Probing the dynamics of the charmonium interactions in the coherent photoproduction off nuclei at moderate energies

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We calculate the coherent charmonium photoproduction in the photon energy domain where the coherence and formation lengths exceed the average internucleon distance in nuclei but are comparable to the nuclear radii. In this kinematical regime we use the generalized vector dominance model (GVDM) adjusted to account for the physics of bound charmonium states and for the color screening phenomenon. We find significant oscillations in the energy dependence of the total and forward photoproduction cross sections due to the oscillating behavior of the longitudinal nuclear form factor. Within the GVDM these oscillations are strongly modified by the nondiagonal rescatterings of the charmonium. We demonstrate how to employ the oscillating behavior of the photoproduction cross sections off nuclear targets to determine the elementary charmonium photoproduction amplitudes and the genuine charmonium-nucleon cross sections in the forthcoming SLAC E160 experiment.

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I. INTRODUCTION

One of the striking quantum chromodynamics (QCD) predictions is the dependence of the hadron interaction strength on the size of the region occupied by the color fields within the hadrons. Initially, this phenomenon was suggested within the constituent quark model of hadrons and the two-gluon exchange model for hadron-hadron interactions [1,2]. Later, the existence of such a dependence was proved for the interaction of spatially small quark-gluon wave packages as another form of the QCD factorization theorem [3,4]. The interaction of the charmonia with nuclei is a natural field in which to explore this idea. Within charmonium models (see, e.g., Ref. [5]) the ψ' radius is twice as large as the J/ψ radius. Hence, one can expect that their interactions with nuclei should differ greatly. At present, the uncertainties in their total cross sections for interactions with nucleons are very large—the values are ranging from 1 mb up to 8 mb for $J/\psi N$ and, correspondingly, from 0.8 mb to 20 mb for $\psi' N$ interactions. This is due to both the experimental and the theoretical issues (for a review and an extensive list of references, see Ref. [6]). The cross sections of $J/\psi N$ and $\psi' N$ interactions cannot be measured directly. However, it may be possible to determine them from the charmonium photoproduction and hadroproduction off nuclear targets where J/ψ and ψ' mesons interact with the nucleons upon production during the passage through the nucleus.

In the discussion of the heavy quarkonium photoproduction we distinguish several energy ranges which require different approximations. At high photon energies ω, both the coherence length $l_c \approx 2\omega m_V^{-2}$ and the formation length $l_f \approx 2\omega[m^2_{\psi'} - m^2_{J/\psi}]^{-1}$ are large, and the color transparency phenomenon reveals itself explaining the fast increase of the cross section with energy observed at HERA (for a review, see Ref. [7]). The value of the elementary cross section extracted from the charmonium photoproduction in this energy region characterizes the interaction of the squeezed $c\bar{c}$ pair with a nucleon rather than the charmonium-nucleon interaction. In the high energy limit the very small $c\bar{c}$ distances in the wave function of the photon dominate. In this limit, the interaction is proportional to the nuclear gluon density which is expected to be strongly shadowed [8]. This shadowing effect leads to a significant suppression of the J/ψ photoproduction off nuclei [9].

A qualitatively different picture should be observed at intermediate energies where the onium states are formed inside the nucleus. In this case, the nonperturbative effects hidden in the charmonium wave function become important. These effects can be approximately accounted for within a hadronic basis description of the charmonium photoproduction. Initially, the vector dominance model (VDM), which is grounded on a hadronic basis, was used to describe the charmonium photoproduction off nuclear targets. The VDM analysis of the corresponding SLAC data [10] gives the total cross section $\sigma_{J/\psi N} \approx 1.3 \pm 0.3$ mb for $J/\psi N$ interaction and an even smaller value $\sigma_{\psi' N} \sim 1.0$ mb for $\psi' N$. This result contradicts the QCD expectation that the cross sections scale as the transverse area occupied by color and that the ratio of cross sections should approximately be $\sigma_{\psi' N}/\sigma_{J/\psi N} \propto r^2_{\psi'}/r^2_{J/\psi} \approx 4$. Hence, the VDM failed to reproduce the QCD-based estimate even on a qualitative level. The VDM neglects an essential feature of the charmonium photoproduction—the J/ψ and ψ' photoproduction amplitudes are determined by the $\sim 1/m_c$ relative distances in the $c\bar{c}$ component of the photon wave function [11,12]. The dominance of these small $c\bar{c}$ configurations is responsible for the significant probability of nondiagonal $J/\psi \leftrightarrow \psi'$ diffractive transitions. Within the hadronic basis this color screening phenomenon [11–13] can be accounted for in the generalized VDM (GVDM). However, we want to emphasize that the GVDM can be applied to describe the quarkonium photoproduction only in the region of photon energies where the leading twist gluon shadowing is still unimportant, i.e., at $\omega \leqslant m_\psi^2/2x_{sh}m_N$($x_{sh}\approx 0.03$ is value of x for the onset of the gluon shadowing).

