Statistical and direct aspects of ^{64}Zn (γ,n) and (γ,np) decay channels in the giant dipole resonance and quasideuteron energy regions

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The investigation of statistical and direct aspects related to the (γ,n) and (γ,np) decay channels of ^{64}Zn in the giant dipole resonance (GDR) and quasideuteron (QD) energy regions was performed by a trial function fitting to the respective (e,n) and (e,np) electrodisintegration yields measured by residual activity. The trial function incorporated the GDR and QD models to describe the initial photoabsorption mechanism and the geometry dependent hybrid exciton model used in the ALICE/LIVERMORE-82 code to calculate the relevant branching ratios, with the $E1$ virtual photon spectra being calculated in the distorted wave Born approximation. We compared our results for the (γ,n) cross section with other existing experimental measurements, and the long-standing normalization issue among different laboratories was revisited and addressed. We obtained for the first time the absolute (γ,np) cross section from threshold to 60 MeV. We succeeded in separating statistical and direct contributions of the (γ,np) process, the latter being remarkably well described by the QD model in the interval 40–60 MeV. A possible direct contribution for the (γ,n) decay in the GDR is also addressed. Finally, the total photoabsorption cross section of ^{64}Zn was reevaluated up to 21 MeV, and the results were compared with previous estimates performed by other groups.

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I. INTRODUCTION

Photonuclear reactions in the giant dipole resonance (GDR) and quasideuteron (QD) energy regions have been widely studied in the past, as they provide a wide range of information either on the initial nuclear excitation mechanism or on characteristics of the compound nucleus decay channels. In fact, photoneutron cross sections in the GDR energy region have been compiled [1] for most of the nuclei in the periodic table, while measurements in the QD region were mainly focused on heavy nuclei [2], thus leading to a gap of information on intermediate nuclei. Additionally, the expected shift of interest toward higher energy studies, as it has been verified in the last 40 years or so, left behind some important uninvestigated issues like Pauli-blocking effects in the lower QD energy range.

The relevant photonuclear reactions for ^{64}Zn in the GDR energy region were studied using different methods [3,4]. The cross sections obtained with monochromatic photons are considered to be the most accurate. However, these measurements, performed mostly at the laboratories of Livermore (USA) and Saclay (France), have exhibited systematic discrepancies when compared with each other. These discrepancies were already discussed in previous publications [5], where measurements performed in São Paulo were used to elucidate a systematic discrepancy between the Saclay and Livermore data, suggesting that the data from Livermore are problably more reliable than those obtained at Saclay. From this framework, new measurements of some important cross sections in the GDR energy region of ^{64}Zn, such as $\sigma(\gamma,n)$ and $\sigma(\gamma,np)$, are still of interest. In fact, Carlos *et al.* [3] have also reported that some impurities (around 9%), associated with the isotopic composition of natural zinc in the ZnO target used in their experiment, were not taken into account, thus providing another source of uncertainty. Another aspect motivating new measurements of these cross sections is that the Saclay data do not discriminate between the (γ,np) and the (γ,n) channels, as their detection system was completely insensitive to protons. So, with new absolute measurements it would be possible to separate the two major contributions to the compound nucleus decay process in the GDR.

The main goal of this work is the determination of the absolute cross section for the (γ,np) reaction from threshold to 60 MeV, since the available data were obtained only up to 40 MeV and in relative scale [4]. Those data would enable one to explore both the GDR statistical decay process in the (γ,np) channel and the direct reaction mechanism due to the QD effect, which is expected to become more significant at energies above 40 MeV. The Pauli-blocking effect, then, can be thoroughly discussed if one is able to separate the statistical and direct aspects in this decay channel.

Combining the experimental results for the (e,n) and (e,np) electrodisintegration yields, and using the geometry dependent hybrid exciton model (GDH) [6], incorporated into the ALICE/LIVERMORE-82 code [7], to calculate the relevant branching ratios, the total photoabsorption cross section can be evaluated and compared with some previous results reported by the JENDL group [8]. The combination of the trial function method, virtual photon spectra calculated in distorted wave Born approximation (DWBA) [9], and the ALICE/LIVERMORE-82 code provides a consistent framework to analyze yield functions.

Instead of detecting both neutron and proton in coinci-

TABLE I. Parameters of two Lorentz curves fitted in the 14–21 MeV interval of the photoneutron cross section for ^{64}Zn. The experimental data were taken from Ref. [3] and the parameters were compiled by Berman *et al.* [1].

