Probing coherent charmonium photoproduction off light nuclei at medium energies

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We demonstrate how the elementary amplitudes $\gamma N \rightarrow \Psi N$, the amplitude of the nondiagonal $J/\psi N \leftrightarrow \psi' N$ transition, and the total $J/\psi N$ and $\psi' N$ cross sections can be determined from measurements of the coherent $J/\psi$ and $\psi'$ photoproduction off light nuclei at moderate energies. For this purpose we provide a detailed numerical analysis of the coherent charmonium photoproduction off silicon within the generalized vector dominance model (GVDM) adjusted to account for the physics of charmonium models and color transparency phenomenon.

I. INTRODUCTION

First measurements of quasielastic photoproduction of $J/\psi$ and $\psi'$ mesons off nucleon and nucleus targets at moderate energies were performed in the seventies at SLAC and Cornell [1–3]. The measurement of the $A$-dependence of $J/\psi$ photoproduction [2] was used by the authors to extract the $J/\psi$ - nucleon absorption cross section $\sigma(J/\psi N) = 3.5 \pm 0.8$ mb, using a semi-classical model for $J/\psi$ - nucleus interactions. At the same time the estimates of $\sigma(J/\psi N)$ based on the Vector Dominance Model and the optical theorem yield $\sigma(J/\psi N) = 1.3 \pm 0.3$ mb and $\sigma(\psi' N) \approx 0.7\sigma(J/\psi N)$ [1]. This small value of the $J/\psi N$ cross section comparing to that for $\pi N$ interaction is in variance with the preQCD ideas on universal hadron-hadron interaction. On the contrary, these observations can be considered [4] as evidence for the previously predicted [5,6] genuine QCD effect of the dependence of the cross section on the size of the region occupied by color within a hadron. Besides, QCD predicts that $\sigma_{\psi' N}$ should be significantly larger then $\sigma_{J/\psi N}$ because the radius of the $\psi'$ is two times larger than the radius of the $J/\psi$. Recently first data on the hadroproduction of $J/\psi$ and $\psi'$ in $pA$ collisions confirmed these QCD predictions but large experimental errors and the complicated theoretical analysis preclude an unambiguous extraction of the charmonium-nucleon cross sections from the data. As a result the general situation with the extraction of these cross sections is still unsatisfactory - the determined values of $\sigma_{J/\psi N}$ range from 2 mb to 6 mb and, correspondingly, the range of $\sigma_{\psi' N}$ is from 8 mb to almost 20 mb [7]. On the other hand the precise values of these cross sections are urgently needed for the unambiguous interpretation of the yield of particles with hidden charm produced in the ultrarelativistic heavy ion collisions (for the review and references see e.g. [8]).

Since direct measurements of the charmonium-nucleon cross sections are impossible, the photoproduction of the $J/\psi$ and $\psi'$ off nuclei at coherent moderate energies appears to be one of the most promising tool to measure these quantities. Really, in the moderate energy domain both the coherence length and the formation length are smaller or comparable to the radii of nuclei. So, a photon produces a $cc$ pair which transforms to a charmonium state inside the nucleus with a noticeable probability and this meson can interact with the surrounding nucleons. However, it appears that the standard analysis of the data within the Glauber based Vector Dominance Model (VDM) which provides a more or less reasonable treatment of the light vector meson photoproduction at low and moderate photon energies fails in the case of the charmonium photoproduction. It was understood that according to the charmonium models the very small size of the $cc$ pair which is controlled in the production point by the mass of the $c$-quark leads to the radical change of the predictions based on the VDM [9–11].