We use the GVDM to calculate the coherent photoproduction of hidden charm mesons off nuclei at moderate photon energies 20 GeV$\leqslant \omega \leqslant$60 GeV. In this region, the coherence length l_c for the $\gamma \to V$ transition is close to the internucleon distance in nuclei while the formation length l_f is comparable to the radii of heavy nuclei. At such moderate energies there is a noticeable probability for rescattering of charmonia, at least, in the photoproduction off heavy nuclei. Hence, such processes reveal the fluctuation of the charmonium-nucleon interaction strength as being due to the diagonal $\psi N \to \psi N$ and nondiagonal $\psi N \Leftrightarrow \psi' N$ rescatterings. We built the generalized Glauber model (GGM) by combining the multistep production Glauber model with the GVDM. The model neglects inelastic shadowing corrections related to the production of higher mass states [14] since they are still insignificant at moderate energies. Within this approach we perform calculations aimed at investigating how the color fluctuations reveal themselves in the interactions of charmonium states with the nuclear medium. It should be noted that the charmonium photoproduction electroproduction off nuclei in a wide range of photon energies is a subject of active investigation (see, for example, Ref. [15]). In this paper we observe and investigate the significant cross section oscillations in the total and forward cross sections of the J/ψ and the ψ' photoproduction off nuclei at low and moderate energies of photons. Our analysis indicates that these oscillations can be observed in the forthcoming experimental measurement (E160) of the charmonia photoproduction planned at SLAC [16] and can be used to obtain a reliable experimental estimate for the genuine cross sections of $J/\psi N$ and $\psi' N$ interactions.

II. DESCRIPTION OF THE MODEL

At moderate energies the produced $c\bar{c}$ pair expands before it reaches a second nucleon. Therefore, it has sufficient time to fragment into charmonium states before further interactions with the target nucleus can take place. Thus an accurate treatment of the photoproduction cross section can be achieved within a hadronic basis where the multichannel Glauber approach formulas [17] are combined with the GVDM [18,19]. In such an approach the cross section is given by the Glauber formula

$$\sigma_{\gamma A\to VA}(\omega)=\int_{-\infty}^{t_{min}} dt\frac{\pi}{k_V^2}|F_{\gamma A\to VA}(t)|^2 = \frac{\pi}{k_V^2}\int_{-\infty}^{0} dt_\perp \left|\frac{ik_V}{2\pi}\int d\vec{b}\, e^{i\vec{q}_\perp\cdot\vec{b}}\Gamma_V(\vec{b})\right|^2. \quad (1)$$

Here $V=J/\psi,\psi',\ldots,$ $q_\perp^2=-t_\perp=t_{min}-t,$ $-t_{min}=M_V^4/4\omega^2,$ is the longitudinal momentum transfer in the $\gamma\to V$ transition, and $\Gamma_V(\vec{b})$ is the diffractive nuclear profile function

$$\Gamma_V(\vec{b})=\lim_{z\to\infty}\Phi_V(\vec{b},z). \quad (2)$$

To evaluate the amplitude of the charmonium photoproduction it is reasonable to make the following approximation: restrict the basis of the GVDM by the lowest J/ψ and ψ' states in the photon wave function. Then, with the accuracy $O(\sqrt{\alpha_{em}})$, the eikonal functions $\Phi_{J/\psi,\psi'}(\vec{b},z)$ are determined as the solutions of the coupled two-channel equations

$$2ik_{J/\psi}\frac{d}{dz}\Phi_{J/\psi}(\vec{b},z)=U_{\gamma A\to J/\psi A}(\vec{b},z)e^{iz\cdot q_\parallel^{\gamma J/\psi}} + U_{J/\psi A\to J/\psi A}(\vec{b},z)\Phi_{J/\psi}(\vec{b},z) + U_{J/\psi A\to\psi' A}(\vec{b},z)e^{iz\cdot q_\parallel^{J/\psi\psi'}}\Phi_{\psi'}(\vec{b},z), \quad (3)$$

$$2ik_{\psi'}\frac{d}{dz}\Phi_{\psi'}(\vec{b},z)=U_{\gamma A\to\psi' A}(\vec{b},z)e^{iz\cdot q_\parallel^{\gamma\psi'}} + U_{\psi' A\to\psi' A}(\vec{b},z)\Phi_{\psi'}(\vec{b},z) + U_{\psi' A\to J/\psi A}(\vec{b},z)e^{iz\cdot q_\parallel^{\psi' J/\psi}}\Phi_{J/\psi}(\vec{b},z), \quad (4)$$

with the initial condition $\Phi_{J/\psi,\psi'}(\vec{b},-\infty)=0$. The exponential factors $\exp[iq_\parallel^{i\to j}z]$ account for the dependence of the amplitudes on t_{min}: $i,j=\gamma,J/\psi$ resp. $\psi',q_\parallel^{i\to j}=(M_j^2-M_i^2)/2\omega$. They are responsible for the coherence length effect.

In the short-range approximation the generalized Glauber-based optical ($A\gg 1$) potentials are given by the expression

$$U_{iA\to jA}(\vec{b},z)=-4\pi f_{iN\to jN}\varrho(\vec{b},z). \quad (5)$$

Here $f_{iN\to jN}$ are the elementary forward amplitudes. The nuclear density, $\varrho(\vec{b},z)$ is normalized by the condition $\int d^2\vec{b}dz\,\varrho(\vec{b},z)=A$. We calculated $\varrho(\vec{b},z)$ in a Hartree-Fock-Skyrme (HFS) model. This HFS approach describes accurately not only the global nuclear properties of many spherical nuclei from carbon to uranium [20] but also the shell momentum distributions in the high energy $(p,2p)$ [21] and $(e,e'p)$ [22] reactions.