Lorentz parameters	(σ_{mi})(mb)	(E_{mi})(MeV)	(Γ)(MeV)
Lower-energy line	41.4	16.23	3.27
Higher-energy line	56.1	19.19	5.98

dence, which is a complex and difficult task, the residual activity analysis, as performed in this work, is an alternative and accurate method to determine the (γ,np) cross section.

II. RELEVANT THEORY

A. Statistical mechanisms

From the Hauser-Feshbach theory, one can write the cross section of a process with initial and final channels a and b as follows [10]:

$$\sigma_{a,b} \propto \xi_a \xi_b , \tag{1}$$

where ξ_a and ξ_b are quantities which depend only on their respective channels. With the compound nucleus (CN) hypothesis [11], the process (a,b) can be described by two steps: (1) compound nucleus formation, and (2) statistical decay of the equilibrated system. Thus,

$$\sigma_{a,b}(E_a) = \sigma_{a,CN}(E_a)\frac{\Gamma_b}{\Gamma_T}(E^*), \tag{2}$$

where $\sigma_{a,CN}$ stands for the compound nucleus reaction cross section due to the entrance channel a, Γ_b/Γ_T represents the branching ratio associated with the exit channel b, and E^* is the excitation energy of the compound nucleus.

For photonuclear reactions in the GDR energy region, and also considering the compound nucleus hypothesis, one can write the cross section $\sigma(\gamma,b)$ in the form

$$\sigma_{\gamma,b}(E_\gamma) = \sigma^{GDR}_{\gamma,abs}(E_\gamma)\frac{\Gamma_b}{\Gamma_T}(E_\gamma), \tag{3}$$

$\sigma^{GDR}_{\gamma,abs}(E_\gamma)$ being the GDR photoabsorption cross section. From the semiclassical theory of the interaction between photons and nuclei, the shape of a fundamental resonance in the absorption cross section is a Lorentz curve [12,13]:

$$\sigma^{GDR}_{\gamma,abs}(E_\gamma) = \sum_{i=1}^{2} \frac{\sigma_{mi}}{1+[(E_\gamma^2 - E_{mi}^2)^2/E_\gamma^2\Gamma_i^2]}, \tag{4}$$

where E_{mi}, σ_{mi}, and Γ_i are the resonance energy, peak cross section and full width at half maximum, respectively.

From the analysis of photoneutron cross sections with monoenergetic photons, the resonance parameters for ^{64}Zn were established and are shown in Table I [1,3]. In the data analysis and interpretation presented below, we introduce a normalization factor to the cross section [Eq. (4)], which keeps the shape of the resonance unchanged.

The cross sections for statistical decay through the (γ,n) and (γ,np) channels for ^{64}Zn in the GDR energy region can then be calculated in full knowledge of the initial photoexcitation mechanism (GDR), together with the description of the CN decay, the latter being performed using the ALICE/LIVERMORE-82 code to calculate the evaporation process [7]. The relevant cross sections for the statistical processes can be written as

$$\sigma^{stat}_{\gamma,n}(E_\gamma) = C\left[\sigma^{GDR}_{\gamma,abs}(E_\gamma)\frac{\Gamma_n}{\Gamma_T}(E_\gamma)\right], \tag{5}$$

$$\sigma^{stat}_{\gamma,np}(E_\gamma) = C\left[\sigma^{GDR}_{\gamma,abs}(E_\gamma)\frac{\Gamma_{np}}{\Gamma_T}(E_\gamma)\right], \tag{6}$$

where C is an energy independent normalization factor for the GDR parameters.

B. Direct mechanisms

Since the aim of this work is to describe both (γ,n) and (γ,np) processes in ^{64}Zn, one has to account for direct reaction mechanisms.

In this framework, the (γ,n) reaction cross section in the GDR may be assumed as constituted by a major statistical part and a minor direct one. This direct contribution may be written as a fraction of the total $\sigma(\gamma,n)$ cross section:

$$\sigma^{dir}_{\gamma,n}(E_\gamma) = k(E_\gamma)\sigma^{tot}_{\gamma,n}(E_\gamma), \tag{7}$$

where $k(E_\gamma)$ is an undimensional slow varying energy function, $\sigma^{dir}_{\gamma,n}(E_\gamma)$ is the direct contribution, and $\sigma^{tot}_{\gamma,n}(E_\gamma)$ is the total cross section.

