Cross Section Oscillations in the Coherent Charmonium Photoproduction off Nuclei at Moderate Energies

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ABSTRACT

We calculate the coherent charmonium photoproduction at intermediate energies accounting for the physics of the charmonium bound states and the dependence of the cross section on the region occupied by color using a correspondingly adjusted generalized vector dominance model (GVDM). In the photon energy domain where the coherence lengths are comparable to the average internucleon distances in nuclei and the nuclear radii we found that significant oscillations of the total and forward photoproduction cross sections governed by the longitudinal nuclear form factor are strongly modified by the charmonium rescatterings accounting for the nondiagonal transitions related to the color screening phenomenon. We discuss how these oscillations can influence the determination of the genuine charmonium-nucleon cross sections in the forthcoming SLAC E160 experiment on low energy $J/\psi$ and $\psi'$ photoproduction off nuclei.

1 Introduction

One of striking QCD predictions is the dependence of the hadron interaction strength on the volume occupied by color. This phenomenon has been suggested initially within the constituent quark model of hadrons and the two gluon exchange model for a hadron-hadron interaction \[1\] and proved later for the interaction of spatially small quark-gluon wave packages as another form of QCD factorization theorem \[2\]. The interaction of the charmonia with nuclei is a natural field for exploring this idea. The probability of spatially small $c\bar{c}$-configurations within these hadrons is large as follows from the observed cross section of charmonium photoproduction \[3\] \[4\] \[5\]. Within the charmonium models(see e.g. \[6\]) the radius of the $\psi'$ is twice as large as the radius of the $J/\psi$, hence, one can expect that their interaction with a nucleus should be strongly different. Strong activity in the search
of the quark-gluon plasma resulted in an enhanced interest to the accurate treatment of charmonium-nucleus interactions. Really, the suppression of the charmonia yield in the central ultrarelativistic heavy ion collisions has been suggested as one of the most promising signals of the Quark Gluon Plasma (QGP) (for a review see e.g. [9]). However, competing suppression of the charmonia yield is due to the ordinary final state charmonia interaction with hadron matter - the interaction with target and projectile nucleons and the effect of co-movers [10], hence, well determined $J/\psi N$ and $\psi^\prime N$ cross sections are urgently needed. Obviously these quantities can’t be found by direct measurements. Also they cannot be extracted from the studies of the photo/electro production off a nucleon since average $c\bar{c}$ separation in this process is significantly smaller than the average size of oniums. Hence the only way is to extract them from the measurement of charmonia nuclear photo- and hadroproduction processes where $J/\psi$ and $\psi^\prime$ interact with the nucleons during their passage through the nucleus from the production point. At present the uncertainties in the extracted cross sections are too 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 $\psi^\prime N$. This is due to both the purely experimental problems and the theoretical issues(for review and extensive list of references see [11]).

In the discussion of vector meson photoproduction one needs to distinguish several different energy ranges which correspondingly require different approximations. They are related to the energy dependence of the coherence length $l_c \approx \frac{m_V^2}{2\omega}$. At low energies the meson is formed at the distances smaller than the typical interaction length of a meson in the nucleus. In this case one should take into account the significant probability of multiple rescattering with different mesons in the intermediate state (i.e. $\gamma + A \rightarrow V^\prime + A \rightarrow V + A$) due to the presence of the nondiagonal interactions of vector mesons with nucleons ($VN \rightarrow V^\prime N$). The opposite limit is that of very high energies in which a photon converts to a system of $q\bar{q}$ and higher Fock-components before the target and one has to account for the interactions of this system with the media and subsequent transition of the system to a vector meson. In the case of the production of light mesons the soft physics dominates in both cases and hence the use of the Gribov-Glauber model should be applicable in a wide range of energies (for most of the cases the inelastic shadowing remains a small correction and the Gribov approximation effectively reduces to the eikonal model) As a result one can use the Vector Dominance Model(VDM) with nondiagonal transitions - the Generalized Vector Dominance Model (GDVM) to describe the $\rho, \rho^\prime$ production in a wide range of energies, see e.g. [12, 13].