The elementary photoproduction amplitudes in the GVDM with restricted two-state basis are given by

$$f_{\gamma N\to J/\psi N}=\frac{e}{f_{J/\psi}}f_{J/\psi N\to J/\psi N}+\frac{e}{f_{\psi'}}f_{\psi' N\to J/\psi N},$$

$$f_{\gamma N\to \psi' N}=\frac{e}{f_{\psi'}}f_{\psi' N\to \psi' N}+\frac{e}{f_{J/\psi}}f_{J/\psi N\to \psi' N}. \tag{6}$$

The coupling constants f_V are usually determined from the widths of the $V\to e\overline{e}$ vector meson decays

$$\left(\frac{e^2}{4\pi f_V}\right)^2=\frac{3}{4\pi}\frac{\Gamma(V\to e\overline{e})}{m_V}, \tag{7}$$

with [23]

$$\Gamma(J/\psi\to e\overline{e})=5.26\pm0.37\text{ keV and }\Gamma(\psi'\to e\overline{e})=2.12\pm0.18\text{ keV}. \tag{8}$$

This yields

$$\frac{f^2_{J/\psi}}{4\pi}=10.5\pm0.7\text{ and }\frac{f^2_{\psi'}}{4\pi}=30.9\pm2.6. \tag{9}$$

The distinctive feature of the coherent charmonia photoproduction at moderate energies is the large size of the amplitude for nondiagonal transitions. This can be roughly demonstrated from the observation that the photons produce $c\overline{c}$ pairs in spatially small configurations [24]. The interaction of the small size $c\overline{c}$ configuration with a nucleon should be strongly suppressed due to the smallness of the transverse area occupied by color. Hence, one can neglect for a moment the relatively small hard photoproduction amplitude as compared to the soft one, and obtain from Eq. (6) the rough estimate of the nondiagonal amplitude

$$f_{\psi' N\to J/\psi N}\approx-\frac{f_{\psi'}}{f_{J/\psi}}f_{J/\psi N\to J/\psi N}\approx-1.7f_{J/\psi N\to J/\psi N}. \tag{10}$$

An even larger value can be found for the amplitude of the diagonal $\psi' N$ interaction,

$$f_{\psi' N\to \psi' N}\approx\frac{f^2_{\psi'}}{f^2_{J/\psi}}f_{J/\psi N\to J/\psi N}\approx 3f_{J/\psi N\to J/\psi N}. \tag{11}$$

Data on ψ' absorption in nucleus-nucleus collisions suggest the value of $\sigma_{\psi' N}\sim 20$ mb [25]. Combined with the SLAC data [26], this corresponds to $\sigma_{\psi' N}/\sigma_{J/\psi N}\approx 5-6$ with large experimental and theoretical errors. Large values of nondiagonal amplitudes are a characteristic QCD property of the hidden charm and bottom meson interaction with a nucleon. Note that the negative sign of the nondiagonal amplitude is dictated by the suppression of the perturbative contribution. A positive sign of the forward photoproduction $f_{\gamma N\to J/\psi(\psi')N}$ amplitudes as well as the signs of the coupling constants $f_{J/\psi}$ and $f_{\psi'}$ are determined by the signs of the charmonium wave functions at $r=0$.

In order to fix the elementary amplitudes in the GVDM more accurately, we have used the following logic: We parametrize the cross section in the form used by the experimentalists of HERA to describe their data. This form has no firm theoretical justification but it is convenient for the fit,

$$\frac{d\sigma_{\gamma+N\to V+N}}{dt}\propto F_{2g}(t)\left(\frac{s}{s_0}\right)^{2\lambda}. \tag{12}$$

Here $s=2\omega m_N+m_N^2$ is the center-of-mass energy and F_{2g} is the two-gluon form factor of a nucleon. The parameter λ is derived from the fit to the experimental data [10],

$$\left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=t_{min}}=17.8\pm1.5\text{ nb GeV}^{-2}\text{ at }s_0=40.4\text{ GeV}^2,$$

$$\left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=t_{min}}=40\pm13\text{ nb GeV}^{-2}\text{ at }s_0=188.9\text{ GeV}^2. \tag{13}$$

We also use the experimentally found relation between forward photoproduction cross sections,

$$\left.\frac{d\sigma_{\gamma N\to \psi' N}}{dt}\right|_{t=t_{min}}=0.15\left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=t_{min}}, \tag{14}$$

which practically does not depend (or depends only weakly) on the energy. The two-gluon form factor, extracted from the analysis of J/ψ photoproduction data in Ref. [27], can be used to evaluate the nucleon form factor at $t=t_{min}$:

$$F_{2g}=\left(1-\frac{t_{min}}{m^2_{2g}}\right)^{-2}. \tag{15}$$

The quantity m^2_{2g} is defined by

$$\frac{1}{m^2_{2g}}=\frac{1}{\text{GeV}^2}+\frac{0.06}{\text{GeV}^2}\ln\left(\frac{s}{s_0}\right). \tag{16}$$

As a result, for the photoproduction of the J/ψ we found $\lambda=0.2$. The value of λ for the ψ' production is somewhat less, $\lambda=0.15$, but in this case λ is determined with much larger uncertainties. Hence, in our calculations we use the same value, $\lambda=0.2$, for both processes.