Since we are dealing only with energy integrated cross sections, we may approximate $k(E_\gamma)$ by an energy independent mean value, which suffices for our estimation purpose:

$$\overline{k} \equiv \frac{1}{\Delta E}\int_{E_0}^{E_1} k(E_\gamma)\,dE_\gamma , \tag{8}$$

where $\Delta E = E_1 - E_0$ is the GDR energy interval and $\overline{k}$ is the corresponding mean value. With this approximation the direct contribution takes this form:

$$\sigma^{dir}_{\gamma,n}(E_\gamma) = \overline{k}\sigma^{tot}_{\gamma,n}(E_\gamma). \tag{9}$$

On the other hand, the direct contribution to the (γ,np) process at energies above the GDR is expected to be related to the quasideuteron photoabsorption mechanism. At these energies the photon interacts most probably with a correlated n-p pair inside the nucleus, the well-known quasideuteron mechanism. This mechanism was first proposed and modeled by Levinger [14], and since then has been subjected to substantial modifications [15,16]. From this model one may relate the photoabsorption cross section $\sigma^{QD}_{\gamma,abs}(E_\gamma)$ of a quasideuteron pair to the photodisintegration cross section of a free deuteron $\sigma_D(E_\gamma)$:

$$\sigma^{QD}_{\gamma,abs}(E_\gamma)=L\frac{NZ}{A}\sigma_D(E_\gamma)f(E_\gamma), \tag{10}$$

where L/A represents the fraction of n-p pairs inside the nucleus which may be correlated, NZ is the total number of n-p pairs inside the nucleus, and $f(E_\gamma)$ is a function that accounts for the Pauli-blocking effects on the final state densities. The free deuteron cross section was taken as [17]

$$\sigma_D(E_\gamma)=\frac{61.2(E_\gamma-B)^{3/2}}{E_\gamma^3}, \tag{11}$$

where $B=2.224$ MeV is the binding energy of the deuteron.

Chadwick *et al.* [18] have determined the function $f(E_\gamma)$, using Fermi-gas state densities which conserve linear momentum. Their approach provides a more accurate calculation than the usual *ad hoc* phenomenological exponential factor introduced by Levinger. This result was then expanded in a polynomial function in the energy range 20–140 MeV:

$$\begin{aligned} f(E_\gamma)=&8.3714\times10^{-2}-(9.8343\times10^{-3})E_\gamma \\ &+(4.1222\times10^{-4})E_\gamma^2-(3.7462\times10^{-6})E_\gamma^3 \\ &+(9.3537\times10^{-9})E_\gamma^4, \end{aligned} \tag{12}$$

where the Levinger parameter $L=6.5$ is now a constant value obtained directly from the model.

Assuming that after the initial photoabsorption the n-p pair splits, and that during the emission process there are no final state interactions (FSI), one can equate the cross section of a typical direct reaction process $\sigma^{dir}_{\gamma,np}(E_\gamma)$ to the cross section of photoabsorption in the QD model:

$$\sigma^{dir}_{\gamma,np}(E_\gamma)=\sigma^{QD}_{\gamma,abs}(E_\gamma). \tag{13}$$

III. EXPERIMENT

The experiment was performed using the 60-MeV linear electron accelerator of the University of São Paulo. Details of the accelerator characteristics and of the experimental setup can be found elsewhere [5]. The electrodisintegration cross sections were obtained by bombarding natural Zn targets and measuring, off-line, their residual activity, counting the 511-keV annihilation γ rays from the β^+ decay of the reaction products. The measurements were performed in the 12.5–60 MeV energy range, in 2.5-MeV steps. Two ^{nat}Zn foils [8.87(56) and 7.33(47) mg/cm^2, determined by weighing] were irradiated in a vacuum chamber at the end of the beam pipe, while the irradiated charge was measured with a Faraday cup. The charge was recorded with a multichannel scaler in 10-s intervals.

A clock was started at the end of the irradiation, and the target, after removal from the irradiation chamber, was placed in a target holder fastened to a HPGe detector. The detector was calibrated with a standard ^{22}Na source, mounted in the same geometry used for the targets. The elapsed time between the end of the irradiation and the start of counting was less than 5 min.

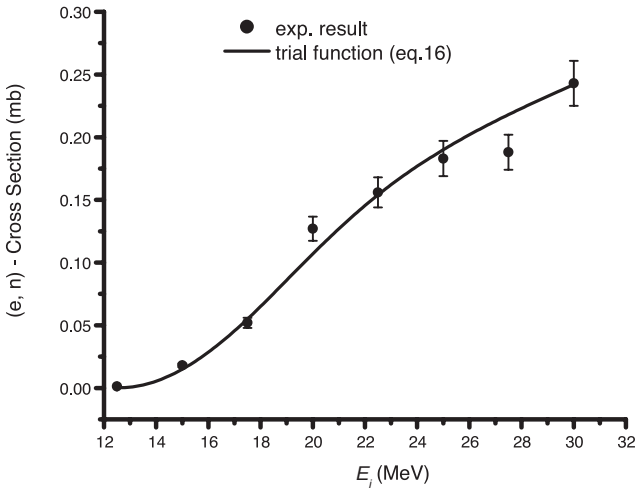

FIG. 1. Electrodisintegration cross section $\sigma(e,n)$ for ^{64}Zn measured at São Paulo (data points). The solid line is the fitted trial function obtained by a least squares fitting to the experimental datasets of both reactions simultaneously. Results: $C/(1-\overline{k})=1.04(3)$, $C=0.95(4)$, $\overline{k}=0.08(5)$, χ^2 per degree of freedom $=1.309$, and $P=18.15\%$. The theoretical threshold is 11.86 MeV.

