}Co to ^{209}Bi) in many photon energy regions do not satisfy the criteria mentioned. It was shown that many F_1^{exp} are negative and/or F_2^{exp} are negative or larger than 0.5 and/or F_3^{exp} are negative or larger than 0.33, …, etc.

The third reason for doubts in cross-section reliability is the noticeable difference between F_i^{exp} and F_i^{theor}. The results of our evaluations based on using F_i^{theor} are in agreement with the corresponding experimental results obtained for ^{181}Ta [23] and ^{209}Bi [24] nuclei using the activation method. In this method, an alternative to the method of neutron multiplicity sorting, the

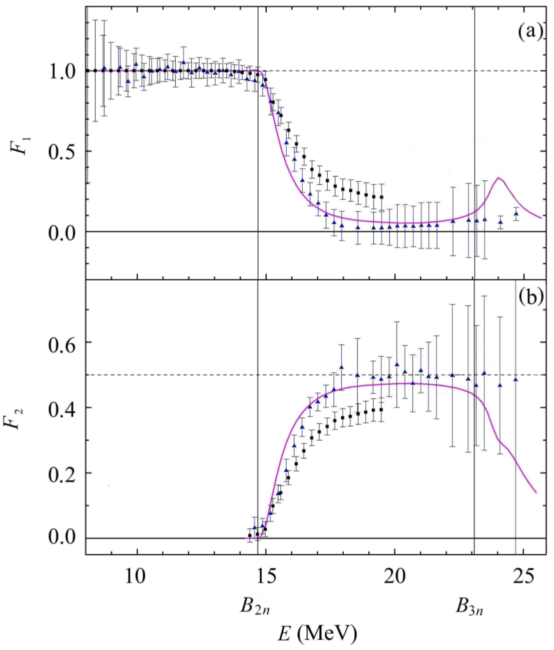

FIG. 1. (a) F_1^{exp} and (b) F_2^{exp} data obtained for ^{197}Au using experimental data of Livermore ([19]: triangles) and Saclay ([20]: squares) in comparison with results of $F_{1,2}^{\mathrm{theor}}$ calculated in the model ([25,26]: lines).

direct identification of each partial reaction is based on the final nuclei. So it could be concluded that if F_i^{exp} noticeably different from F_i^{theor} one has definite doubts about experimental data reliability. This is the case in the data for ^{197}Au; namely, F_i^{exp} noticeably and systematically differs from F_i^{theor}.

For ^{197}Au the ratios F_1^{exp} and F_2^{exp} in [19,20] but not [21] were analyzed, because data in [19,20] were obtained in a wider energy range. Concerning normalization procedures, it should be pointed out that if we use any normalization for results of a definitive experiment it means that we multiply both numerator and denominator of (2) and the ratio F remains the same.

The ratios F_1^{exp} and F_2^{exp} obtained for the experimental Livermore [19] and Saclay [20] data for ^{197}Au are presented in Fig. 1 in comparison with the results of calculated $F_{1,2}^{\mathrm{theor}}$ in the combined photonucleon reaction model (CPNRM) [25,26]. This model is based on a combination of the Hauser-Feshbach evaporation model and preequilibrium mechanisms of nucleon emission, and takes into account nuclear deformation and isospin splitting of the nucleus GDR. The results of various reaction cross sections calculations using the CPNRM agree well with neutron yield reaction cross sections (1) for many medium and heavy nuclei.

There is a surprising peak (∼0.35 around 23–24 MeV) in the calculated F_1 [Fig. 1(a)] which consequently appears also in the evaluated data [Fig. 2(a), see below]. Although the energy of this peak is equal to the energy of the reaction $(\gamma,1n1p)$ cross section maximum (24.3 MeV, ∼5 mb), as was calculated in the model, this is a possible artifact.