The $J/\psi N$ cross section can be parametrized as the sum of soft and hard physics:

$$\frac{\sigma_{J/\psi N}(s)}{\sigma_{J/\psi N}(s_0)}=c\left(\frac{s}{s_0}\right)^{0.08}+(1-c)\left(\frac{s}{s_0}\right)^{\lambda}. \tag{17}$$

According to the SLAC data [26],

$$\sigma_{J/\psi N}(s=s_0)=3.5\pm0.8\text{ mb} \tag{18}$$

at $s_0=38.5$ GeV^2. We evaluated $c\approx1$ in our previous paper on the absorption of ψ produced in AA collisions [28] with

$$\sigma(\text{hard})=2\pi\int_{-\infty}^{\infty}dz\int_{0.1\text{ fm}}^{0.2\text{fm}}|\phi(b,z)|^2\sigma(b)b\,db. \tag{19}$$

Here $\phi(b,z)$ is the wave function of the J/ψ and $\sigma(b)$ is the perturbative dipole cross section from Ref. [4]. When the upper limit of the integral over b is increased to 0.35 fm, then $c=0.915$, i.e., $\sigma(\text{hard})=(1-c)\sigma_{J/\psi N}(s_0)$

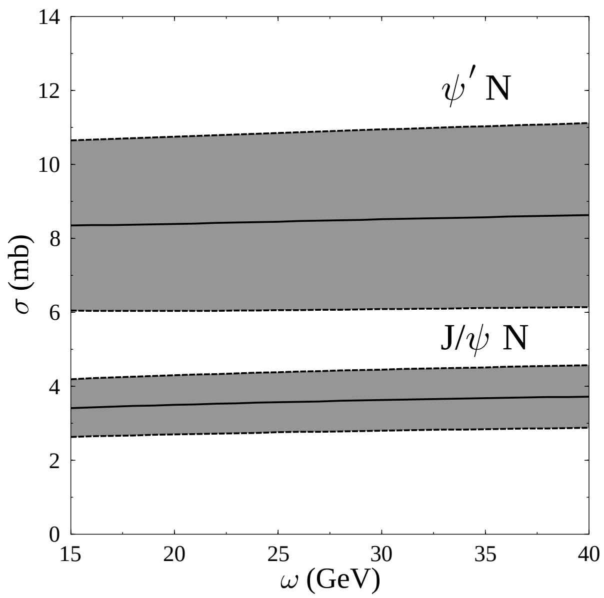

FIG. 1. The energy dependence of the elementary charmonium-nucleon cross sections found in the GVDM. The filled areas show the variation of the cross sections due to the uncertainty of the experimental $J/\psi N$ cross section.

$=0.3$ mb. This is an uncertainty of the model since it is not evident up to which values of b the PQCD is applicable. Hence, in the following calculations we use $c=0.915$ and our parametrization of cross section is

$$\sigma_{J/\psi N} = 3.2 \text{ mb}\left(\frac{s}{s_0}\right)^{0.08} + 0.3 \text{ mb}\left(\frac{s}{s_0}\right)^{0.2}. \qquad (20)$$

Using this total cross section, we find the imaginary part of the amplitude from the optical theorem $\text{Im}f_{J/\psi N\to J/\psi N} = s\sigma_{J/\psi N}$ and the real part from the Gribov-Migdal relation

$$\text{Re}f_{J/\psi N\to J/\psi N} = \frac{s\pi}{2}\frac{\partial}{\partial \ln s}\frac{\text{Im}f_{J/\psi N\to J/\psi N}}{s}. \qquad (21)$$

Once the amplitudes of the photoproduction and the $J/\psi N$ diagonal interaction are found, we determine all other forward amplitudes from the GVDM equations (6). That is, all parameters are fixed. However, the experimental cross sections of the forward elementary photoproduction and, especially, the value of $\sigma_{J/\psi N}$, used as input of the GVDM, are known with large uncertainties. We checked how a variation of $\sigma_{J/\psi N}$ within the experimental errors will influence the results of our calculations. The ranges of the total $J/\psi N$ and $\psi' N$ cross sections obtained within this procedure are shown in Fig. 1.

III. RESULTS AND DISCUSSION

Within the model described in Sec. II we calculated the cross sections for coherent photoproduction of J/ψ and ψ' off light (Si) and heavy (Pb) nuclear targets. To start with, let us consider the results for the heavy nuclear target where the rescattering effects should be more pronounced. The energy dependence of the cross sections integrated over transverse momentum is compared (Fig. 2) to that obtained in the impulse approximation (IA). In the IA all rescatterings of the produced vector mesons are neglected and the cross section is given by

