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Shadowing in low-energy photonuclear reactions

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The photonuclear reaction in the multi-GeV region occurs because of the electromagnetic and hadronic interactions. The latter originates due to the hadronic fluctuation, i.e., vector meson, of the photon. The total cross section of the reaction is shadowed because of the vector meson–nucleus (hadronic) interaction. To estimate it quantitatively, the cross section of the photonuclear reaction was calculated in the low energy region (∼1–3 GeV) using the simple vector-meson dominance (SVMD) model, i.e., the low-lying vector mesons (ρ^0, ω, and ϕ mesons) were considered. The nuclear shadowing is reinvestigated using the generalized vector meson (GVMD) model, where the higher ρ meson effective state (ρ' meson) is taken into account along with the low-lying vector mesons. Using the GVMD model, the total cross section of the photonuclear reaction are calculated in the above mentioned energy region. The calculated results are compared with the measured spectra.

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I. INTRODUCTION

The ratio of the total cross section of the nuclear reaction to A (nuclear mass number) times that of the nucleonic reaction is called the transparency T of the nuclear reaction. The transparency of the photonuclear reaction, i.e., $T = \frac{\sigma_t^{\gamma A}}{A\sigma_t^{\gamma N}}$, in the GeV region is found to be less than unity. This phenomenon is called shadowing in the photonuclear reaction. Indeed, it is a feature of hadron-nucleus reactions. Therefore, shadowing in the photonuclear reaction indicates the hadronic behavior of photons [1–3]. Photon can fluctuate into hadronic states, i.e., vector mesons, which undergo multiple scattering while traversing through the nucleus. This scattering leads to the reduction of the cross section of the photonuclear reaction.

The total cross section of the photonuclear reaction can be evaluated by applying the optical theorem to the amplitude of the forward Compton scattering, illustrated in Fig. 1. The forward scattering of a photon from a nucleon, shown in Fig. 1(a), occurs due to the electromagnetic interaction; i.e., it does not indicate the hadronic content of the photon. Therefore, it leads to the unshadowed cross section of the reaction. Figure 1(b) describes the vector meson mediated forward Compton scattering on a nucleon in the nucleus, which gives rise to the nuclear shadowing because of the hadronic interaction of the vector meson with the nucleus. Using Glauber model, the amplitude of the forward nuclear Compton scattering can be expressed in terms of the vector meson–nucleon interaction [2]. In fact, the shadowing in high energy (multi-GeV) photonuclear reactions can be understood quantitatively using Glauber formalism [1,3].

The data of the photonuclear reaction at $E_\gamma = 1$–2.6 GeV [4,5] show early onset of the nuclear shadowing which could not be explained by newer models [6,7]; i.e., the calculated results, according to these models, either slightly underestimate or overestimate the data. Falter *et al.*, [4] considered the simple vector meson dominance (SVMD) model in the Glauber approach to describe the nuclear shadowing seen in the data in the region 1–3 GeV. In the SVMD model, the low-lying vector mesons, i.e., $V = \rho^0$, ω, and ϕ mesons, are considered because a low energy photon beam, as mentioned above, was used in the measurements. According to them, the nuclear shadowing can be understood by the proper choice of $\alpha_{\rho N}$, i.e., the ratio of the real to the imaginary part of the ρ-nucleon scattering amplitude. The use of $\alpha_{\rho N}$ evaluated by Kondratyuk *et al.*, [8] gives a good description of the shadowing in the considered reaction [4].

As pointed out in Ref. [9], the shadowing in the ρ meson photoproduction reaction in the multi-GeV region is better accounted for by using generalized vector meson dominance (GVMD) model. In this model, the higher vector meson states V' are used along with the low-lying vector mesons V. The elementary scattering of the vector meson in the SVMD model is described as $VN \to VN$, where as the additional processes $V'N \to VN$, $V'N \to V'N$, and $VN \to V'N$ are incorporated in the GVMD model. In fact, this model has been extensively used by many authors to study nuclear shadowing [10]. For example, Frankfurt *et al.* [11] show the existence of the hard and soft components of the virtual photon within the GVMD model and predict nuclear shadowing in deep inelastic scattering (DIS) similar to that within the parton model. Using Glauber model, the shadowing in the photonuclear reaction is calculated at $E_\gamma > 3$ GeV, where GVMD model is included in the parametric form of the scattering amplitude used to evaluate the profile function of the reaction [12]. This model is also used to study the scaling behavior of the shadowing effect in deep inelastic μ-nucleus scattering [13].