The situation is much more involved in the case of (charm)onium production. At high energies both the coherence length and the formation length $l_f \approx 2\omega [m_{\psi^\prime}^2 - m_{J/\psi}^2]^{-1}$ (distance on which the squeezed $q\bar{q}$ pair transforms into the ordinary meson) 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. [14]). Then the value of the cross section extracted from the charmonium photoproduction 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 interquark distances in the wave function of the photon dominate and one has to treat the interaction of small dipoles with nuclei. In this case the eikonal approximation gives a qualitatively wrong answer since it does not take into account the leading twist effect of the gluon shadowing(see the detailed analysis in [15]) while the leading twist analysis predicts large shadowing effects [16]. On the other hand at the intermediate energies when onium states are formed inside the nucleus the nonperturbative
effects at a transverse distance scale comparable to the charmonium size becomes important. Obviously, the hadronic basis description would be more relevant in this case but the VDM which is grounded on such a basis failed to account properly for the basic QCD dynamics of interaction. In particular, SLAC data show that $0.15 \cdot \sigma_{\gamma^{+}N \rightarrow \psi^{0}N} \approx \sigma_{\gamma^{+}N \rightarrow \psi^{0}N}$ which within VDM corresponds to: $\sigma_{\psi^{0}N}/\sigma_{J/\psi N} \approx 0.7$. This conclusion is in evident contradiction with the QCD expectation where the hadron interaction depends on the volume occupied by color and the cross sections should be scaled approximately as the transverse area occupied by color: $\sigma_{\psi^{0}N}/\sigma_{J/\psi N} \propto r^{2}_{\psi}/r^{2}_{J/\psi}$. So within this naive QCD picture the cross section of the $\psi^{0}N$ interaction could be larger by a factor of the order of four. A QCD explanation of such failure of VDM is based on the observation that in photoproduction of both the $J/\psi$ and $\psi'$ mesons the small relative distances dominate in the $c\bar{c}$ component of the photon wave function. As a result the relative suppression of the $\psi'$ production as compared to the $J/\psi$ production is primarily related to a larger nonconservation of mass in the $\gamma \rightarrow \psi'$ transition and is of the order of $m_{\psi}^{2}/m_{\psi'}^{2}$. Overall the $J/\psi$, $\psi'$ photoproduction data strongly indicate that the dependence of the interaction on the size of the region occupied by color takes place already at moderate energies. The dominance of small $c\bar{c}$ configurations in photoproduction processes is relevant for the significant probability of nondiagonal $J/\psi \leftrightarrow \psi'$ diffractive transitions and the proper account for QCD dynamics within a hadronic basis can be provided by using the Generalized Vector Dominance Model (GVDM) adjusted to account for the color screening phenomenon in the regime of small coherence lengths where leading twist shadowing is not important.

In this paper we use the GVDM to consider the coherent photoproduction of hidden charm mesons off nuclei at moderate photon energies $20 \text{ GeV} \leq \omega \leq 60 \text{ GeV}$ where the coherence length for the $\gamma V$ transition $l_{c}$ is still close enough to the internucleon distance in nuclei while the formation length $l_{f}$ is comparable to the radii of heavy nuclei (the problem of interpolating between this regime and the regime of the leading twist gluon shadowing dominance is beyond the scope of this paper). In this energy range it is reasonable to expect that, at least, with a heavy nucleus target there is a noticeable probability for rescattering of charmonia, hence, one would be able to reveal the fluctuation of the charmonium-nucleon interaction strength as due to the diagonal $\psi N \rightarrow \psi N$ and nondiagonal $\psi N \leftrightarrow \psi' N$ rescatterings. We would like to emphasize that at moderate energies using the Generalized Vector Dominance Model (GVDM) whose parameters are chosen to guarantee the validity of color screening phenomena allows to account for the space-time evolution of spatially small $c\bar{c}$ pair together with the Glauber model approximation generalized to account for the physics related to the coherence length. It is important that the inelastic shadowing corrections related to the production of higher mass states are still insignificant.

We built an approach, the Generalized Glauber Model (GGM), based on combining of the multistep production Glauber model with the GVDM. Within this approach we perform calculations aimed to investigate how the color fluctuations reveal themselves in the interactions of charmonium states with nuclear medium in coherent photoproduction off nuclei. It should be noted that the charmonium photo(electro)production off nuclei in the wide range of the photon energies is a subject of active investigation (see for example ). However, as far as we find this paper for the first time raises and investigates the question of the significant cross section oscillations in the total and forward cross sections of the $J/\psi$ and $\psi'$ photoproduction off nuclei at low and moderate energies of photons. Our analysis indi-
cates that this new observation should be very useful and important for the experimental measurement (E160) of the charmonia photoproduction planned at SLAC [21] to obtain a reliable experimental estimate for the genuine cross sections of $J/\psi N$ and $\psi' N$.

2 Description of the model

Our interest in this paper is in moderate energy range phenomena where the $c\bar{c}$ configuration is spatially small in the production point. The large mass of $c$ quark is important to ensure the applicability of PQCD for the description of photoproduction processes and the interaction with target of this initial $c\bar{c}$ configuration. However, the spatially small configuration transforms into a hadron state before it can collide with a second nucleon. So a more accurate treatment of the photoproduction cross section

$$\sigma_{\gamma A\to V A}(\omega) = \int_{-\infty}^{t_{\text{min}}} dt \frac{\pi}{k^2_V} |F_{\gamma A\to V A}(t)|^2 = \frac{\pi}{2k^2_V} \int_0^\infty d\lambda |i \frac{k}{k^2_V} \int d\vec{b} e^{i\vec{q}_\perp \cdot \vec{b}} \Gamma_V(b)|^2 .$$

(1)

can be achieved within a hadronic basis. Here $V = J/\psi, \Psi', \cdots$, $\vec{q}_\perp = t - t_{\text{min}}$, $t_{\text{min}} = \frac{M^2_{\text{ee}}}{4\omega^2}$ is the longitudinal momentum transfer in the $\gamma \to V$ transition, and $\Gamma_V(b)$ is the diffractive nuclear profile function

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

(2)

The eikonal function $\Phi_V(b, z)$ takes into account the phase difference between the incident photon and the intermediate resp. final states due to the longitudinal momentum transfer. It is calculated in the Generalized Glauber model where the modified Glauber approach formulae [22] were combined with the GVDM [23, 24].