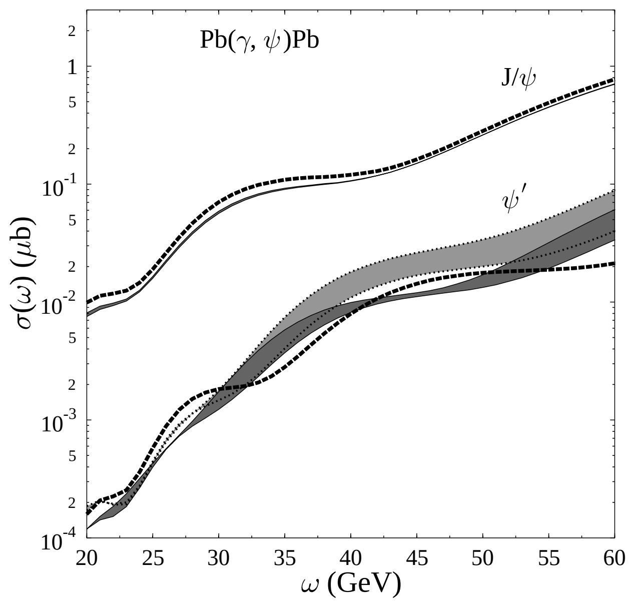

FIG. 2. The energy dependence of the integrated over transverse momentum coherent Pb($\gamma,J/\psi$)Pb and Pb(γ,ψ')Pb cross sections calculated in the GGM (dark shaded area) compared to the cross sections in the IA (dashed lines) and in the GGM without diagonal rescatterings, i.e., with $f_{VN\to VN}=0$ (dotted lines, light shaded area). The filled areas depict the variation of results due to the experimental uncertainties in the $J/\psi N$ cross section.

$$\sigma_{\gamma A\to VA}(\omega) = \frac{d\sigma_{\gamma N\to VN}(t_{min})}{dt}\int_{-\infty}^{0} d\, t_\perp \left| \int_0^\infty e^{i\vec{q}_\perp\cdot\vec{b}} d\,\vec{b} \times \int_{-\infty}^{\infty} d\, z\, e^{iz\cdot q_\parallel^{\gamma V}}\varrho(\vec{b},z)\right|^2. \qquad (22)$$

Because $\sqrt{-t_{min}}=q_\parallel^{\gamma V}=m_V^2/2\omega$, a decrease of the photon energy corresponds to an increase in the longitudinal momentum transfer in the coherent photoproduction off nuclei. This results in a stronger suppression of the cross section by the longitudinal nuclear form factor.

The cross section of photoproduction in the GGM is close to that calculated in the IA. The shapes of the curves are very similar, and the values of the cross sections are slightly reduced, with reduction being larger at energies below 40 GeV. The distinctive feature of the coherent charmonium photoproduction at low and moderate energies is the oscillating behavior of the cross section as a function of ω. The major cause of such a behavior in the considered kinematical region is the oscillating longitudinal nuclear form factor at the relatively large value of t_{min} in the photoproduction vertex. The pronounced oscillations are also revealed in the coherent ψ' photoproduction off nuclei but in this case both the shape and the values of the cross section are significantly changed relative to the IA results. The ψ' photoproduction off a nucleon is suppressed by a factor of ≈ 7 relative to the

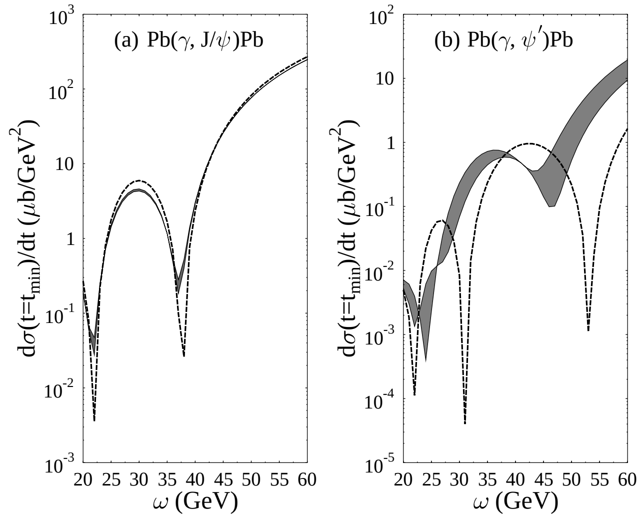

FIG. 3. The energy dependence of the coherent forward cross sections in the GGM (shaded area) compared to the cross sections in the IA (dashed lines): (a) Pb(γ,J/ψ)Pb and (b) Pb(γ,ψ')Pb. The filled areas depict the variation of results due to the experimental uncertainties of the $J/\psi N$ cross section.

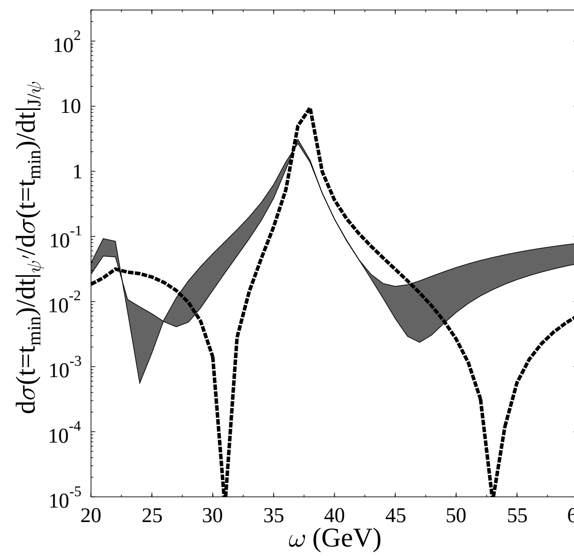

FIG. 4. The energy dependence of the ratio of forward Pb(γ,ψ')Pb and Pb(γ,J/ψ)Pb cross sections in the GGM (dark shaded area) and in the IA (dashed line). The filled area depicts uncertainty due to the variation of the $J/\psi N$ cross section.