The shadowing in the photonuclear reaction in the low energy region (∼1–3 GeV) is reexamined using both SVMD and GVMD models in the Glauber formalism (modified for the correlated system) for the reaction. The photoproduction of the vector meson and its interaction with the nucleus are described by the measured vector meson–nucleon scattering parameters. The calculated results for the nuclear shadowing due to SVMD and GVMD models are compared with the measured spectra in the considered energy region.

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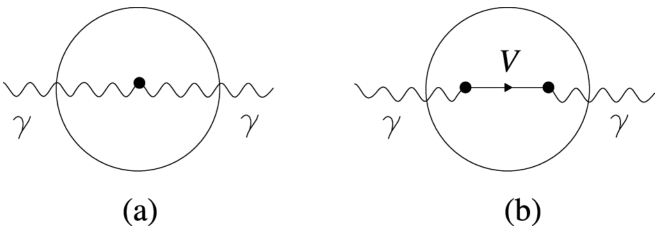

FIG. 1. The pictorial presentation of Compton scattering on the nucleus.

II. FORMALISM

The total scattering cross section of the photonuclear reaction, $\sigma_t^{\gamma A}$, as discussed earlier, is composed of the unshadowed and shadowed parts, i.e.,

$$\sigma_t^{\gamma A} = A\sigma_t^{\gamma N} + \sigma_{t,V}^{\gamma A}, \quad (1)$$

where $\sigma_t^{\gamma N}$ is the total cross section of the photonucleon reaction. The first part of the equation, i.e., $A\sigma_t^{\gamma N}$, is the unshadowed total cross section of the photonuclear reaction, addressed in Fig. 1(a). The cross section $\sigma_{t,V}^{\gamma A}$ originates due to the vector meson scattering on the nucleus [shown in Fig. 1(b)], which leads to the shadowing in the photonuclear reaction. Using the fixed scatterer (or frozen nucleon) approximation, $\sigma_{t,V}^{\gamma A}$ in the SVMD model is given by [2]

$$\sigma_{t,V}^{\gamma A} = \sum_{V=\rho,\omega,\phi} \frac{8\pi^2}{k_\gamma k_V} \mathrm{Im}\Big\{ i f_{VN\to\gamma N} f_{\gamma N\to VN} \times \int d\mathbf{b} \int_{-\infty}^{+\infty} dz \int_z^{+\infty} dz' \times \varrho_2(\mathbf{b},z',z) e^{-iq_V(z'-z)} \times \exp\Big[-\frac{1}{2}\sigma_t^{VN}(1-i\alpha_{VN}) \int_z^{z'} dz_\iota \varrho(\mathbf{b},z_\iota)\Big]\Big\}, \quad (2)$$

where k_γ and k_V are the momenta of the incoming γ boson and vector meson respectively. q_V $(= k_\gamma - k_V)$ is the momentum transfer to the nucleus. All other quantities appearing in the above equation are described below. The widths of the vector mesons are neglected in this equation [4,9]. It is shown later that the distinctly dominant contribution to the nuclear shadowing arises due to the ρ meson. The intrinsic width of this meson is so large ($\Gamma_\rho \sim 150$ MeV [14]) that it dominantly decays ($\rho^0 \to \pi^+\pi^-$) inside the nucleus [15]. The effect of the ρ meson width is largely canceled by the corrections arising from the pions scattering in the nucleus [9]. The widths of the ω and ϕ mesons (i.e., $\Gamma_\omega \sim 8.5$ MeV and $\Gamma_\phi \sim 4.3$ MeV [14,16]) are much smaller than that of the ρ meson, and therefore they decay outside the nucleus. The contributions of the ω and ϕ mesons to the nuclear shadowing, as discussed later, are insignificant. It should be mentioned that Eq. (2) can be interpreted in terms of the vector meson properties in the nucleus; see the details in Ref. [4].