A reasonable starting approximation to evaluate the amplitude of the charmonium-nucleon interaction is to restrict ourselves to the basis of $J/\psi$ and $\psi'$ states for the photon wave function. Then

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

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

(3)

Here the coupling constants $f_V$ are determined from the widths of the vector meson decays $V \to e\bar{e}$

$$\left( \frac{e^2}{4\pi f_V} \right)^2 = \frac{3}{4\pi} \frac{\Gamma(V \to e\bar{e})}{m_V} .$$

(4)

with [25]

$$\Gamma(\psi \to e\bar{e}) = 5.26 \pm 0.37 \text{ keV} \text{ and } \Gamma(\psi' \to e\bar{e}) = 2.12 \pm 0.18 \text{ keV} .$$

(5)

This yields

$$\frac{f^2_\psi}{4\pi} = 10.5 \pm 0.7 \text{ and } \frac{f^2_{\psi'}}{4\pi} = 30.9 \pm 2.6 .$$

(6)
In the optical limit \((A \gg 1)\) the generalized Glauber-based optical potentials in the short-range approximation are given by the expression

\[ U_{iA \to jA}(\vec{b}, z) = -4\pi f_{iN \to jN} g(\vec{b}, z) \]  

(7)

where \(f_{iN \to jN}\) are elementary forward amplitudes and the nuclear density \(g(\vec{b}, z)\) is normalized by the condition \(\int d^2b dz \, g(\vec{b}, z) = A\). Thus in the optical limit, with 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

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

(8)

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

(9)

with the initial condition \(\Phi_{J/\psi, \psi'}(\vec{b}, -\infty) = 0\). The exponential factors \(e^{iz\cdot q_i^\parallel}\) account for the dependence of the amplitudes on \(t_{min}\). They are responsible for the coherent length effect, \(i,j=\gamma,J/\psi\) resp. \(\psi', q^{i\to j}_\parallel = \frac{M_j^2-M_i^2}{2z}\). We calculated \(g(\vec{b}, z)\) in the Hartree-Fock-Skyrme (HFS) model which provided a very good (with an accuracy \(\approx 2\%\)) description of the global nuclear properties of spherical nuclei along the periodical table from carbon to uranium \([26]\) and the shell momentum distributions in the high energy \((p,2p)\) \([27]\) and \((e,e'p)\) \([28]\) reactions.

The distinctive feature of the coherent charmonia photoproduction off nuclei at moderate energies is that the amplitude for nondiagonal transitions is large. As an educated guess it can be estimated from the observation that in the photoproduction processes \(c\bar{c}\)-pairs are produced within a spatially small configuration. Within the framework of charmonium models the overlapping integral between the wave functions of photons and mesons with hidden charm is proportional to the charmonium wave function at zero distances. Thus at not too large energies the interaction with a nucleon of such small \(c\bar{c}\) configuration should be strongly suppressed by the small transverse area occupied by color. If one neglects for the moment the relatively small photoproduction amplitude, one obtains from eq. \((8)\) for the nondiagonal amplitude

\[ f_{\psi' N \to J/\psi N} \approx -f_{J/\psi} \cdot f_{J/\psi N \to J/\psi N} \approx -1.7 \cdot f_{J/\psi N \to J/\psi N} \]  

(10)

and an even larger value for \(\psi' N\) interaction

\[ f_{\psi' N \to \psi' N} \approx f_{J/\psi}^2 \cdot f_{J/\psi N \to J/\psi N} \approx 3 \cdot f_{J/\psi N \to J/\psi N} \]  

(11)

Data on \(\psi'\) absorption in nucleus-nucleus collisions suggest the value of \(\sigma_{\psi' N} \sim 20\) mb \([29]\) which combined with the SLAC data \([30]\) corresponds to \(\sigma_{\psi' N}/\sigma_{J/\psi N} \approx 5/6\) with large experimental and theoretical errors. Large values for nondiagonal amplitudes are a characteristic
QCD property of hidden charm and beauty meson-nucleon interaction. Note that the negative sign of the nondiagonal amplitude is dictated by the QCD factorization theorem. A positive sign of the forward photoproduction $f_{\gamma N \rightarrow J/\psi(N)}$ 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

$$\sigma_{\gamma+N\rightarrow V+N} \propto F_{2g}^2 \left( \frac{s}{s_0} \right)^{2\lambda}.$$  \hspace{1cm} (12)

Here $s = 2\omega m_N + m_N^2$ is the center-of-mass energy, $F_{2g}$ is the two-gluon form factor of a nucleon and $\lambda$ is derived from experimental data [17].