J/ψ production [10]. In the case of a nuclear target there is an additional suppression by the nuclear form factor because $q_\parallel^{\gamma\psi'} \approx (m_{\psi'}^2/m_{J/\psi}^2) q_\parallel^{\gamma J/\psi} > q_\parallel^{\gamma J/\psi}$. The difference in the minimal longitudinal momentum transfer is also reflected in the shift of the positions of the minima in the energy dependence of the cross section. To illustrate separately the influence of the diagonal and the nondiagonal transitions, we show calculations in the GGM without the diagonal rescatterings (dotted lines, light shaded area), i.e., with $f_{VN\to VN}=0$. The contribution of the nondiagonal transitions $\gamma\to J/\psi\to\psi'$ significantly increases the ψ' yield and shifts the minima in the spectrum to lower photon energies [29].

The oscillating behavior and influence of rescatterings are seen best in the forward differential cross sections (Fig. 3) and in the ratio of the cross sections for the ψ' and the J/ψ production. In Fig. 4 we present this ratio calculated in the GGM (solid lines, shaded area) and in the IA (dashed line). We emphasize that measurement of such ratios removes the nuclear model dependence since the same longitudinal nuclear form factor enters in the numerator and the denominator. The ratio of the cross sections in the IA can be used as a model independent reference curve. It can be easily calculated for many nuclei using the nuclear form factors measured in high energy, elastic, electron scattering experiments and the photoproduction cross sections measured with a nucleon target. Furthermore, we would like to note that one can also remove the dependence of the procedure on the elementary photoproduction cross sections using the double ratio of the relative ψ'-to-J/ψ yield in the coherent photoproduction off a heavy nucleus and a light one.

Now let us consider how to extract the genuine $J/\psi N$ and $\psi' N$ cross sections from a measurement of the coherent charmonium photoproduction at moderate energies. The conventional procedure is based on a comparison of the data with calculations which estimate the suppression of the particle yield due to final state interactions. The cross sections, characterizing this interaction, are used as fitting parameters. In the case of the charmonium photoproduction, such a procedure seems to be rather complicated.

The sensitivity of the nuclear photoproduction cross sections to the values of the elementary amplitudes is revealed in our calculations. However, the interplay of diagonal and nondiagonal transitions and their interference with the amplitude of the direct production leads to a rather formidable problem. One can naively estimate that the final state diagonal $J/\psi N$ interaction can suppress the yield of produced mesons from the heavy nucleus by $\approx$30–40%. However, from the calculation within the GGM we find [Fig. 5(a)] the energy dependent suppression of the J/ψ yield: $\approx$15–20% at $\omega \leqslant 40$ GeV and $\approx$6–7% at $\omega \geqslant 40$ GeV. The increase of the elementary $J/\psi N$ cross section by a factor 1.5, within the experimental uncertainties (see Fig. 1), changes the suppression by only $\approx$5% at low energies and is practically negligible at higher energies. Hence, even at low energies, where the $\gamma N\to\psi' N$ amplitude is small, we find a noticeable compensation of the suppression by the contribution of the two-step $\gamma A\to A+\psi'\to A+J/\psi$ production.

With increasing photon energies in the considered region, this compensation effect becomes stronger. It is due to the gradual onset of the regime of color transparency for the propagation of the J/ψ through the nuclear medium. The analysis of the ψ' photoproduction shows [Fig. 5(b)] a significant influence of the two-step photoproduction $\gamma+A \to J/\psi+A\to\psi'+A$. In a wide range of energies, we also find a noticeable effect due to the interference of the two-step amplitude with the direct production and with the amplitude comprising diagonal rescatterings.

Therefore, we conclude that such a complicated interplay of rescatterings will preclude any unique determination of the genuine $J/\psi N$ and $\psi' N$ cross sections from measurements with heavy nuclear targets. We suggest a new solution to this

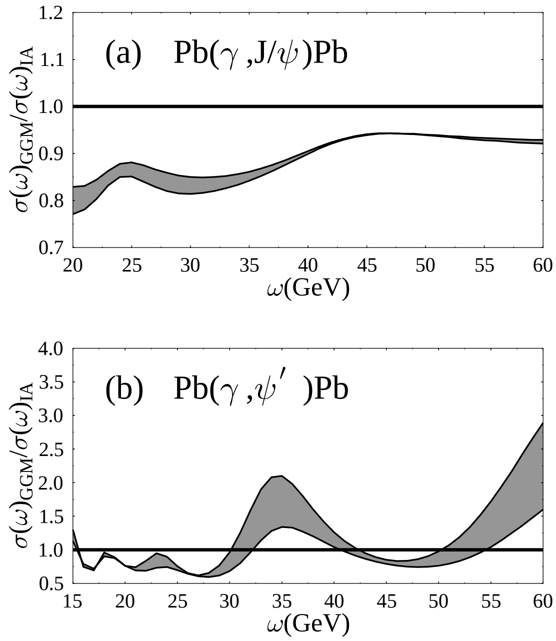

FIG. 5. The energy dependence of the ratio of the coherent Pb(γ,J/ψ)Pb (a) and Pb(γ,ψ')Pb (b) cross sections in the GGM (dark shaded area) to the cross section in the IA (dashed line). The filled areas depict uncertainty due to the variation of the $J/\psi N$ cross section.

problem based on the measurement of the coherent charmonium photoproduction off a light nucleus. Analyzing the results of calculations for a series of nuclei [30] we choose silicon as an optimal target. For silicon, the cross sections are not too small, and one could envision an active target which would allow one to select the coherent events in a cleaner way.