The terms $\varrho(\mathbf{b},z_\iota)$ and $\varrho_2(\mathbf{b},z',z)$ in Eq. (2) represent one-body and correlated two-body density distributions of the nucleus. For the uncorrelated system (i.e., independent particle approximation), $\varrho_2(\mathbf{b},z',z)$ is expressed in terms of one-body nuclear densities, i.e., $\varrho_2(\mathbf{b},z',z) = \varrho(\mathbf{b},z')\varrho(\mathbf{b},z)$, and the cross section in Eq. (2) represents the optical model approximation in the Glauber multiple scattering approach in the photonuclear reaction [1,7]. The two-body correlated nuclear density distribution $\varrho_2(\mathbf{b},z',z)$, given in Refs. [4,7], is

$$\varrho_2(\mathbf{b},z',z) = \varrho(\mathbf{b},z')\varrho(\mathbf{b},z) + \Delta(\mathbf{b},|z'-z|), \quad (3)$$

where $\varrho(\mathbf{r})$ denotes single-particle nuclear density distribution. The form of it is discussed later. $\Delta(\mathbf{b},|z'-z|)$ denotes two-body correlation function. Considering Bessel function parametrization, it can be written as $\Delta(\mathbf{b}|z'-z|) = -j_0(q_c|z'-z|)\varrho(\mathbf{b},z')\varrho(\mathbf{b},z)$, with $q_c = 0.78$ GeV [4,7]. Since $\varrho_2(\mathbf{b},z',z)$ is equal to zero for $z' = z$, there cannot be overlap of nucleons in the nuclear density distribution. Therefore, the inclusion of $\Delta(\mathbf{b}|z'-z|)$ in the nuclear density distribution avoids the unphysical results.

In Eq. (2), σ_t^{VN} is the vector meson–nucleon total scattering cross section and α_{VN} denotes the ratio of the real to the imaginary part of the vector meson–nucleon scattering amplitude $f_{VN\to VN}$. According to the simple vector meson dominance (SVMD) model, $f_{VN\to VN}$ is related to the photoproduction amplitude $f_{\gamma N\to VN}$ [9,15] as

$$f_{\gamma N\to VN} = f_{VN\to\gamma N} = \frac{\sqrt{\pi\alpha_{em}}}{\gamma_{\gamma V}} f_{VN\to VN}, \quad (4)$$

where α_{em} $(= 1/137.036)$ is the fine structure constant. $\gamma_{\gamma V}$ is the photon γ to vector meson V coupling constant, which is determined from the measured $V \to e^+e^-$ decay widths [14]: $\gamma_{\gamma\rho^0} = 2.48$, $\gamma_{\gamma\omega} = 8.53$, and $\gamma_{\gamma\phi} = 6.72$ [17].

III. RESULT AND DISCUSSIONS

The transparency T, i.e., $\frac{\sigma_t^{\gamma A}}{A\sigma_t^{\gamma N}}$, is calculated using Eq. (1) to study the shadowing in the photonuclear reaction in the energy region of 1–3 GeV. Data for the transparency T exist for ^{12}C, ^{27}Al, ^{63}Cu, ^{112}Sn, and ^{208}Pb nuclei. The total cross section $\sigma_t^{\gamma N}$ of the photonucleon reaction is defined as $\sigma_t^{\gamma N} = \frac{Z}{A}\sigma_t^{\gamma p} + \frac{A-Z}{A}\sigma_t^{\gamma n}$, where $\sigma_t^{\gamma p}$ and $\sigma_t^{\gamma n}$ are the total cross sections of the gamma-proton (γp) and gamma-neutron (γn) scattering respectively. The energy dependent measured values for them are taken from Refs. [14,18].

The form of the single-particle density distribution of the nucleus $\varrho(\mathbf{r})$, as extracted from an electron scattering experiment, is given in Ref. [19]. $\varrho(\mathbf{r})$ for ^{12}C is described by the harmonic oscillator Gaussian form [19], i.e.,

$$\varrho(r) = \varrho(0)[1 + w(r/c)^2]e^{-(r/c)^2}, \quad (5)$$

with $w = 1.247$ and $c = 1.649$ fm. For other nuclei mentioned above, $\varrho(\mathbf{r})$ is described by the two-parameter Fermi (2pF) distribution function [19]:

$$\varrho(r) = \varrho(0)\frac{1}{1 + e^{-(r-c)/z}}. \quad (6)$$

The parameters c (half-density radius) and z (diffuseness) for nuclei appearing in the equation are taken from Ref. [19]. The density is normalized to the mass number of the nucleus.