In the case of ^{197}Au, for both Livermore and Saclay the $F_{1,2}^{\mathrm{exp}}$ data within the uncertainty limits do not contradict the reliability criteria. It is important to point out that because the

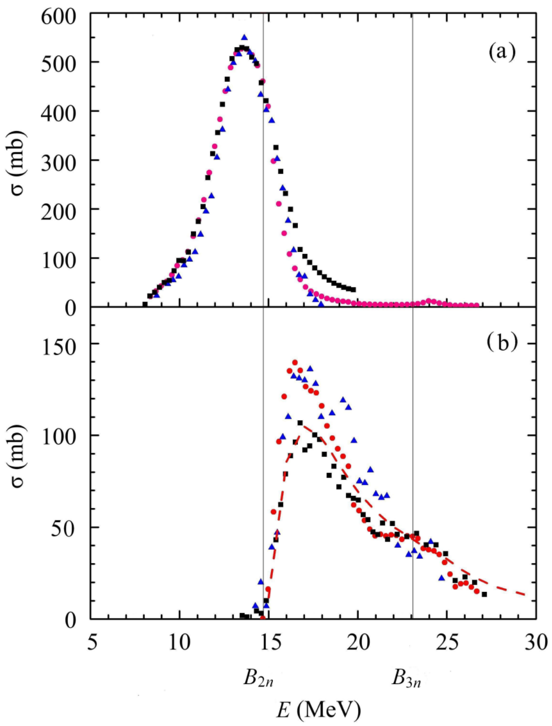

FIG. 2. (a) ^{197}Au$(\gamma,1n)$ reaction, (b)^{197}Au$(\gamma,2n)$ reaction. Comparison of experimental (Livermore [19]: triangles; Saclay [20]: squares) and evaluated ([14]: circles; [13]: dotted line) data.

$(\gamma,1n)$ and $(\gamma,\ Sn)$ cross-section uncertainties are close just above the threshold, the error bars probably reflect the statistical uncertainties which are common to both reactions' data. Thus, the real uncertainty of the ratio could be much smaller.

At the same time one can see that F_i^{exp} obtained by both Livermore and Saclay are noticeably and systematically different from F_i^{theor}. In accordance with all the topics discussed above, F_1^{exp} obtained by Saclay are overestimated and F_2^{exp} are underestimated in comparison with the corresponding F_i^{theor}. For Livermore data the situation is opposite, although the Livermore data are closer to calculated data than Saclay data.

III. RELIABLE PARTIAL REACTION CROSS SECTIONS EVALUATED USING THE EXPERIMENTAL-THEORETICAL METHOD

The experimental-theoretical method for evaluating the partial reaction cross sections, not dependent on experimental neutron multiplicity sorting, was proposed [14] to overcome the problems described above. This method uses the only neutron yield cross section $\sigma^{\mathrm{exp}}(\gamma,Sn)$ (1), independent of neutron multiplicity sorting problems, as initial experimental data. Evaluated partial cross sections $\sigma^{\mathrm{eval}}(\gamma,in)$ are obtained using $F_{\mathrm{i}}^{\mathrm{theor}}(\gamma,in)$ calculated in the model [25,26],

$$\sigma^{\mathrm{eval}}(\gamma,in) = F_i^{\mathrm{theor}}(\gamma,in)\,\sigma^{\mathrm{exp}}(\gamma,Sn). \tag{3}$$

This evaluation method means that the experimental neutron yield cross section (1) is divided into the partial reaction in accordance with the equations of the model.