The dominant electrodisintegration reactions taking place in the GDR energy region are the (e,n), (e,np), and $(e,2n)$. In ^{64}Zn those reactions lead to the formation of ^{63}Zn ($t_{1/2}=38.47$ min), ^{62}Cu ($t_{1/2}=9.74$ min), and ^{62}Zn ($t_{1/2}=9.186$ h), which decay by positron emission. The other isotope contributing to the residual β^+ activity is ^{65}Zn ($t_{1/2}=243.7$ d), from the (e,n) reaction in ^{66}Zn, or $(e,2n)$ in ^{67}Zn. Due to the long half-life of the residual nucleus, the contribution to the residual activity was beyond the experimental sensitivity, and was considered negligible. According to these considerations, the counting rates at the end of the irradiation were determined by a least squares fitting of three exponentials to the decay curve.

The number of residual nuclei produced from the reaction (e,x) and still present at the end of the irradiation is given by

$$N_{0,x}=p_x\sigma_{e,x}\left\{\sum_i q_i[1-e^{-\lambda_x(t_i-t_{i-1})}]e^{-\lambda_x(t_m-t_i)}\right\}, \tag{14}$$

where p_x is the number of target nuclei per cm^2, $\sigma_{e,x}$ the corresponding cross section, t_i the time at the end of the ith interval, q_i the number of electrons delivered during the ith interval, and t_m the total irradiation time. The factor in the curly brackets accounts for the fluctuation in the beam current and corrects for the decay of the residual nuclei formed during this irradiation.

Figures 1 and 2 present the results obtained for the electrodisintegration cross sections of the (e,n) and (e,np) reactions, respectively. The error bars represent the statistical uncertainties of the measurements. The overall uncertainty of the absolute scale is better than 15%.

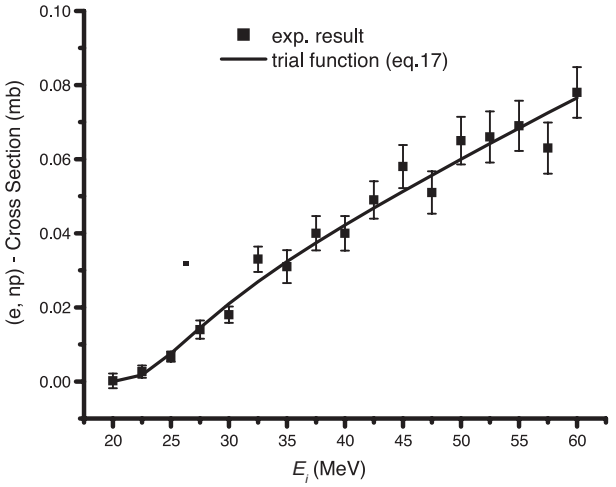

FIG. 2. Electrodisintegration cross section $\sigma(e,np)$ for ^{64}Zn measured at the São Paulo (data points). The solid line is the fitted trial function (see Fig. 1). The theoretical threshold is 18.57 MeV.

IV. DATA ANALYSIS

The electrodisintegration cross sections may be written in terms of their corresponding photodisintegration cross sections via the virtual photon formalism as follows [19]:

$$\sigma_{e,x}^{\lambda L}(E_i) = \int_{E_{Th}}^{E_i} dE_\gamma \frac{S^{\lambda L}(E_i,E_\gamma)}{E_\gamma} \sigma_{\gamma,x}^{\lambda L}(E_\gamma), \qquad (15)$$

where E_i is the incident electron energy, λ the type of transition (E or M), L the angular momentum transferred, E_{Th} the reaction threshold, E_γ the virtual (or real) photon energy, and $S^{\lambda L}(E_i,E_\gamma)$ the virtual photon spectrum. The virtual photon spectra were calculated in DWBA [9] taking into account both the nuclear charge and the nuclear finite size. Magnetic and $L>1$ electric transitions were neglected in the calculations due to the much smaller contribution they present, when compared to the dominant $E1$ transitions in both the GDR and QD mechanisms.