The ρN scattering amplitude $f_{\rho N\to\rho N}$ is taken from the analysis by Kondratyuk *et al.* [8]. The experimentally determined imaginary part of the ωN scattering amplitude $f_{\omega N\to\omega N}$ is given in [20,21]. For the real part of $f_{\omega N\to\omega N}$, the ratio $\alpha_{\omega N}$ $(=\frac{\mathrm{Re} f_{\omega N\to\omega N}}{\mathrm{Im} f_{\omega N\to\omega N}})$ has been calculated using the additive quark model and Regge theory [20]: $\alpha_{\omega N}=\frac{0.173(s/s_0)^{\epsilon}-2.726(s/s_0)^{\eta}}{1.359(s/s_0)^{\epsilon}+3.164(s/s_0)^{\eta}}$, with $s_0=1$ GeV^2, $\epsilon=0.08$, and $\eta=-0.45$. s is the ωN center-of-mass (c.m.) energy. According to vector meson dominance (VMD) model [15,17], the forward cross section of the $\gamma p\to\phi p$ reaction, i.e., $\frac{d\sigma}{dq^2}(\gamma p\to\phi p)|_{q^2=0}$, is given by

$$\frac{d\sigma}{dq^2}(\gamma p\to\phi p)|_{q^2=0}=\frac{\alpha_{em}}{16\gamma_{\gamma\phi}^2}\left(\frac{\tilde{k}_\phi}{\tilde{k}_\gamma}\right)^2\left[1+\alpha_{\phi N}^2\right](\sigma_t^{\phi N})^2, \tag{7}$$

where $\tilde{k}_\phi$ and $\tilde{k}_\gamma$ are the c.m. momenta in the ϕN and γN systems respectively, evaluated at the c.m. energy of the γN system. Using $\alpha_{\phi N}=-0.3$ [1] and the parametrized form of $\frac{d\sigma}{dq^2}(\gamma p\to\phi p)$ given in Eq. (3.85a) in Ref. [1], the imaginary part of the ϕN scattering amplitude $f_{\phi N\to\phi N}$ is extracted from the above equation.

The shadowing in the photonuclear reaction was defined earlier by the transparency $T=\frac{\sigma_t^{\gamma A}}{A\sigma_t^{\gamma N}}<1$. Among the ρ, ω, and ϕ mesons in SVMD model, the shadowing in the photonuclear reaction, as shown by the dot-dashed curve in Fig. 2, distinctly originates due to the ρ meson. The momentum transfer to the nucleus is large for the massive vector meson production [see Eq. (2)], which leads to less cross section or shadowing in the reaction. Although the mass m_ρ (= 775.26 MeV) $\sim m_\omega$ (=782.65 MeV) and the elementary cross section $\sigma_t^{\omega N}\sim\sigma_t^{\rho N}$, the ω meson weakly contributes to the nuclear shadowing; see the dot-dot-dashed curve in the figure. This occurs because the ω meson photoproduction amplitude, according to Eq. (4), is the least, i.e., $\gamma_{\gamma\omega}=8.53$. The small ϕ meson photoproduction amplitude ($\gamma_{\gamma\phi}=6.72$) and relatively large mass ($m_\phi\sim 1020$ MeV) lead to negligible contribution of the ϕ meson (shown by the short-dashed curve) to the nuclear shadowing.

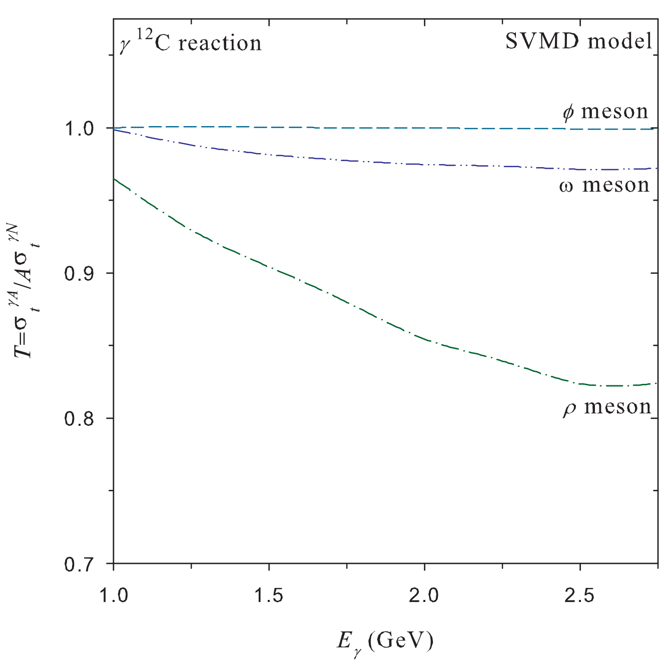

FIG. 2. The shadowing ($T<1$) in the γ ^{12}C reaction due to ρ^0, ω, and ϕ mesons used in the SVMD model. The figure shows that the nuclear shadowing distinctly occurs due to the ρ meson.