The aim of this paper is to suggest a new option for the extraction of charmonium-nucleon amplitudes from measurements of the coherent charmonium photoproduction off light nuclei at moderate photon energies. In a recent paper [12] we demonstrated that large masses of the charmonium states ($m_\Psi$) and the fluctuations of the strength of the interaction of different charmonium states with nucleons inside the nuclear medium expected in QCD lead to significant cross section oscillations in this process. We are interested in the photon energy range $15 \text{ GeV} \leq E_\gamma \leq 40 \text{ GeV}$ relevant for the planned SLAC experiment [13]. In this case the minimal momenta $q_L = \frac{m_\Psi^2}{2E_\gamma}$ transferred to nucleus are $0.35 \text{ GeV} \geq q_L \geq 0.15 \text{ GeV}$ and the significant oscillations due to the oscillating nuclear form factor are spectacularly revealed [12] in the energy dependence of the coherent charmonium photoproduction cross sections. Another source of oscillations predicted by the QCD color screening phenomenon is the significant difference of the amplitudes of $J/\psi N \rightarrow J/\psi N$, $\psi' N \rightarrow \psi' N$, and $J/\psi N \leftrightarrow \psi' N$ which leads to oscillations of the rescattering strengths.
and noticeably modifies the energy dependence of the cross sections. We suggest to explore these oscillations as a new method of determining the elementary photoproduction amplitudes and the amplitudes of $J/\psi$ and $\psi'$ interactions with nucleons.

Experimentally the suggested approach can be realized at SLAC where measuring of the charmonium photoproduction at low energies (15 - 35 GeV) is planned [13].

II. DESCRIPTION OF THE MODEL

The key feature of the charmonium photoproduction is that the $c\bar{c}$ configuration of the photon wave function is spatially small in the production point because its transverse size is controlled by the large mass of the $c$-quark. However, at the photon energies of $15 \div 40$ GeV we are interested in, the charmonium formation length, $l_f \approx \omega[2m_c(m_{\psi'} - m_{J/\psi})]^{-1}$, is still comparable to the internucleon distance and the nucleus radius. Hence, the noticeable probability exists that at these moderate energies a spatially small configuration would transform to hadron states before a collision with a second nucleon. In this case using a hadronic basis which properly takes into account nonperturbative QCD effects seems to be relevant for the calculation of the photoproduction cross section

$$\sigma_{\gamma A \rightarrow \Psi A}(\omega) = \pi \int_{-\infty}^{t_{\min}} dt |F_{\gamma A \rightarrow \Psi A}(t)|^2 .$$

Here $\Psi = J/\psi$ resp. $\psi'$, $-t_{\min} = m_A^4 / M^2$ is the longitudinal momentum transfer in the $\gamma \rightarrow \Psi$ transition. The photoproduction amplitude $F_{\gamma A \rightarrow \Psi A}(t)$ is normalized so that $\sigma_{\gamma A \rightarrow \Psi A}(\omega)$ is in $\mu b$. To calculate this amplitude the multistep production Glauber approach formulae [14] were combined with the GVDM [15] which we adjusted for the charmonium case in order to account the color screening effects. A more detailed description of this Generalized Glauber Model (GGM) (which we successfully tested [16] in the case of the $\rho$-meson coherent photoproduction) is given in ref. [12]. Here we briefly summarize several essential points. Since the coherent production of heavy charmonium states off nuclei at low and moderate energies is suppressed by the target form factor it is legitimate to build the GVD model restricted to two states - $J/\psi$ and $\psi'$.

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

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

The charmonium-nucleon coupling constants $f_{J/\psi}^2 / 4\pi = 10.5 \pm 0.7,$ and $f_{\psi'}^2 / 4\pi = 30.9 \pm 2.6$ are determined from the widths of the vector meson decays $\Psi \rightarrow e^+e^-$. Since in the photoproduction processes $c\bar{c}$ pair is produced within spatially small configuration one can neglect for a moment the direct photoproduction amplitude and obtain from eqs. (2,3) the approximative relations between amplitudes

$$f_{\psi' N \rightarrow \psi' N} \approx - \frac{f_{\psi'}}{f_{J/\psi}} f_{\psi' N \rightarrow J/\psi N} \approx \frac{f_{\psi'}}{f_{J/\psi}} f_{J/\psi N \rightarrow J/\psi N} .$$