Our goal is to provide a self-consistent solution for the photonuclear yield equation, Eq. (15), based on the following assumptions.

(1) The initial photoexcitation mechanism is well described by the GDR and QD approaches.

(2) The DWBA method propitiates an accurate and detailed calculation of the E1 virtual photon spectrum, and has been subject to experimental verification [9].

(3) The statistical decay process of the compound nucleus is well described by the geometry dependent hybrid exciton model (GDH) [6], with calculations performed by the ALICE/LIVERMORE-82 code [7], where we have chosen the following input options: Fermi gas model to calculate the level densities, sharp cutoff approximation to calculate inverse cross sections, reaction cross sections computed by optical model, and transition rates calculated from nucleon-nucleon scattering. Preequilibrium emissions are negligible, as their contribution is important only at energies greater than 35 MeV, where the GDR mechanism is no longer significant.

(4) The (γ,n) reaction channel in the GDR is assumed to be composed by the statistical and direct components, where the former dominates the whole process and the latter is small and energy independent. Both components are to be determined by the data analysis.

(5) The (γ,np) reaction channel in the GDR and QD energy regions is assumed to be composed by statistical and direct parts, the latter being ascribed to the QD mechanism in Eq. (13), and the former to be determined by the analysis.

(6) After absorption of an incident photon by a correlated n-p pair inside the nucleus (QD model), it is assumed that the pair splits and that there are no FSI during their emissions.

Under these assumptions the trial functions can be written as

$$\sigma_{\gamma,n}(E_\gamma) = \sigma_{\gamma,n}^{stat}(E_\gamma) + \sigma_{\gamma,n}^{dir}(E_\gamma) = \frac{C}{1-\bar{k}}\left[\sigma_{\gamma,abs}^{GDR}(E_\gamma)\frac{\Gamma_n}{\Gamma_T}(E_\gamma)\right] \qquad (16)$$

and

$$\sigma_{\gamma,np}(E_\gamma) = \sigma_{\gamma,np}^{stat}(E_\gamma) + \sigma_{\gamma,np}^{dir}(E_\gamma) = C\left[\sigma_{\gamma,abs}^{GDR}(E_\gamma)\frac{\Gamma_{np}}{\Gamma_T}(E_\gamma)\right] + \sigma_{\gamma,abs}^{QD}(E_\gamma), \qquad (17)$$

by further assuming a nonstatistical contribution $\bar{k}$ to the (γ,n) channel and also a normalization factor C to the GDR cross section.

Inserting Eqs. (16) and (17) in Eq. (15), one then finally gets

$$\sigma_{e,n}(E_i) = \frac{C}{1-\bar{k}}\int_{11.86}^{E_i}\left[\frac{S^{E1}(E_i,E_\gamma)}{E_\gamma}\sigma_{\gamma,abs}^{GDR}(E_\gamma)\frac{\Gamma_n}{\Gamma_T}(E_\gamma)\right]dE_\gamma, \qquad (18)$$

and

$$\sigma_{e,np}(E_i) = C\int_{18.57}^{E_i}\left[\frac{S^{E1}(E_i,E_\gamma)}{E_\gamma}\sigma_{\gamma,abs}^{GDR}(E_\gamma)\frac{\Gamma_{np}}{\Gamma_T}(E_\gamma)\right]dE_\gamma + \int_{18.57}^{E_i}\left[\frac{S^{E1}(E_i,E_\gamma)}{E_\gamma}\sigma_{\gamma,abs}^{QD}(E_\gamma)\right]dE_\gamma. \qquad (19)$$

Equations (18) and (19) represent a set of linear equations, with the free parameters $C/(1-\bar{k})$ and C being the only unknown quantities. The solution was obtained by a least squares fitting to the experimental datasets of both reactions simultaneously. Results are shown in Figs. 1 and 2.

The photodisintegration cross sections $\sigma_{\gamma,n}(E_\gamma)$ and $\sigma_{\gamma,np}(E_\gamma)$, their sum, the QD model prediction for the photoabsorption cross section, and relative measurements from Cook *et al.* [4] are all shown in Fig. 3. [The notation $\sigma_{\gamma,x}(E_\gamma) = (\sigma_{\gamma,x})^{SP}$ for our results will be incorporated from now on in order to distinguish between different laboratory