$$\frac{d\sigma_{\gamma N \rightarrow J/\psi N}}{dt} \bigg|_{t\sim t_{\text{min}}} = 17.8 \pm 1.5 \text{ nbGeV}^{-2} \text{ at } s_0 = 40.4 \text{ GeV}^2,$$

$$\frac{d\sigma_{\gamma N \rightarrow J/\psi N}}{dt} \bigg|_{t\sim t_{\text{min}}} = 40 \pm 13 \text{ nbGeV}^{-2} \text{ at } s_0 = 188.9 \text{ GeV}^2,$$  \hspace{1cm} (13)

and

$$\frac{d\sigma_{\gamma N \rightarrow \psi' N}}{dt} \bigg|_{t\sim t_{\text{min}}} = 0.15 \cdot \frac{d\sigma_{\gamma N \rightarrow J/\psi N}}{dt} \bigg|_{t\sim t_{\text{min}}},$$  \hspace{1cm} (14)

and practically doesn’t depend (or depends only weakly) on the energy. The two gluon form factor as extracted from analysis of the $J/\psi$ photoproduction data in [31] can be used to evaluate the nucleon form factor at $t = t_{\text{min}}$:

$$F_{2g} = \left(1 - \frac{t_{\text{min}}}{m_{2g}^2}\right)^{-2}.$$  \hspace{1cm} (15)

The quantity $m_{2g}^2$ is defined by

$$\frac{1}{m_{2g}^2} = \frac{1}{\text{GeV}^2} + \frac{0.06}{\text{GeV}^2} \ln \left( \frac{s}{s_0} \right).$$  \hspace{1cm} (16)

As a result for the photoproduction of the $J/\psi$ we found $\lambda = 0.2$ while the value for the $\psi'$ production is somewhat less $\lambda = 0.15$ but with much larger uncertainties. Hence, for the preliminary estimates one can use the same value of $\lambda$ for both processes.

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

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

The SLAC data [30] shows that at $s_0 = 38.5 \text{ GeV}^2$

$$\sigma_{J/\psi N}(s = s_0) = 3.5 \pm 0.8 \text{ mb}.$$  \hspace{1cm} (18)
We evaluated \( c \approx 1 \) in our previous paper on the absorption of \( \psi \) produced in AA collisions \[32\] with

\[
\sigma(\text{hard}) = 2\pi \cdot \int_{0.1 \text{fm}}^{0.2 \text{fm}} |\phi(b, z)|^2 \cdot \sigma(b) db \, dz .
\]

Here \( \phi(b, z) \) is the wave function of the \( \psi \), \( \sigma(b) \) the perturbative dipole cross section from \[4\]. The limits of the integration are for the \( b \) integration, the integration over the longitudinal direction \( z \) is from \(-\infty\) to \(+\infty\).

When the upper limit of the integral is increased to 0.35 fm then \( c = 0.915 \), i.e. \( \sigma(\text{hard}) = (1 - c) \cdot \sigma_{J/\psi N}(s = s_0) = 0.3 \) mb. This is an uncertainty of the model since it is not clear up to which value of \( b \) PQCD is applicable. However, in the following \( c = 0.915 \) is used. That is

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

The existence of a hard part of the \( J/\psi N \) cross section is consistent with the GVDM, because the photoproduction amplitude has a stronger energy dependence than the Pomeron exchange, i.e. soft scattering amplitudes. size meson is not surprising, since pQCD amplitudes for colorless dipoles have an energy dependence similar to the photoproduction amplitude due to the energy dependence of the gluon density distribution. Therefore the energy dependence of the dipole nucleon cross section should gradually increase with decreasing size of the dipole (the meson), otherwise there would be a jump in the energy dependence from soft to hard processes. The energy dependence of the total cross section of the charmonium-nucleon interaction as described by eq. \[20\] differs from that in \[7\] who assumed a dominance of pQCD and therefore a significantly faster increase of this cross section with energy.

Now one can find the imaginary part of the amplitude from the optical theorem

\[
\Im f_{J/\psi N \rightarrow J/\psi N} = s \sigma_{J/\psi N} \text{ and the real part using the Gribov-Migdal relation}
\]

\[
\Re f_{J/\psi N \rightarrow J/\psi N} = \frac{s \pi}{2} \frac{\partial}{\partial \ln s} \frac{\Im f_{J/\psi N \rightarrow J/\psi N}}{s} .
\]

Since the amplitudes of the photoproduction and the \( J/\psi N \) diagonal interaction are fixed we find all other forward amplitudes from the GVDM equations \[3\]. As a result we have determined all parameters of the model. In particular, we found the value \( \sigma_{\psi'N} \approx 8 \text{ mb} \). 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 results of our calculations. The ranges of the elementary \( J/\psi N \) and \( \psi'N \) cross sections which we have got within this procedure are shown in fig. \[1\].