Since the distinctly dominant contribution to the nuclear shadowing (as illustrated in Fig. 2) arises because of the ρ meson, the higher states of this meson (discussed in GVMD model) should be considered, as the shadowing due to the ρ meson can be modified because of those states. There exist a few higher ρ meson states [14] but, unfortunately, the dielectron decay widths $\Gamma_{V\to e^+e^-}$ of these mesons are not known. The measured $\Gamma_{V\to e^+e^-}$, as mentioned below Eq. (4), is used to extract the photon to vector meson coupling constant $\gamma_{\gamma V}$. Unless those (i.e., $\gamma_{\gamma V}$'s) are known for the higher ρ meson states, they cannot be incorporated in the GVMD model to describe photon induced reactions. As done by Pautz and Shaw [9], the contributions of all higher ρ meson states are approximated with that of an effective state (called the ρ' meson) whose mass and coupling (to photon) constant can be expressed by those of the ρ meson. The calculated results with those values account very well for the measured ρ meson photoproduction data in the multi-GeV region. Therefore, the effective ρ meson state, i.e., the ρ' meson, is considered in the GVMD model, and the scattering amplitude of the ρ meson, predicted by the SVMD model in Eq. (4), is replaced by those of the ρ and ρ' mesons in the GVMD model [22] as

$$\begin{aligned} f_{\gamma N\to\rho N} &= \frac{\sqrt{\pi\alpha_{em}}}{\gamma_{\gamma\rho}} f_{\rho N\to\rho N}+\frac{\sqrt{\pi\alpha_{em}}}{\gamma_{\gamma\rho'}} f_{\rho' N\to\rho N}, \\ f_{\gamma N\to\rho' N} &= \frac{\sqrt{\pi\alpha_{em}}}{\gamma_{\gamma\rho'}} f_{\rho' N\to\rho' N}+\frac{\sqrt{\pi\alpha_{em}}}{\gamma_{\gamma\rho}} f_{\rho N\to\rho' N}, \end{aligned} \tag{8}$$

where $\gamma_{\gamma\rho'}$ denotes the photon to ρ' meson coupling constant. The properties of the ρ' meson (i.e., mass $m_{\rho'}$ and $\gamma_{\gamma\rho'}$) are given by $m_{\rho'}=\sqrt{3}m_\rho$, $\gamma_{\gamma\rho'}=\frac{m_{\rho'}}{m_\rho}\gamma_{\gamma\rho}$ [9,22]. The scattering amplitudes are related to each other as $f_{\rho' N\to\rho' N}=f_{\rho N\to\rho N}$, $f_{\rho' N\to\rho N}=f_{\rho N\to\rho' N}=-\epsilon f_{\rho N\to\rho N}$, with $\epsilon=0.18$ [9,22]. The above equations illustrate the reduction of $f_{\gamma N\to\rho N}$ due to the inclusion of the ρ' meson (GVMD model) which leads to less shadowing in the photonuclear reaction. As explained earlier, the nuclear shadowing due to the vector meson decreases with the increase in its mass m_V and coupling constant to photon $\gamma_{\gamma V}$. Due to these reasons, the contribution of the higher states of the vector mesons (i.e., ρ', ω', and ϕ' mesons) to the shadowing is much less. The ω' and ϕ' mesons are not included in the respective photoproduction amplitudes $f_{\gamma N\to\omega N}$ and $f_{\gamma N\to\phi N}$, since the contribution of the ω and ϕ mesons (SVMD model) to the shadowing in the considered reaction (as shown in Fig. 2) is insignificant. The inclusion of the ω' and ϕ' mesons would further reduce the nuclear shadowing due to the ω and ϕ mesons respectively, which are already negligibly small.