The cross section of the J/ψ production off silicon, calculated in the GGM, practically coincides with the result of the IA [Fig. 6(a)]. The deviation does not exceed 4–5% and varies weakly when the rescattering amplitudes are changed as is allowed by the uncertainties in the input values of the $J/\psi N$ cross section. This implies that an unprecedented accuracy is required both in the measurement and in the theoretical analysis in order to extract the $J/\psi N$ cross section from such measurements. However, these data can be used to determine precisely the forward photoproduction cross section off a nucleon. As it turns out, the contribution of the diagonal $J/\psi N$ rescattering can safely be neglected. Then the forward $\gamma N \rightarrow J/\psi N$ cross section can be determined from a comparison of the data with the calculations in the IA [Eq. (22)], where the nuclear form factor is fixed by the high energy electron-nucleus elastic scattering. At low values of t the cross section of the J/ψ production off silicon is considerably larger than $d\sigma_{\gamma N \rightarrow J/\psi N}(t_{min})/dt$ [dotted line in Fig. 6(a)]. Hence, one may significantly improve the accuracy of the determination of $d\sigma_{\gamma N \rightarrow J/\psi N}(t_{min})/dt$.

The cross section of the coherent ψ' photoproduction off silicon, calculated within the GGM, significantly exceeds the cross section of the IA [Fig. 6(b)]. The suppression due to the diagonal ψ' rescatterings is negligible relative to the enhancing two-step nondiagonal $\gamma A \rightarrow J/\psi A \rightarrow \psi' A$ contribution. At

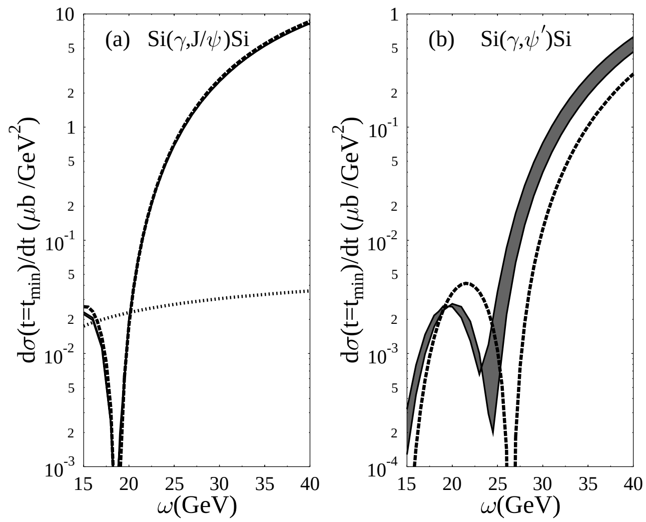

FIG. 6. (a) The forward coherent γ+Si$\rightarrow J/\psi$+Si cross section in the GGM (dark shaded area) compared to the cross section in the IA (dashed line). The forward elementary $\gamma N \rightarrow J/\psi N$ cross section is shown by the dotted line. (b) The forward coherent γ+Si$\rightarrow \psi'$ +Si cross section in the GGM (dark shaded area) compared to the cross section in the IA (dashed line).

the photon energy coinciding with the position of the minimum of the nuclear form factor, the two-step mechanism $\gamma A \rightarrow J/\psi A \rightarrow \psi' A$ dominates (Fig. 7) because the direct ψ' photoproduction tends to zero. Hence, measuring the forward relative ψ'-to-J/ψ yield in this region of ω one can extract from the data the nondiagonal elementary $J/\psi N \rightarrow \psi' N$ amplitude. In such a ratio, all other inputs, namely, the nuclear

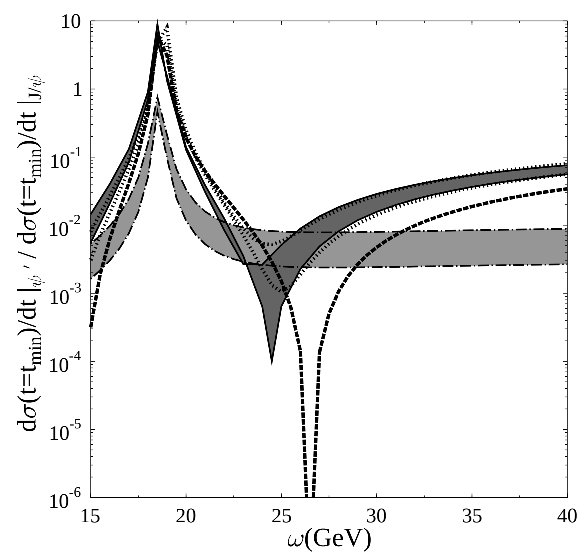

FIG. 7. The ratio of forward coherent γ+Si$\rightarrow \psi'$+Si cross section to the cross section of γ+Si$\rightarrow J/\psi$+Si calculated in the GGM (dark shaded area) compared to the same ratio in the IA (dashed line), to the ratio in the GGM with the nondiagonal $J/\psi N \Leftrightarrow \psi' N$ rescatterings only (area between dotted lines), and to the ratio in the GGM calculated neglecting the direct ψ' production (light shaded area).

density and the elementary $\gamma N \to J/\psi N$ amplitude, are already fixed and, since they enter both in the numerator and the denominator, the major uncertainties are canceled out.