### 3 Results and discussion

First of all let us discuss one of the key approximations we have used in our calculations. We build the GVDM restricting the basis by accounting for only two \( \psi \) meson states - the ground \( 1S \) state \( (J/\psi) \) and the lowest excited \( 2S \) state \( (\psi') \). Since the coherent production of heavy charmed states off nuclei at low energies is suppressed by the target form factor
Figure 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.
it seems to be quite reasonable. However the presence of two nearly degenerate states $\psi'$ ($M_{\psi'} = 3.686$ GeV) and $\psi''$ ($M_{\psi''} = 3.77$ GeV) requires a separate treatment. The following discussion heavily uses the fact that the properties of the $\psi''$ are well described (actually has been predicted) on the basis of the charmonium model by Eichten and collaborators [33, 34]. Within this approach they have found that the $\psi''$ is the $3^3D_1$ state with a small admixture of the $S$ wave and correspondingly $\psi'$ has a small admixture of the $D$ wave. Namely

$$
|\psi'\rangle = \cos \theta \langle 2S \rangle + \sin \theta \langle 1D \rangle ,
$$

$$
|\psi''\rangle = \cos \theta \langle 1D \rangle - \sin \theta \langle 2S \rangle .
$$

(22)

Since only the S-wave contributes to the decay of $\psi$ states into $e^+e^-$ (at least in the nonrelativistic charmonium models) the value of $\theta$ can be determined from the data on the $e^+e^-$ decay widths $\Gamma(\psi' \to e^+e^-) = 2.14$ KeV and the $\Gamma(\psi'' \to e^+e^-) = 0.26$ KeV as

$$
\tan^2 \theta = \frac{\Gamma(\psi'' \to e\bar{e})}{\Gamma(\psi' \to e\bar{e})} \approx 0.1 \Rightarrow \theta = 19^o \pm 2^o .
$$

(23)

Due to the small difference of masses between the $\psi'$ and $\psi''$ mesons the produced $c\bar{c}$-state corresponding to the S-wave does not loose coherence while going through the media at any conceivable energies\(^1\). Also the soft interactions cannot transform the S-state to D-state with any significant probability. In the soft QCD processes data show that the cross sections of exclusive nondiagonal transitions are negligible for the forward angle scattering. The same conclusion is valid in the PQCD model for the charm dipole-nucleon interactions. Hence instead of writing a two-state matrix with $J/\psi$ and $\psi'$ states it would be more appropriate to use the $1S - 2S$ basis. The only changes we would encounter would be the necessity of a change of $f_V$ since the amplitude of the $2S$ state production is larger by a factor of $1/\cos \theta$ than the amplitude of the $\psi'$ production. This yields a $\sim 10\%$ effect which is within the uncertainties of the model. In principle, one should account for the other charmonium states and such extension of the basis could lead to some renormalization of the elementary amplitude but should not influence strongly coherent processes off nuclei because contributions of the higher mass states are suppressed by the nuclear form factor.

Within the model described in the previous section we calculated the forward cross sections of the coherent photoproduction of $J/\psi$ and $\psi'$ off lead. The energy dependence of these cross sections is compared (Figs.2 and 3) to that obtained in the Impulse Approximation where all rescatterings of the produced vector mesons are neglected and the cross section is given by the simple formula

$$
\frac{d\sigma_{\gamma A \to V A}(\omega_\gamma)}{dt} = \int e^{i\vec{q} \cdot \vec{b}} \int d\vec{z} e^{iz\cdot q^V} \rho(\vec{b}, \vec{z}) \left| \int e^{i\vec{q} \cdot \vec{b}} \int d\vec{z} e^{iz\cdot q^V} \rho(\vec{b}, \vec{z}) \right|^2 .
$$

(24)

\(^1\)Interesting enough is that the mixing model allows us to predict the ratio of the $\psi'$ and $\psi''$ production cross section in hard processes. It is

$$
\frac{\sigma(\psi'')}{\sigma(\psi')} = \tan^2(\theta) \approx 0.1 .
$$

This ratio should be a universal number for a hard processes, almost independent on the process, hence, can be used for the cross check whether charm production in the pA and in AA collisions is dominated by hard processes.
Figure 2: The energy dependence of the forward coherent $Pb(\gamma, J/\psi)Pb$ cross section calculated in the Generalized Glauber Model compared to the cross section in the Impulse Approximation (dashed line). The filled area depicts the uncertainty due to the uncertainty of the elementary cross sections shown in fig.
Figure 3: The energy dependence of the forward coherent $Pb(\gamma, \psi')Pb$ cross section calculated in the Generalized Glauber Model compared to the cross section in the Impulse Approximation (dashed line). The filled area depicts the uncertainty due to the uncertainty of the elementary cross sections shown in fig.
Figure 4: The energy dependence of the ratio of the forward coherent charmonium photo-production cross sections calculated in the Generalized Glauber Model (light-blue, solid lines) compared to the ratio of cross sections in the Impulse Approximation (black dotted line) and in the GGM with diagonal amplitudes $f_{V,N \rightarrow V,N} = 0$ (yellow, dashed lines). The filled areas depict the uncertainty due to the uncertainty of the $J/\psi N$ elementary cross section shown in fig. [1].
Remember that $\sqrt{-t_{\min}} = q^V = m_{\Psi'}^2/2\omega$, hence, decrease of the photon energy corresponds to increasing of the longitudinal momentum transfer in the coherent photoproduction off nuclei. Note that we neglected the transverse momentum transfer dependence of the elementary amplitudes since the dominating effects are determined by the dependence of the nuclear form factor on $t_\perp$ (influence of the $t$-dependence of the elementary amplitudes will be considered in the forthcoming papers).