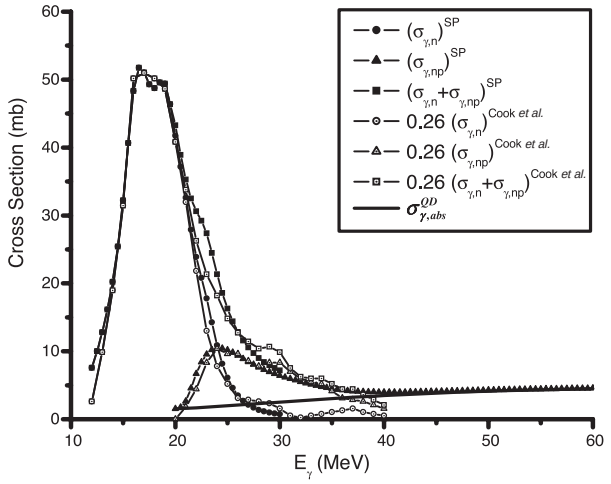

FIG. 3. Photodisintegration cross sections $\sigma(\gamma,n)$ and $\sigma(\gamma,np)$ for ^{64}Zn: this work and from Cook *et al.* [4]. The solid line shows the photoabsorption cross section for ^{64}Zn as predicted by the QD model.

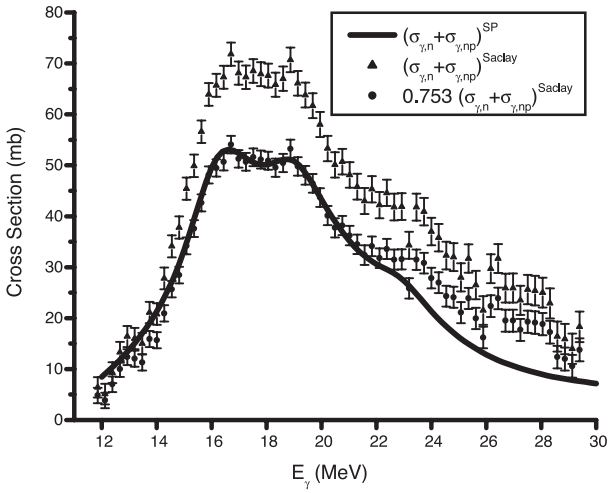

FIG. 4. Photodisintegration cross section $\sigma(\gamma,1n)=\sigma(\gamma,n)+\sigma(\gamma,np)$ for ^{64}Zn: this work and from Saclay [3].

measurements]. As noticed, the agreement between the structures is quite reasonable, differing only by a scaling factor of 0.26, since the measurements from Cook *et al.* are in relative scale. These results, combined with the fact that the constraint imposed by the QD model in the (γ,np) channel reproduces accurately the experimental electrodisintegration yield (Fig. 2), show that both shape and absolute value are simultaneously reproduced by the trial function proposed in Eqs. (18) and (19), with $C/(1-\bar{k})=1.04(3)$, $C=0.95(4)$, and consequently, $\bar{k}=0.08(5)$. Although not being very accurate, this estimate for the direct contribution (about 8%) in the (γ,n) decay channel is within the expectation for this mass region. The agreement between $(\sigma_{\gamma,np})^{SP}$ and the prediction of the QD model in the energy range 40–60 MeV (Fig. 3) is consistent with the fact that at these energies the statistical contribution from the resonant state decay does not play a significant role and, also, constitutes a stringent test for the absolute values of both $(\sigma_{\gamma,n})^{SP}$ and $(\sigma_{\gamma,np})^{SP}$.

The cross section $(\sigma_{\gamma,1n})^{SP}=(\sigma_{\gamma,n}+\sigma_{\gamma,np})^{SP}$ is shown in Fig. 4 together with the Saclay measurements [3], where is also plotted our normalization suggestion for the Saclay data by a factor 0.753(6), obtained from a least squares fitting to our results up to 21 MeV. The upper energy limit of 21 MeV to the fitting was imposed because $B_{2n}=20.97$ MeV, in order to avoid neutron counting uncertainties related to the experimental detection method used by the Saclay group. The agreement between this normalized cross section and our result up to 22 MeV is excellent, with the latter underestimating the former in the range 22–29.5 MeV. This could be related to some impurities in the ZnO target (7% of ^{66}Zn and 2% of ^{68}Zn) as reported by Carlos *et al.* [3].

We plotted in Fig. 5 the cross sections $(\sigma_{\gamma,np})^{SP}$ and $(\sigma_{\gamma,np})^{\text{Cook } et\ al.}$ in a more expanded scale together with some other results of $(\sigma_{\gamma,2nx})^{\text{Saclay}}$,$(\sigma_{\gamma,2n})^{\text{Cook } et\ al.}$, and the prediction of the QD model. Once again, scaling factors of 0.26 and 0.753 have been applied, respectively, to the data from Cook *et al.* and Carlos *et al.* to keep the analysis consistent. The structures in $(\sigma_{\gamma,np})^{SP}$ and $(\sigma_{\gamma,np})^{\text{Cook } et\ al.}$ (Fig. 5) match up to about 35 MeV. Above this energy the results from Cook *et al.* exhibit a sharp drop, while our results remarkably agree with the QD model prediction. The direct and statistical contributions to the cross section $(\sigma_{\gamma,np})^{SP}$ are then presented in Fig. 6.