New, reliable data for many nuclei mentioned above were evaluated [9–12,14–17]. Those data were compared with the results obtained by experimental techniques alternative to the method of neutron multiplicity sorting. In the photon activation method the studied reaction is identified not by the energy of outgoing neutron but by the residual radioactivity of the produced nucleus. γ-ray spectra of the final nucleus are measured with a high resolution spectrometer and thus yields of partial reactions can be obtained directly. To make the comparison, special measurements were performed using the bremsstrahlung photon beam for ^{181}Ta [10,23]. The results clearly shown that Saclay integrated cross-section ratios $\sigma_S^{\text{int}}(\gamma,2n)/\sigma_S^{\text{int}}(\gamma,1n)$ are noticeably underestimated (0.36) but Livermore ratios $\sigma_L^{\text{int}}(\gamma,2n)/\sigma_L^{\text{int}}(\gamma,1n)$ are overestimated (0.67) in comparison with those obtained in the activation measurement (0.49). The same inconsistency was obtained for the ratios of the reaction yields: respectively 0.24 and 0.42 versus 0.34. The last value agrees well with the result of our evaluation (0.33). So it was concluded that data evaluated using data reliability criteria in the framework of the experimental-theoretical method are reliable enough. Analogous results were obtained in the comparison of experimental and evaluated partial photoneutron reaction cross sections for ^{209}Bi [24].

In [14] two versions of evaluated cross sections $\sigma^{\text{eval}}(\gamma,in)$ (3) for the reactions $(\gamma,1n)$ and $(\gamma,2n)$ for ^{197}Au were obtained using Livermore [19] and Saclay [20] data for $\sigma^{\text{exp}}(\gamma,Sn)$ separately. The numerical data (correspondingly, from entries L0002 and L0021]) from the EXFOR database [1–3] were used. The comparison among $\sigma^{\text{eval}}(\gamma,in)$ cross-section data (Ref. [14], EXFOR entries M0798004 for the $(\gamma,1n)$ reaction and M0798003 for the $(\gamma,2n)$ reaction), evaluated using Saclay neutron yield reaction $\sigma^{\text{exp}}(\gamma,Sn)$ data from [20], is presented in Fig. 2. Saclay $\sigma^{\text{exp}}(\gamma,Sn)$ data were chosen for evaluation because there are many more problems with the reliability of the Livermore data.

In Fig. 2(a) one can see that, in accordance with data for F_1^{exp} (Fig. 1) in the energy range below $B2n$, the evaluated $(\gamma,1n)$ cross section is near both experimental [19,20] data, but at larger energies there are significant disagreements. Up to energy ~17.5 MeV the evaluated cross section agrees with Livermore [19] but disagrees with Saclay [20] data.

The comparison of evaluated and experimental $(\gamma,2n)$ cross sections is presented in Fig. 2(b). One can see that, in analogy to the $(\gamma,1n)$ cross-section case, up to energy ~17.5 MeV the evaluated $(\gamma,2n)$ cross section also agrees with Livermore [19] but disagrees with Saclay [20] data. In the energy region ~17.5–22.0 MeV the evaluated $(\gamma,2n)$ cross section disagrees with both experimental cross sections. At energies above ~22.0 MeV the evaluated $(\gamma,2n)$ cross section agrees with Saclay data [20]. It could be because of noticeable and different systematic uncertainties of the method of neutron multiplicity sorting used in both laboratories.

IV. COMPARISON OF THE NEW AND THE OLD EVALUATED $(\gamma, 2n)$ CROSS SECTIONS

Additionally the result of previous evaluation [13] is also presented by the dotted line in Fig. 2(b). Generally it is near the experimental [20] cross section. This also is the case for the $(\gamma,1n)$ cross section. The previously evaluated cross-section generally coincides [13] with the experimental [20] cross section, and because of that there one can not see the corresponding dotted line in Fig. 2(a).