Note that a comparatively large absolute value of the nondiagonal amplitude and the negative value of the ratio of nondiagonal and diagonal amplitudes follow from the presence of the color screening in the charmonium photoproduction as dictated by QCD. For a more accurate determination of the elementary $\psi' N \rightarrow \psi' N$ and $J/\psi N \leftrightarrow \psi' N$ amplitudes within GVDM (for the details see [12]) we use as an input in eqs. (2,3) the absolute values of the forward $\gamma N \rightarrow J/\psi N$ cross section, the relation $d\sigma_{\gamma N \rightarrow \psi' N}(t_{\min})/dt = 0.15d\sigma_{\gamma N \rightarrow J/\psi N}(t_{\min})/dt$ and the $J/\psi N$ cross section $\sigma_{J/\psi N} \approx (3.5 \pm 0.8)$ mb found at moderate energies at SLAC [1,2]. To show explicitly how uncertainty in the value of $\sigma_{J/\psi N}$ influences on the photoproduction cross section we used estimates of amplitudes determined within the corridor of the experimental errors. This is shown by the filled area in all results of calculations.

We performed calculations within the Generalized Glauber Model (GGM). Note however, that in the case of coherent photoproduction of charmonium off light nuclei at moderate energies, the parameter $\rho_{\psi' N} R_A$ is small and one can simplify calculations by taking into account only one rescattering of the produced heavy meson. Then only two forward amplitudes provide the dominating contribution and the coherent charmonium photoproduction is described by the sum of the diagrams in fig. 1. The first graph is the direct photoproduction amplitude while the second one accounts for one rescattering of the produced charmonium states within the nuclear medium.
Since $V, V' = J/\psi, \psi'$ the second diagram includes the diagonal as well as nondiagonal rescatterings. We want to emphasize that in the case of nondiagonal transition the effect of charmonium absorption enters in the next to leading order.

### III. RESULTS AND DISCUSSION

Within the Generalized Glauber Model we performed calculations for a wide range of nuclei trying to choose the optimal nuclei for determining the elementary amplitudes from measurements of the coherent photoproduction of the $J/\psi$ and the $\psi'$. The rates are small for the lightest nuclei while for sufficiently heavy nuclei multiple rescattering effects become noticeable. Hence we found that nuclei with $A = 20 \div 40$ are optimal for our purposes. Thus in the following we will present the results for silicon nuclei. The silicon target is also of interest since one could envision an active silicon target which would allow to select the coherent events in a cleaner way.

The energy dependence of the $J/\psi$ cross section is compared (fig. 2) to that obtained within the Impulse Approximation where

$$\frac{d\sigma_{A \rightarrow \Psi_A}(t_{\text{min}})}{dt} = \frac{d\sigma_{N \rightarrow \Psi_N}(t_{\text{min}})}{dt} \cdot |F_{A \rightarrow \Psi_A}(t_{\text{min}})|^2.$$

(5)

The nuclear density $\rho(\vec{b}, z)$ is normalized by the condition $\int d\vec{b} dz \rho(\vec{b}, z) = A$. We calculated $\rho(\vec{b}, z)$ 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 [17] and the shell momentum distributions in the high energy $(p,2p)$ [18] and $(e,e'p)$ [19] reactions.
FIG. 2. Energy dependence of the forward coherent $\gamma + Si \rightarrow J/\psi + Si$ photoproduction cross section calculated in the Generalized Glauber Model compared to the cross sections in the Impulse Approximation (dotted line). The forward elementary $\gamma N \rightarrow J/\psi N$ cross section is shown by the dashed line.