Since the scaling factor C was already determined, the total photoabsorption cross section for ^{64}Zn may be evaluated as a sum of GDR and QD components where the former, as our approach suggests, is proportional to the Lorentz curve introduced by Eq. (4):

$$[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{SP}=C\sigma^{GDR}_{\gamma,abs}(E_\gamma); \tag{20}$$

therefore,

$$[\sigma^{Tot}_{\gamma,abs}(E_\gamma)]^{SP}=[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{SP}+\sigma^{QD}_{\gamma,abs}(E_\gamma). \tag{21}$$

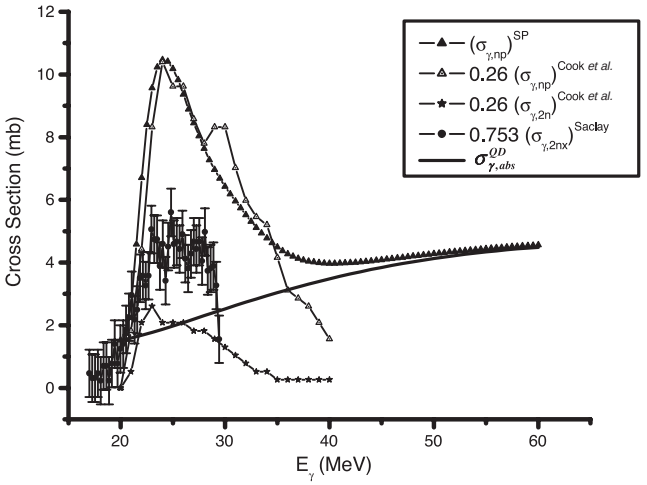

FIG. 5. Photodisintegration cross sections $\sigma(\gamma,np)$, $\sigma(\gamma,2n)$, and $\sigma(\gamma,2nx)$ for ^{64}Zn. The solid line shows the photoabsorption cross section for ^{64}Zn as predicted by the QD model.

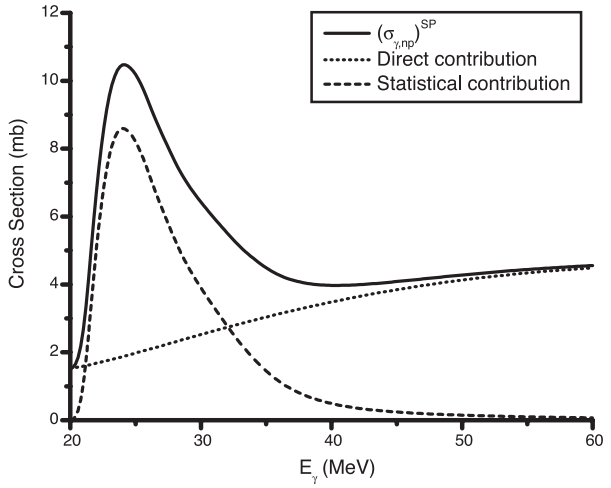

FIG. 6. Photodisintegration cross section $\sigma(\gamma,np)$ for ^{64}Zn obtained in this work. The dotted and dashed lines represent the direct and statistical contributions, respectively.

Results up to 21 MeV are shown in Fig. 7 with a result from Fukahori [8], where in the inset is the ratio between the resonant components $[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{SP}$ and $[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{\mathrm{JENDL}}$ (**R**) and its mean value of 0.74, which agrees within 1% with our proposed normalization factor for the Saclay data (0.753), showing that our result for $[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{SP}$ is compatible with the one obtained by the JENDL group. This normalization problem seems to have originated in the experimental data $(\sigma_{\gamma,1n})^{\mathrm{Saclay}}$ used by JENDL to perform their calculations. The relationship between the ratios $(\sigma_{\gamma,1n})^{SP}/(\sigma_{\gamma,1n})^{\mathrm{Saclay}}$ and $[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{SP}/[\sigma^{GDR}_{\gamma,abs}(E_\gamma)]^{\mathrm{JENDL}}$ is due to the fact that the $(\gamma,1n)$ channel is responsible for the major part of the GDR decay, and any normalization problem in the original experimental data reflects almost linearly in the calculation of the resonant contribution of the total photoabsorption cross section.