To compare the nuclear shadowing in SVMD and GVMD models, the transparencies T are calculated using those models, and the calculated results along with the data [4,5] are presented in Fig. 3. The dot-dashed curves describe the nuclear

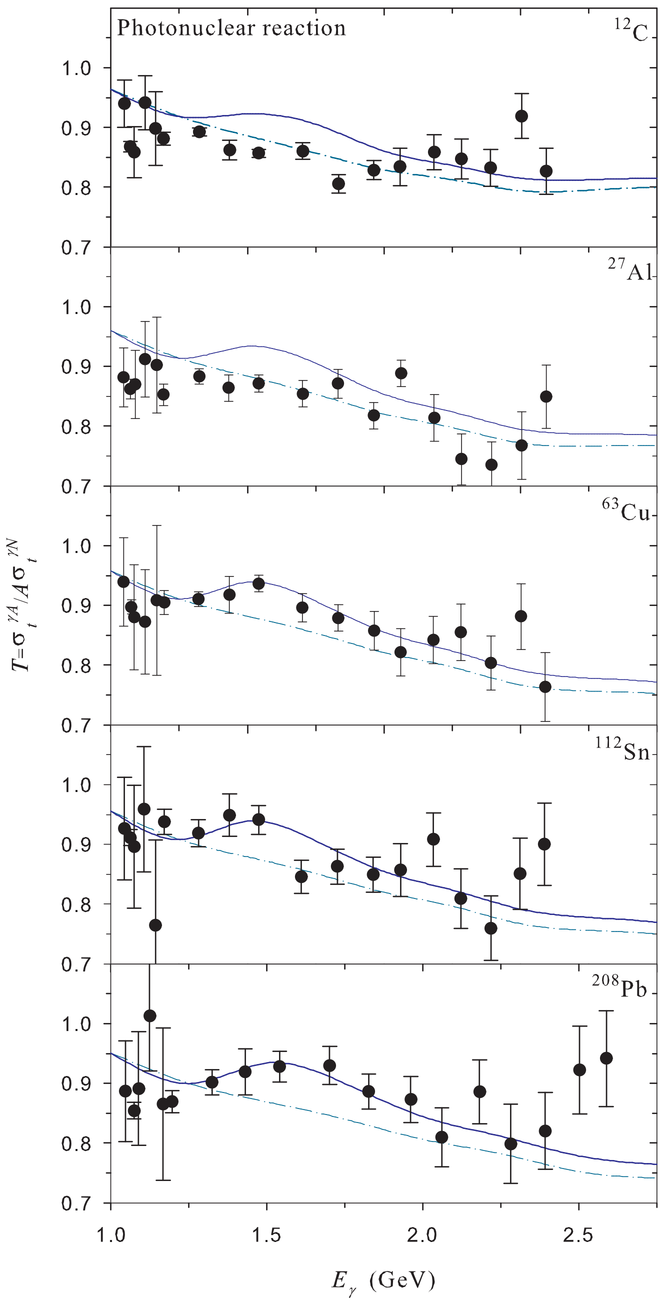

FIG. 3. The shadowing in the photonuclear reactions compared with data. The dot-dashed curves describe the nuclear transparencies due to SVMD model, whereas the solid curves represent those due to the GVMD model (see text).