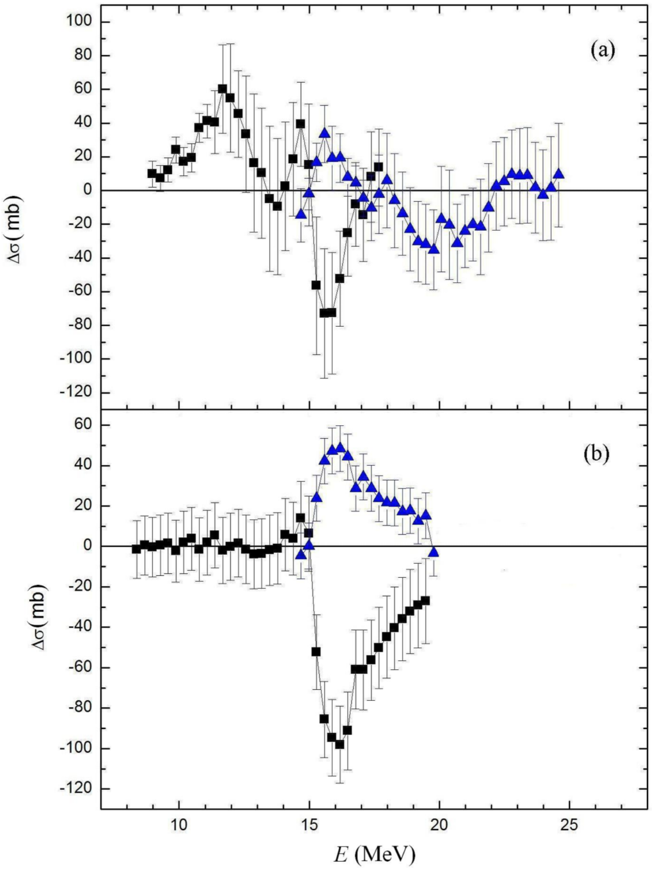

FIG. 3. (a) Differences (4) among the newly evaluated [14] and the experimental reaction cross sections obtained at Livermore [19]; (b) analogous differences (4) for data obtained at Saclay [20] [$(\gamma,1n)$: squares; $(\gamma,2n)$: triangles].

In Fig. 2(b) one can see that the cross section evaluated using objective physical data reliability criteria based on the neutron yield reaction cross sections (1) and equations of the CMPNR [25,26] is definitely different from the cross section evaluated before using well-known codes GUNF and GNASH [13].

This can be seen more clearly in Fig. 3, where the differences,

$$\Delta\sigma = \sigma^{\text{new eval}} - \sigma^{\text{exp}} \tag{4}$$

are presented separately for $(\gamma,1n)$ and $(\gamma,2n)$ cross sections obtained at Livermore [Fig. 3(a)] and Saclay [Fig. 3(b)]. One can see that those values are noticeably different for various ranges of photon energies. It is very important to point out that similar disagreements between old and new evaluations were found for ^{91}Zr and ^{159}Tb [27]. The reason for such disagreements can be that the previous evaluation [13] "relied on the GUNF and GNASH codes in order to infer the photoabsorption cross section on the GDR regime, in order to model accurately the Saclay ^{197}Au(γ,tot) data", experimental data from Ref. [20] were used.

The point is that the total photoneutron reaction cross section,

$$\sigma(\gamma,\text{tot}) = \sigma(\gamma,1n) + \sigma(\gamma,2n) + \sigma(\gamma,3n) \qquad (5)$$

at energies below $B3n$ is in reality the difference,

$$\sigma(\gamma,\text{tot}) = \sigma(\gamma,Sn) - \sigma(\gamma,2n). \qquad (6)$$

So the cross section $\sigma(\gamma,\text{tot})$ depends on neutron multiplicity sorting uncertainties. It is evident that the large systematic errors in $\sigma(\gamma,2n)$ can lead to corresponding systematic errors in $\sigma(\gamma,\text{tot})$ and therefore to those in data for partial reaction cross sections evaluated on the basis of using $\sigma(\gamma,\text{tot})$.

V. COMPARISON WITH THE RESULTS OF OTHER EXPERIMENTS

As was shown, the results of new evaluations based on the objective physical data reliability criteria [14] noticeably differ from the results of old evaluations [13] and both results of experiments carried out using the method of neutron multiplicity sorting [19,20]. It was mentioned that the experimental-theoretical method of evaluation using Eq. (3) gives for nuclei ^{181}Ta and ^{209}Bi results in agreement with those obtained using the activation method [10,23,24]. So it is of interest to compare the results of our new evaluation for ^{197}Au with the results of experiments carried out by different methods.