FIG. 3. Energy dependence of the ratio of the forward coherent $\gamma + Si \rightarrow J/\psi + Si$ photoproduction cross section calculated in the Generalized Glauber Model to that in the Impulse Approximation.
The distinctive feature of the coherent charmonium photoproduction cross sections in the kinematics we are interested in is that the dependence of the cross section on the photon energy is governed by the longitudinal nuclear form factor at a relatively large value of $t_{\text{min}}$ which becomes more important with a decrease of the photon energy. We want to emphasize that the use of a realistic nuclear density in our calculations ensures a reasonable description of the nuclear form factor in the relevant momentum transfer range. One can infer from fig. 3 that the cross section of the $J/\psi$ production off the silicon calculated in GGM practically coincides with the Impulse Approximation result. The deviation does not exceed $4 \div 5\%$ and it varies weakly when the rescattering amplitudes are changed within region allowed by the uncertainties of the input values of the $J/\psi N$ cross section as determined at SLAC [2]. This implies that one should have an unprecedented accuracy both in the measurements and in the theoretical analysis in order to extract the $J/\psi N$ elementary cross section from such measurements. However these measurements can be used to determine precisely the elementary forward photoproduction cross section. Really, the contribution of the diagonal $J/\psi N$ rescattering can be neglected. Then the comparison of the data with the cross section calculated in the Impulse Approximation (eq. 5) with the nuclear form factor which is well determined from the high energy electron-nucleus elastic scattering immediately provides us with the forward elementary $\gamma N \rightarrow J/\psi N$ cross section. As it is seen from fig. 2, the low $t$ cross section of $J/\psi$ production off the silicon in spite of the strong suppression by the nuclear form factor is considerably larger than the $d\sigma_{\gamma N \rightarrow J/\psi N}(t_{\text{min}})/dt$ (dashed line in fig. 2). Hence, one may significantly improve the accuracy of the determination of $d\sigma_{\gamma N \rightarrow J/\psi N}(t_{\text{min}})/dt$.

FIG. 4. The energy dependence of the forward coherent $\gamma + Si \rightarrow \psi' + Si$ photoproduction cross section calculated in the Generalized Glauber Model (solid lines, filled blue) compared to the cross section in the Impulse Approximation (dotted line) and to the cross section calculated in GGM without accounting for the diagonal $\psi N \rightarrow \psi N$ rescattering (dashed lines, yellow).
FIG. 5. The energy dependence of the ratio of forward coherent $\psi'$-to-$J/\psi$ photoproduction cross sections calculated in the Generalized Glauber Model compared to the ratio in the Impulse Approximation (dotted line), to the ratio of cross sections calculated in GGM without accounting for the diagonal rescatterings (dashed line, yellow filled) and to the ratio without accounting for the direct $\psi'$ photoproduction (dashed lines, violet filled).

The situation is qualitatively different for the coherent $\psi'$ photoproduction off silicon (fig. 4). The cross section calculated within GGM significantly exceeds the Impulse Approximation cross section. This is because the suppression due to the diagonal rescatterings is negligible as compared to the enhancement due to the contribution of the two-step nondiagonal $\gamma A \rightarrow J/\psi A \rightarrow \psi'A$ process. The range of energy in the vicinity of the form factor minimum for the forward $\psi'$ production is especially interesting. In this case the main contribution to the cross section (fig. 5) originates from the nondiagonal rescattering. In particular, at $\omega \approx 0.13 R_A m_\psi^2$, one can extract from the data the nondiagonal elementary $J/\psi N \rightarrow \psi'N$ amplitude by measuring the forward relative $\psi'$-to-$J/\psi$ yield. In such a ratio all other inputs, namely, the nuclear density and the elementary $\gamma N \rightarrow J/\psi N$ amplitude are already fixed. Moreover, since they enter both in the numerator and denominator, the major uncertainties are canceled out.

In the discussed energy range the soft $\Psi N$ rescattering processes within the nuclear medium are characterized by a rather weak energy dependence, like $s^{0.08}$, which can be neglected to a very good accuracy in the ratio of the forward $\psi'$ and $J/\psi$ photoproduction cross sections. Hence the energy dependence of this ratio (fig. 5) should originate primarily due to the contribution of the direct $\psi'$ production. Thus one would be able to determine the $\gamma N \rightarrow \psi'N$ amplitude by measuring the relative $\psi'$-to-$J/\psi$ yield.