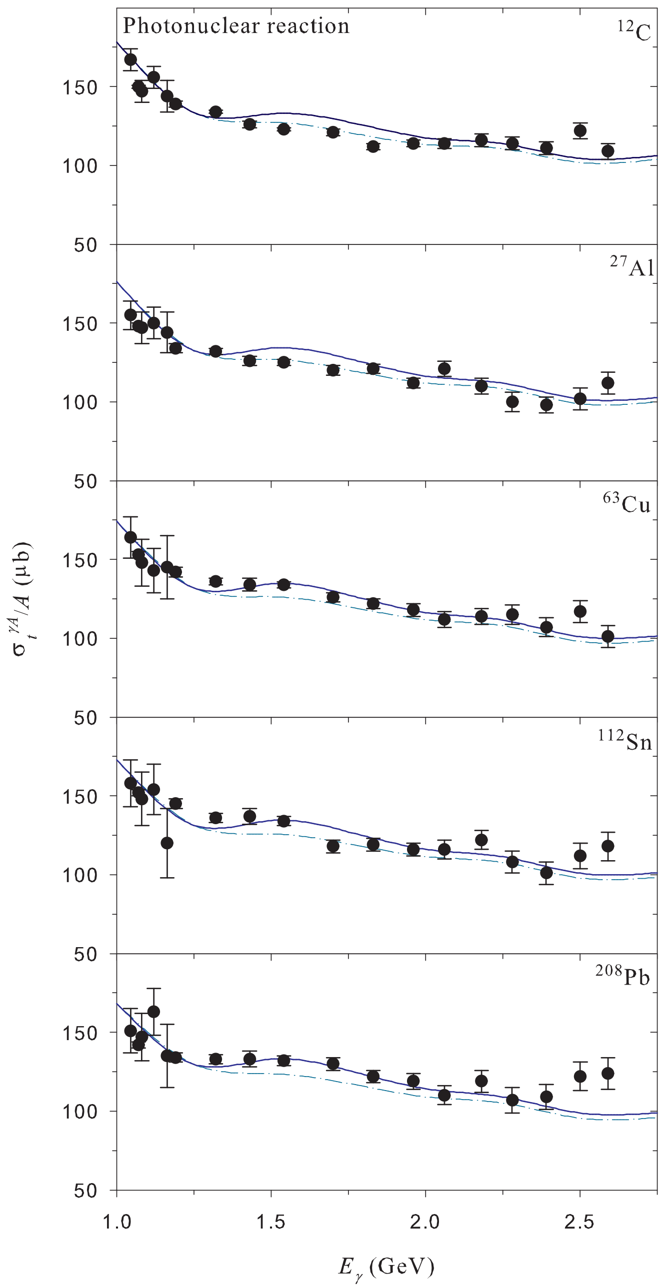

FIG. 4. The total cross section per nucleon of the photonuclear reactions presented with the measured spectra [5]. The curves represent the calculated results due to SVMD and GVMD models, as explained in Fig. 3.

shadowing due to SVMD model; i.e., the ρ, ω, and ϕ mesons are taken into account to describe the reaction. The solid curves arise because of the GVMD model; i.e., the effective higher ρ meson state (ρ' meson), in addition to the above vector mesons, is used to calculate the nuclear transparency. Figure 3 distinctly shows that the nuclear shadowing is reduced because of the ρ' meson in the GVMD model, and the bump appearing at $E_\gamma \sim 1.6$ GeV for heavier nuclei is well reproduced by this model. The calculated results accord well with the data of the shadowing in the photonuclear reaction.

The total cross sections per nucleon of the photonuclear reaction, i.e., $\sigma_t^{\gamma A}/A$ calculated using Eq. (1), are compared with the data [5] in Fig. 4. The dot-dashed curves in this figure are due to the SVMD model whereas the solid curves arise because of the GVMD model. The figure shows that the cross section increases because of the ρ' meson in GVMD model. The calculated results reproduce the data reasonably well.

Figures 3 and 4 show that the calculated results based on the SVMD model reproduce well the measured spectra for lighter nuclei, i.e., ^{12}C and ^{27}Al, throughout the considered beam energy region. The results for heavier nuclei (i.e., ^{63}Cu, ^{112}Sn, and ^{208}Pb) also accord well with data except in the beam energy region $E_\gamma \sim 1.5$–1.7 GeV, where they underestimate the measured spectra. It is noticeable that the calculated results due to the GVMD model trend differently. The results based on this model overestimate the data for the lighter nuclei in the energy region $E_\gamma \sim 1.5$–1.7 GeV. Beyond this region, those results accord well with the data. For the heavier nuclei, the calculated results due to the GVMD model reproduce the measured spectra remarkably well.

IV. CONCLUSIONS

The shadowing of the photonuclear reaction in the 1–3 GeV region is studied using the optical theorem in the Glauber approach for the multiple scattering of vector mesons in the nucleus. Both SVMD and GVMD models are used to interpret the vector meson production in the considered reaction. In the first model, the low-lying vector mesons (i.e., ρ^0, ω, and ϕ mesons) are considered, whereas the latter model adds an effective higher ρ meson state, i.e., the ρ' meson. The shadowing in the photonuclear reaction distinctly occurs because of the ρ meson. The cross section of the photonuclear reaction increases due to the inclusion of the ρ' meson (GVMD model) which leads to the reduction of the shadowing in the reaction. The calculated results accord well with data. Specifically, the GVMD model reproduces noticeably well the bump appearing in the measured spectrum for the heavy nuclei.

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