Certainly the photoactivation data for ^{197}Au$(\gamma,1n)$ reaction cross section are among the most interest. The accurate photoactivation data for ^{197}Au$(\gamma,xn),x = 1-6$ were obtained using bremsstrahlung [28]. Multineutron reaction cross sections were calculated as a function of the bombarding photon energy by using the TALYS 1.6 computer code with default parameters. The data for ^{197}Au$(\gamma,1n)$ reaction cross section ($x = 1$) also are compared with the evaluated data in Fig. 4. In this figure the results of some other experiments are presented also. The results obtained by measurements of the ^{197}Au$(\gamma,1n)$ reaction cross section using the activation method in the energy range up to 9.9 MeV [22] were mentioned above. The parametrization of those data for the energy range up to 17 MeV is presented in Fig. 4.

In [29] the ^{197}Au$(\gamma,1n)$ reaction cross section was obtained from the experimental yield measured using the activation method and data analysis based on the GEANT4 simulation code.

Two experiments to obtain the ^{197}Au(γ,n) reaction cross section were carried out using direct neutron counting with quasimonoenergetic γ rays produced in inverse Compton scattering of laser photons with relativistic electrons [30–32]. Different methods, such as the photon difference method and the least-squares method, were used to deduce photoneutron cross sections in various energy ranges. The results obtained for the energy range up to 14.0 MeV agree enough with each other, with the results of other experiments, and with evaluated data.

From the comparison presented in Fig. 4 one can conclude that in the energy range from about 10.5 MeV up to $B2n = 14.7$ MeV the experimental data [19,20,28,31,32] in general agree with each other and with the evaluated cross section [14] and disagree with data from [29].

One can see that for energies larger than $B2n = 14.7$ MeV the ^{197}Au$(\gamma,1n)$ reaction cross section evaluated using the experimental-theoretical method based on the objective physical criteria of partial photoneutron reaction data reliability noticeably disagree with data from [19,20,22,29] but is near the activation data [28]. For [22] this could be explained as the result of using, in the wide energy range, parametrization of data measured in a narrow energy range (up to 9.9 MeV). For [29] it can be the result of using, to obtain the cross section, an insufficiently reliable method of χ^2 minimization.

In Fig. 5 the comparison of experimental [19,20,28] and evaluated [14] ^{197}Au$(\gamma,2n)$ reaction cross sections is presented. One can see that data [14] generally agree with activation data [28] for ^{197}Au$(\gamma,2n)$, which is ^{197}Au(γ,xn) at $x = 2$. The small disagreements of those data for the energy range ∼19–23 MeV probably could be the results of the

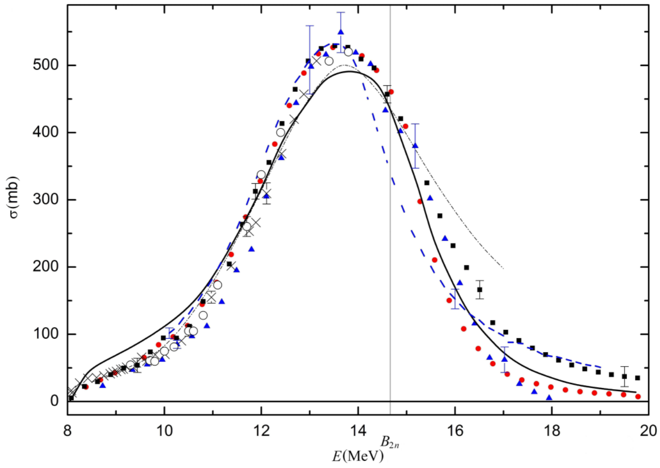

FIG. 4. Comparison of experimental data ([19]: triangles; [20]: squares; [22]: dot-dash line; [28]: solid line; [29]: dotted line; [31]: crosses; [32]: open circles) with evaluated cross section ([14]: circles) for the ^{197}Au$(\gamma,1n)$ reaction.