The cross section of the $J/\psi$ photoproduction in the GGM is close to that calculated in the Impulse Approximation - the shapes of curves are very similar and the values of the cross sections are slightly reduced at energies below 40 GeV. A more striking difference is found comparing the two approaches for the yield of $\psi'$ where both the shape and the value of the cross section are essentially modified. The distinctive feature of the coherent charmonium photoproduction cross sections is their oscillating behavior with the photon energy. The major source for such a behavior is due to the oscillating longitudinal nuclear form factor at the relatively large value of $t_{\min}$ in the photoproduction vertex in the kinematically region we are interested in. One can easily check that the positions of the first minimum satisfy the relation $qR_A \approx 3.8$ well known from diffraction. We want emphasize that the use of a realistic nuclear density in our calculations ensures a reasonable description of the nuclear form factor. No such oscillations exist in the case of frequently used Gaussian form for the nuclear form factors. From the comparison of calculations in the GGM and in the IA it is seen that the rescattering don’t change noticeably the cross section of the coherent $J/\psi$ photoproduction off nuclei except for the filling of the minima. All effects of the $J/\psi N$ rescattering are obviously small compared to the direct photoproduction and the longitudinal form factor is weakly distorted by the final state $J/\psi$-nucleus interaction. Hence, analyzing the coherent $J/\psi$ photoproduction off the spherical nuclei one can use the nuclear form factor determined from the study of the high energy elastic electron-nucleus scattering. The picture is qualitatively different for the coherent $\psi'$ photoproduction off nuclei. Due to the higher threshold $(E_{\psi'} - E_{J/\psi}) \approx 3$ GeV the direct $\psi'$ production off nuclei (impulse approximation) is suppressed compared to that of $J/\psi$ by the nuclear form factor at the same photon energy.

Since $q^\Psi' \approx \frac{m_{\psi'}^2}{m_{J/\psi}}q_{J/\psi}$ the minima of the impulse approximation distribution are shifted. The contribution of the nondiagonal term $\gamma \rightarrow J/\psi \rightarrow \psi'$ essentially increases the yield of the $\psi'$ and shifts the minima in the spectrum to lower photon energies. This results in significant effects, especially, if one measure the relative $\psi' - to - J/\psi$ forward yield shown in fig. 2.

To quantify the role of diagonal and nondiagonal rescatterings we presented this ratio calculated in the Generalized Glauber model (solid line) and in the impulse approximation (dotted line). Besides, to show separately the influence of the diagonal and the nondiagonal transitions the master matrix in eq. (9) governing the $z$ dependence of the eikonal phase for the charmonium states in the nuclear medium is similar to that for the coherent $K_L - K_S$ regeneration in the nuclear medium. The similarity is enhanced by the fact that the $J/\psi$ state dominates in the initial condition for these equations because of the dominance of spatially small $c\bar{c}$ configurations in the photoproduction processes and significantly smaller size of $J/\psi$ state. Thus the color screening phenomenon reveal itself in the well familiar quantum mechanical phenomenon - oscillations between two states in the medium. The distinctive feature of the charmonium state production is the large (on nuclear scale) difference of the longitudinal momentum transfer for the production of $J/\psi$ and $\psi'$ which leads to an oscillating energy dependence of the $\psi'/J/\psi$ ratio.
Figure 5: The energy dependence of the coherent charmonium photoproduction cross sections calculated in the Generalized Glauber Model compared to the cross sections in the Impulse Approximation (dashed line) and in GGM with $f_{V_{N} \rightarrow V_{N}} = 0$ (yellow). The filled areas depict the uncertainty due to the uncertainty of the elementary cross sections shown in fig. [1].
Figure 6: The energy dependence of the ratio of the coherent $Pb(\gamma, J/\psi)Pb$ cross section calculated in the Generalized Glauber Model to the cross section in the Impulse Approximation. The red filled area depicts uncertainty due to the variation of the $J/\psi N$ experimental cross section.
Figure 7: The energy dependence of the ratio of the coherent $Pb(\gamma, \psi')Pb$ cross section calculated in the Generalized Glauber Model to the cross section in the Impulse Approximation. The filled light blue area shows the uncertainty of the results due to the uncertainty in the $J/\psi N$ cross section.
nal transitions we show calculations in the GGM but with accounting for the nondiagonal transitions only (dashed line, $f_{VN 	o VN} = 0$). The position of the minima in the impulse approximation corresponds to the minima in the spectrum of the $\psi'$ forward yield, position of maxima corresponds to minima in the $J/\psi$ yield. Easy to estimate that the energy shift is $\delta \omega \approx R A \gamma (m_{\psi'}^2 - m_{J/\psi}^2)$. The shape is distorted by the energy dependence of the elementary photoproduction amplitudes. The account of the nondiagonal transitions considerably shifts the position of the minima and increases the relative yield. The diagonal rescatterings produce some additional shift and essential modifications of the shape: at some energies one can find suppression, at others -enhancement. We emphasize that the measurement of such a ratio removes the nuclear model dependence since the same longitudinal nuclear form factor enters the numerator and the denominator. Hence, the ratio of cross sections in the impulse approximation can be used as some kind of a model independent reference curve since it can be easily calculated for many nuclei using the nuclear form factors measured in a high energy elastic electron scattering experiments and the ratio of the measured elementary photoproduction cross sections. Besides, we would like to note that one can also remove the dependence on the elementary photoproduction cross sections measuring the double ratio of the relative $\psi'$-to-$J/\psi$ yield in the coherent photoproduction off two nuclei: a heavy nucleus and a light one.