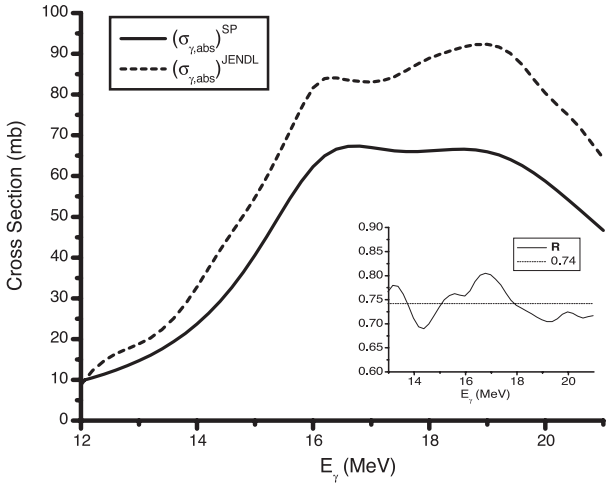

FIG. 7. Total photoabsorption cross section for ^{64}Zn. The solid line represents the calculation performed in this work, and the dashed line is the previous evaluation by JENDL. Inset: ratio **R** between the results from this work and those from JENDL; the dashed line represents the mean value of **R**.

V. DISCUSSION AND CONCLUSIONS

The (e,n) and (e,np) electrodisintegration cross sections of ^{64}Zn were determined from 12.5 MeV to 60 MeV by means of residual activity measurements, thus circumventing the necessity for coincidence (e,np) measurements.

The corresponding (γ,n) and (γ,np) photodisintegration cross sections were obtained by fitting double-parameter trial functions to the electrodisintegration cross sections, via the virtual photon formalism. The trial functions were constructed through an approach developed in this work, where the (γ,n) reaction in the GDR is interpreted as an admixture of a dominant (around 92%) statistical part and a small (around 8%) direct part, and the direct contribution to the (γ,np) reaction is ascribed to the QD model of photoabsorption. Differing from usual unfolding techniques [20], which have the characteristic of smoothing out the structures and also introducing some unwanted extra uncertainties, the trial function method provided consistent solutions to the experimental data (Figs. 1 and 2).

When compared with the relative measurements from Cook *et al.* [4], our cross sections $\sigma(\gamma,n)$ and $\sigma(\gamma,np)$ show similar structures, differing only by a scaling factor of 0.26 (Fig. 3). We note that the main goal of this work is the measurement of the (γ,np) reaction cross section, which we indeed performed for the first time in absolute scale, from the threshold to 60 MeV. The description of the Pauli-blocking function proposed by Chadwick *et al.* [18] proved to be an appropriate improvement to previous QD models as it reproduces fairly well the experimental results in the energy range 40–60 MeV (Fig. 5). The experimental accuracy was not enough to encourage taking into account the nucleon effective mass in the QD model, although this modification could play a role, as recently addressed in Ref. [21].

From the analysis of the compatibility between our data and those of Cook *et al.*, and also considering the QD model prediction enhancing our absolute results, we suggest a renormalization factor of 0.753 to be applied to the Saclay data. Incidentally, these Saclay data for ^{64}Zn were obtained together with those for ^{75}As (both are presented in Ref. [3]). We calculated the ratio of the energy integrated single-photoneutron cross section in the GDR region (as given in Ref. [1]), between the Livermore and Saclay datasets for ^{75}As, obtaining 0.78 which, within the overall uncertainties, is consistent with the correction we are now suggesting for the ^{64}Zn data from Saclay.

The total photoabsorption cross section for ^{64}Zn was re-evaluated up to 21 MeV from the (γ,n) and (γ,np) cross sections, plus the respective branching ratios calculated by the ALICE/LIVERMORE-82 code. A comparison between our results and a previous evaluation performed by JENDL based on the Saclay data (Fig. 7) showed good similarity, differing by a scaling factor of 0.74, which was a direct consequence of the different experimental data sources used by the two groups.

As a final remark, we would like to emphasize that the trial function method incorporating a simplified model to describe the relevant processes, and a detailed calculation of the $E1$ virtual photon spectra in the DWBA allows a com-

plete and self-consistent solution of the photonuclear yield equations, also providing a significant contribution to the delineation of both statistical and direct aspects taking place in the (γ,np) process (Fig. 6). Actually, the evaporation code ALICE/LIVERMORE-82 has proved to be an excellent tool to deal with photonuclear reactions driven by statistical processes. The trial function method of analysis could be a good alternative approach for the study of electronuclear and photonuclear reactions, as demonstrated in this work.

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