We want to emphasize that the suggested procedure for extracting the nondiagonal amplitude and amplitudes of direct $J/\psi$ and $\psi'$ photoproduction from the nuclear measurements is practically model independent.

The task of determining the diagonal $J/\psi N \rightarrow J/\psi N$ and $\psi' N \rightarrow \psi' N$ amplitudes which are relevant for the suppression of the charmonium yield in heavy ion collisions is much more complicated.

If one would naively use the VDM, neglecting nondiagonal transitions and using values of $\sigma_{tot}(J/\psi N)$ based on the SLAC data [2] one would predict a rather significant suppression of the $J/\psi$ yield: $\approx 10\% \div 15\%$ for light nuclei, and $\approx 30\% \div 40\%$ for heavy nuclei. However, we find [12] a strong compensation of the suppression due to the contribution of the nondiagonal transitions. As a result we find that overall the suppression does not exceed $5\% \div 10\%$ for all nuclei along the periodical table. Hence, an extraction of the diagonal amplitudes from the measured cross sections would require a comparison of high precision data with very accurate theoretical calculations including the nondiagonal transitions. Thus one may try another strategy. If the elementary $\gamma N \rightarrow J/\psi N$, and $\gamma N \rightarrow \psi' N$ photoproduction amplitudes, as well as the nondiagonal amplitude $J/\psi N \leftrightarrow \psi' N$ would be reliably determined from moderate energy data it would be possible to determine the imaginary parts of the forward diagonal amplitudes from the GVDM equations (2,3) reversing the procedure which we used in section 2, namely
\[ \Im f_{J/\psi N \rightarrow J/\psi N} = \frac{f_{J/\psi}}{e} \Im f_{\gamma N \rightarrow J/\psi N} - \frac{f_{J/\psi}}{e} \Im f'_{\psi N \rightarrow J/\psi N} \]  \hspace{1cm} (6)

\[ \Im f'_{\psi' N \rightarrow \psi' N} = \frac{f_{\psi'}}{e} \Im f_{\gamma N \rightarrow \psi' N} - \frac{f_{\psi'}}{e} \Im f_{J/\psi N \rightarrow \psi' N} . \]  \hspace{1cm} (7)

The main limitation of the suggested procedure is the restriction of the hadronic basis to the two lowest 1S, 2S charmonium states with the photon quantum numbers: \( J/\psi, \psi' \). This question was discussed in [12]. The disregard by the closest higher charmonium state \( \psi(3770) \) can change the estimate of the \( J/\psi N \) amplitude by \( \approx 10\% \). 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). Besides, the asymptotical freedom in QCD dictates decreasing 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 by a large factor with increasing mass. An additional suppression arises due to the weakening of the soft exclusive nondiagonal \( V N \leftrightarrow V'N \) amplitudes between states with the 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

\[ \Re f_{\psi N \rightarrow \psi N} = \frac{s\pi}{2} \frac{\partial}{\partial \ln s} \Im f_{\psi N \rightarrow \psi N} \]  \hspace{1cm} (8)

Using the suggested procedure one will be able to determine all elementary amplitudes with a reasonable precision by measuring the photoproduction of \( J/\psi \) and \( \psi' \) off the 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. CONCLUSIONS**

We used the Generalized Glauber Model which combines the multistep Glauber approach and the Generalized Vector Dominance Model to calculate the coherent charmonia photoproduction off light nuclei at medium energies corresponding to the kinematics of the planned E160 SLAC experiment. We demonstrate that the nondiagonal amplitudes which follow from the significant QCD color fluctuations within hadrons give a significant contribution to the coherent cross section of the \( \psi' \) photoproduction off light nuclei in this energy domain via the two step production mechanism, while the production of the \( J/\psi \) is well described by the Impulse Approximation. We show how one can determine the elementary amplitudes of the charmonia photoproduction as well as the genuine \( J/\psi N, \psi' N \) cross sections and the nondiagonal amplitude from measurements in this domain.

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