In the case of a setup lacking a sufficient resolution in transverse momentum one can study the energy dependence of the $\psi'$ and $J/\psi$ yields integrated over the transverse momentum. While such integration smears the oscillation pattern significant oscillations still remain as can seen in fig. 5 where we compare the total cross sections calculated in GGM to that in the Impulse Approximation. To emphasize the significant influence of nondiagonal transitions we also show results of calculation in the GGM without diagonal rescattering.

Finally, we want briefly comment the opportunity to extract the genuine $J/\psi N$ and $\psi'N$ cross section from such a measurement. The conventional procedure is based on the estimate of the suppression of the particle yield comparing the data to the calculations within the Impulse Approximation and then describing them using a reasonable theoretical model for the process with the elementary cross sections used as fitting parameters. In the case of the charmonium photoproduction such a procedure seems to be essentially complicated. While the sensitivity of the nuclear photoproduction cross sections to the values of the elementary amplitudes is, in principle, revealed in our calculations the interplay of diagonal and nondiagonal rescattering amplitudes and their interference with the amplitude of the direct production result in rather formidable problem. In fig. 4 we show the calculated ratio of the $J/\psi$ photoproduction cross section in GGM to that in the IA. Despite the energy dependence of the $J/\psi N$ cross section is rather weak at the photon energies considered here we find the energy dependent suppression of the $J/\psi$ yield stronger $\approx (15 \div 20)$% at $\omega \leq 40$ GeV and more or less small $\approx (6 \div 7)$% at $\omega \geq 40$ GeV in the photoproduction off nucleus. Moreover, the increase of the elementary $J/\psi N$ cross section by a factor 1.5 that is allowed by the experimental uncertainties (see fig. 4) changes the suppression by only $\approx 5$% at low energies and is practically negligible at higher energies. Since $\sigma_{J/\psi N}$ is small one can easily estimate that due to the $J/\psi N$ interaction the suppression on the level of $\approx (30 \div 40)$% should be expected in the whole range of energy. Hence, even at low energies where the $\gamma N \to \psi'N$ amplitude is small we find a noticeable compensation of the suppression by contribution of the two-step $\gamma A \to A + \psi' \to A + J/\psi$ production. With increase of the
photon energies in the considered region this compensation effect becomes stronger. This indicates moving to the regime of Color Transparency for a $J/\psi$ passing through the nuclear medium. The analysis of the $\psi'$ photoproduction shows (fig. 6) a significant influence of the two-step photoproduction $\gamma + A \rightarrow J/\psi + A \rightarrow \psi' + A$ and the interference of this amplitude with the direct production and with the amplitude comprising diagonal rescattering in a wide range of energies. Hence, we can conclude that such a complicated interplay of rescatterings will preclude uniqueness of determining of the genuine $J/\psi N$ and $\psi' N$ cross sections from measurements with one heavy nuclear target. Evidently to succeed in this aim the elementary photoproduction and nondiagonal amplitudes in a wide range of the photon energies should be known with high precision. In our forthcoming papers we suggest a new approach to this experimental problem and plan to analyze whether the study of the A-dependence in the photoproduction of charmonium including the oscillation patterns can be used to resolve the issue of determining the $J/\psi N$ and $\psi' N$ cross sections and the accuracy of the two diffractive state approximation and hence provide further insights to the color dynamics at the low energies.

4 Conclusion

We have calculated the coherent charmonia photoproduction off heavy nuclei at moderate energies within the Generalized Glauber Model which combines the multistep production Glauber approach, the Generalized Vector Dominance Model and color screening phenomena. We found that the interplay of the oscillating behavior of the nuclear form factor and the interference of the rescattering amplitudes lead to significant oscillations in the relative $\psi'$-to-$J/\psi$ yield for forward scattering. We show that accounting for the nondiagonal amplitudes, which model in the hadronic basis the QCD color fluctuations within hadrons, results in the noticeable modification of the coherent cross section of the $\psi'$ photoproduction off nuclei. We found sensitivity of oscillations to the cross sections of $J/\psi N$ and $\psi' N$ interaction as well as to the strength of the nondiagonal transitions. Accounting for the higher mass states may lead to larger cross section of $\psi' N$ interactions $\approx 15$ mb, however, it will not change qualitatively the observed pattern of oscillations which is due to the oscillating behavior of the longitudinal nuclear form factor at large (on the nuclear scale) longitudinal momentum transfer and a large value of nondiagonal transitions expected as a basic feature of QCD.