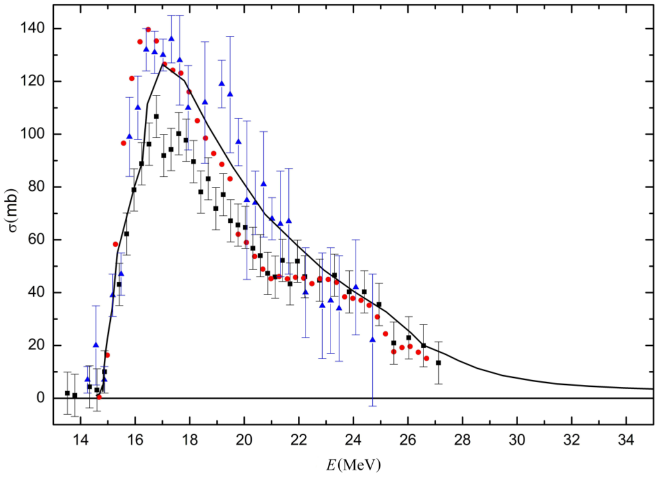

FIG. 5. Comparison of experimental data ([19]: triangles; [20]: squares; [28]: solid line) with evaluated cross section ([14]: circles) for the ^{197}Au$(\gamma,2n)$ reaction.

features of the model (CPNRM) [25,26] used in [14] and the TALYS 1.6 computer code used in [28]. It can be pointed out that data from both [14] and [28] significantly disagree with [19,20] data. This could once more confirm that cross sections evaluated using the experimental-theoretical method, based on the objective physical criteria of partial photoneutron reaction data reliability, are reliable enough.

It is important to point out that using a new kind neutron detector with almost energy-independent efficiency [33] should be able to determine (γ,Sn) cross sections using neutron multiplicity sorting with smaller systematic uncertainties.

VI. SUMMARY

In many experimental partial photoneutron reactions $(\gamma,1n)$, $(\gamma,2n)$, $(\gamma,3n)$ cross sections [1–3] obtained using the neutron multiplicity sorting method do not satisfy to objective physical criteria of data reliability [9–12,14–17]. There are many physically forbidden negative cross-section values or values for which ratios $F_i = \sigma(\gamma,in)/\sigma(\gamma,Sn)$ are larger than physically reliable upper limits (1.0, 0.5, 0.33,... correspondingly for $i = 1-3,\ldots$). The reasons are the significant systematic uncertainties of the neutron multiplicity sorting method used in experiments and based on neutron energy measurement. Many neutrons were erroneously transmitted from one partial reaction to another.

Using the experimental-theoretical method, reliable partial photoneutron reaction cross sections satisfying objective physical reliability criteria were evaluated for many nuclei [9–12,14–17]. It was shown that newly evaluated data noticeably differ from experimental data obtained using the method of neutron multiplicity sorting but agree with accurate data obtained using the activation method [28] and direct neutron counting with quasimonoenergetic γ rays produced in inverse Compton scattering of laser photons with relativistic electrons [30–32].

It was found that newly evaluated reaction cross sections for ^{197}Au [14] noticeably differ from previously evaluated data obtained using GUNF and GNASH codes. It was shown that the reason could be that previous evaluations [13] were based on the total photoabsorption data (really close to the total photoneutron reaction data) but not on the photoneutron yield cross sections, which are rather independent of neutron multiplicity. Such differences were found also for ^{91}Zr and ^{159}Tb [27].

Therefore it was concluded that though the IAEA Photonuclear Data Library [13] has been extremely useful to a broad community, it needs to be revised and updated. The recommendations of the IAEA Consultant's Meeting to update the IAEA Photonuclear Data Library were presented [18] and the new IAEA CRP was approved. It is of interest to compare new evaluation data with new experimental data obtained using a new kind neutron detector with almost energy-independent efficiency [33] which should be able to determine (γ,Sn) cross sections with smaller systematic uncertainties.

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