In the discussed energy range, the soft ψN rescatterings within the nuclear medium are characterized by a rather weak energy dependence, such as $s^{0.08}$. In the ratio of the forward ψ' and J/ψ photoproduction cross sections, one can neglect this dependence to a very good accuracy. Hence, the energy dependence of the relative J/ψ-*to*-ψ' yield (Fig. 7) originates from the contribution of the direct ψ' production. By analyzing this dependence, one would be able to determine the $\gamma N \to \psi' N$ amplitude.

We emphasize that the suggested procedure for extracting the nondiagonal amplitude and the amplitude of the direct J/ψ photoproduction is practically model independent.

The task of determining the diagonal $J/\psi N \to J/\psi N$ and $\psi' N \to \psi' N$ amplitudes directly from the data is much more complicated. We suggest a strategy based on the assumption that all other amplitudes are already found from the data as discussed above. The imaginary parts of the forward diagonal amplitudes can be determined from the GVDM equations (6); that is, reverse the procedure which we used in Sec. II,

$$\mathrm{Im} f_{J/\psi N \to J/\psi N} = \frac{f_{J/\psi}}{e} \mathrm{Im} f_{\gamma N \to J/\psi N} - \frac{f_{J/\psi}}{f_{\psi'}} \mathrm{Im} f_{\psi' N \to J/\psi N},$$

$$\mathrm{Im} f_{\psi' N \to \psi' N} = \frac{f_{\psi'}}{e} \mathrm{Im} f_{\gamma N \to \psi' N} - \frac{f_{\psi'}}{f_{J/\psi}} \mathrm{Im} f_{J/\psi N \to \psi' N}.$$

The main limitation of such a procedure is the restriction of the hadronic basis to the two lowest charmonium states $1S$ and $2S$ with the photon quantum numbers J/ψ and ψ'. This question was discussed in Ref. [31]. The disregard of the closest higher charmonium state $\psi(3770)$ can change the estimate of the $J/\psi N$ amplitude by $\approx 10\%$. The influence of the higher mass resonances is expected to be even weaker—the constants $1/f_V$ relevant for the transition of a photon to a charmonium state V rapidly decrease with the resonance mass. This is because the radius of a bound state, r_V, is increasing with the mass of the resonance, and therefore the probability of the small size configuration being $\propto 1/r_V^3$ is decreasing with an increase of mass (for fixed S,L). Furthermore, the asymptotic freedom in QCD predicts a decrease of the coupling constant relevant for the behavior of the charmonium wave function at small relative distances. Experimentally, one finds from the data on the leptonic decay widths that $1/f_V$ drops very fast with increasing mass. An additional suppression arises due to the weakening of the soft exclusive nondiagonal $VN \leftrightarrow V'N$ amplitudes between states with a different number of nodes. Hence, determining the imaginary parts of diagonal rescattering amplitudes from the GVDM equations seems to be possible. Since in the medium energy domain the energy dependence of soft rescattering amplitudes is well reproduced by a factor $s^{0.08}$, the real parts can be found using the well known Gribov-Migdal relation, Eq. (21).

Thus, with the suggested procedure one will be able to determine all elementary amplitudes with a reasonable precision by measuring the photoproduction of J/ψ and ψ' off a light nucleus at the medium photon energies. The cross check of this approach would be a comparison of the cross sections calculated within GGM with parameters fixed in the analysis of the light nuclei with the experimental cross sections measured in photoproduction of charmonium off heavy nuclei as well as in the quasielastic processes.

IV. CONCLUSION

We built the generalized Glauber Model which combines the multistep photoproduction Glauber approach and the generalized vector dominance model adjusted to account for the color screening phenomenon. Within the GGM we have calculated the coherent charmonia photoproduction cross sections off light and heavy nuclei at moderate energies. We found significant oscillations in the energy dependence of the charmonium photoproduction cross sections due to the oscillating behavior of the longitudinal nuclear form factor and the interference of the rescattering amplitudes.

We show that the nondiagonal rescattering amplitudes, which model in the hadronic basis the QCD color fluctuations within hadrons, significantly change the coherent ψ' photoproduction cross section off nuclei. We found sensitivity of oscillations to the cross sections of $J/\psi N$ and $\psi' N$ interactions as well as to the strength of the nondiagonal transitions. A new procedure is suggested for determining the genuine $J/\psi N$ and $\psi' N$ cross sections from the charmonium photoproduction cross sections off light nuclei at low and medium energies. For the coherent hidden beauty meson photoproduction at low energies the oscillations in the Υ and Υ' yields are expected, but the cross sections will obviously be too small to be seen experimentally.

Another way to check out the predictions for the strength of the charmonium interactions will be to study antiproton interactions with nuclei near the resonance energy for the $\bar{p}p \to$ "charmonium" process. One of the most promising processes is $\bar{p} + A \to \psi' + (A-1)$, which is mostly sensitive to the strength of $\psi' N$ interaction and practically not sensitive to the color transparency effects [32]. It would be possible to study this process at the forthcoming $\bar{p}$ accumulator at GSI.

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