For the coherent hidden beauty meson production at low energies the same oscillations in the $\Upsilon, \Upsilon'$ yields are expected but the cross sections will be obviously too small.

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**References**

[1] F. E. Low, Phys. Rev. D 12, 163 (1975).
[2] J. F. Gunion and D. E. Soper, Phys. Rev. D 15, 2617 (1977).

[3] H. Heiselberg, G. Baym, B. Blaettel, L. L. Frankfurt and M. Strikman, Phys. Rev. Lett. 67, 2946 (1991).

[4] L. Frankfurt, A. Radyushkin, M. Strikman, Phys. Rev. D 55 (1997) 98

[5] L. Frankfurt and M. Strikman, Prog. Part. Nucl. Phys. 27, 135 (1991).

[6] L. Frankfurt, W. Koepf and M. Strikman, Phys. Rev. D 57 (1998) 512

[7] J. Hufner, B. Kopeliovich, Phys. Lett. B426 (1998) 154

[8] W. Buchmuller (ed.), “Quarkonia,” Amsterdam, Netherlands: North-Holland (1992) 316 p.

[9] D. Kharzeev and H. Satz, In R.C. HWA (ed.): Quark-gluon plasma, vol.2, 395-453 and

[10] S. Brodsky, A. Mueller, Phys. Lett. B206 (1988) 685.

[11] R. Vogt, Phys. Rept. 310 (1999) 197;

[12] A. Donnachie and G. Shaw, in Electromagnetic Interactions of Hadrons, edited by A. Donnachie and G. Shaw, (Plenum, New York, 1978), Vol. 2, pp. 164-194.

[13] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B537 (2002) 51;

[14] H. Abramowicz and A. Caldwell, Rev. Mod. Phys. 71 (1999) 1275

[15] L. Frankfurt, V. Guzey, M. McDermott and M. Strikman, JHEP 0202, 027 (2002)

[16] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B540 (2002) 220;

[17] U. Camerini et al., Phys. Rev. Lett. 35 (1975) 483

[18] B. Kopeliovich, J. Nemchik, N. Nikolaev, B. Zakharov, Phys. Lett. B309, 179 (1993); ibid. B324, 469 (1993).

[19] V. N. Gribov, Sov. J. Nucl. Phys. 9 (1969) 369;

Sov. Phys. JETP 29 (1969) 483;

Sov. Phys. JETP 30 (1970) 709.
[20] S. J. Brodsky, E. Chudakov, P. Hoyer and J. M. Laget, Phys. Lett. B 498, 23 (2001) arXiv:hep-ph/0010343;
Y. P. Ivanov, B. Z. Kopeliovich, A. V. Tarasov and J. Hufner, Phys. Rev. C 66 (2002) 024903 arXiv:hep-ph/0202216.

[21] V. Ghazikhanian et al. SLAC-Proposal E-160, 2000

[22] R. J. Glauber, Boulder Lectures in Theoretical Physics, vol.1, (Interscience Publ. Inc., NY)(1959);
K. Gottfried, Lecture in the Summer CERN Program, 1971;
G. V. Bochmann, Phys. Rev. D6, 1938, (1972).

[23] H. Fraas, B. Read, and D. Schildknecht, Nucl. Phys. B86, 346 (1975).

[24] P. Ditsas and G. Shaw, Nucl. Phys. B 113, 246 (1976).
G. Shaw, Phys. Lett. B 228, 125 (1989).
G. Shaw, Phys. Rev. D 47, 3676 (1993).

[25] D.E. Groom et al. [Particle Data Group], Eur. Phys. J. C15 (2000) 1

[26] M. Beiner, H. Flocard, N. Van Giai, P. Quentin, Nucl. Phys. A238, (1975), 29.

[27] S. L. Belostotsky et al., Proceedings of the conference Modern developments in nuclear physics, Novosibirsk 1987, World Scientific, 1988, p. 191.

[28] L. Lapikas, G. van der Steenhoven, L. Frankfurt, M. Strikman and M. Zhalov, Phys. Rev. C 61, 064325 (2000) arXiv:nucl-ex/9905009;
L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B 503, 73 (2001) arXiv:hep-ph/0011088.

[29] M. C. Abreu et al. [NA38 Collaboration], Phys. Lett. B 449 (1999) 128.

[30] R.L. Anderson et al., Phys. Rev. Lett. 38 (1977) 263

[31] L. Frankfurt and M. Strikman, Phys. Rev. D 66, 031502 (2002) arXiv:hep-ph/0205223.

[32] L. Gerland, L. Frankfurt, M. Strikman, H. Stöcker and W. Greiner, Phys. Rev. Lett. 81 (1998) 762.

[33] E. Eichten, K. Gottfried, T. Kinoshita, J. B. Kogut, K. D. Lane and T. M. Yan, Phys. Rev. Lett. 34 (1975) 369 [Erratum-ibid. 36 (1976) 1276].

[34] J. M. Richard, Z. Phys. C 4 (1980) 211.