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QUANTUM EFFECTS AND COLOUR TRANSPARENCY IN CHARMONIUM PHOTOPRODUCTION ON NUCLEI

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1. Introduction. Space-time pattern of charmonium photoproduction

A salient prediction of QCD is a close connection between an interaction cross section of a hadron and its transverse dimension: the more compact is the hadron, the weaker it interacts [1-3]. As a result a nucleus should be transparent for a high-energy hadron participating in a process where only compact fluctuations of the hadron can survive [4,5]. It means that nuclear transparency defined as

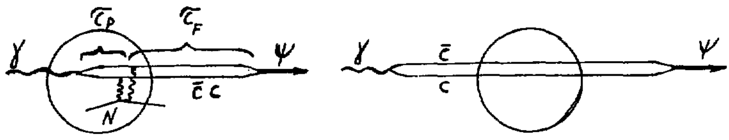
$$Tr = \frac{\sigma_A}{A\sigma_N} , \qquad (1)$$

where σ_A and σ_N are the cross sections of the process on a nuclear and nucleon targets, should be close to unity. Indeed, analyses [6,7] of experimental data from Serpukhov on quasifree charge-exchange scattering $\pi^- p \Rightarrow \pi^0 n$ on bound protons at 40 GeV demonstrates a steep easing of the pion attenuation in a nucleus depending on momentum transfer. It is a clear signal of the colour transparency. On the contrary, measurements of quasielastic pp scattering at 90° in c. m. frame, performed at BNL [8] at energies up to 13 GeV, provided an unexpected fall of the nuclear transparency. Any of existing explanations [9,10] considers a considerable admixture of non point-like hadron configurations. This uncertainty obscures the situation and makes one to look around for another hard processes, where a more definite information about the hadron wave function at the moment of interaction is available. The diffractive photoproduction of charmonium, considered below, is one of the examples.

The influence of the color transparency on the J/Ψ photoproduction on nuclei was considered on a qualitative level in Ref.11. The authors divided conventionally the process of J/Ψ production to two stages, shown in fig.1. The first one is the creation of a compact $\bar{c}c$-pair, localized in a small volume with dimension of about $1/m_c$. Due to the uncertainty principle this stage takes in the laboratory frame a time

$$\tau_p \approx \frac{E}{(2m_c)^2} \approx 0.02 \left(\frac{E}{1\ \mathrm{GeV}}\right) \mathrm{Fm} . \qquad (2)$$

As the matter of fact, this is a time of life of the hadronic fluctuation with $m \approx 2m_c$ in vacuum. According to this estimate the creation of the $\bar{c}c$-pair at energy below 100-150 GeV, can be attributed to the interaction with a single nucleon in the nucleus.



a b

Fig.1. *Space-time pattern of diffractive photoproduction of charmonium in two energy regions: i) the time of $\bar{c}c$ creation, τ_p, is much shorter than internucleon distance (a); ii) the time τ_p considerably exceeds the nuclear radius (b).*

The second stage is the formation of the charmonium wave function. It lasts in the laboratory frame for a period τ_F, related to the reversed distance between low energy levels of the $\bar{c}c$-system, multiplied by the Lorenz-factor.

$$\tau_F \approx \frac{2}{m_{\Psi'} - m_{\Psi}} \left(\frac{E}{2m_c}\right) \approx 0.2 \left(\frac{E}{1\ \mathrm{GeV}}\right) \mathrm{Fm}\,. \qquad (3)$$

This estimate demonstrates that starting from energies of a few tens of GeV the formation zone of the charmonium exceeds nucleus radii. In this case one can expect that transparency should exceed the prediction of the Glauber model due to a weak attenuation of the compact $\bar{c}c$-system in nuclear medium [11]. The Glauber model is valid only at low energies, when τ_F is much shorter than the nuclear radius.

Numerical estimation of the nuclear transparency in the J/Ψ photoproduction was first performed in Ref.12 under assumption that $\bar{c}c$-pair propagate along fixed trajectories starting from point-like configuration. It was assumed that the absorption cross section of the $\bar{c}c$-system increased proportionally a distance covered by the quarks in the laboratory frame. The formation time τ_F was twice as small as ours. The authors of [12] found that the Glauber approach is approximately valid at SLAC energies. However their predictions overestimate the high-energy data [13].

It worthwhile noting that starting from the same arguments the authors of [11] came to the opposite conclusion, they argued that the Glauber approximation should be crudely violated even at energies of SLAC. From our viewpoint a source of the disagreement is the too large value of formation time used in [11], four times higher than ours, (3).

Anyway it is obvious that an approach based only on qualitative arguments and semiclassical estimations can not produce any rigorous quantitative results. It is argued in present paper that an inner dynamics of $\bar{c}c$-system including quantum effects are of great importance. We approximate the wave function of charmonium with the nonrelativistic harmonic oscillator, and find an exact solution for the evolution operator of $\bar{c}c$-system, propagating through a nuclear medium of varying density. Analogous approach was used by the authors earlier [7] for analysis of BNL data [8] on nuclear transparency in quasielastic pp data. Of course the application of the oscillator model in the latter case was rather questionable. As for the $\bar{c}c$-system it is much more justified.

From the point of view of the double-step approach [11] to the process of $\bar{c}c$ photoproduction, shown in fig.1, one can single out two energy-regions, where the treatment is most simplified. The first one corresponds to the case of $\tau_p \ll R_A$, shown in fig.1a. Nuclear transparency can be written in the following form,

$$Tr = \frac{\int d^3\mathbf{r}\ \rho_A(\mathbf{r})\,|\langle\Psi_f|\hat{U}|\Psi_{in}\rangle|^2}{A|\langle\Psi_f|\Psi_{in}\rangle|^2}\ . \qquad (4)$$

Here $\rho_A(r)$ is a nuclear density function; Ψ_{in} is a wave function of the $\bar{c}c$-system originated from the process $\gamma N \Rightarrow \bar{c}cN$ (fig.1a); Ψ_f is a wave function of the produced charmonium, J/Ψ, Ψ' etc.; $\hat{U}$ is the evolution operator of the $\bar{c}c$-system in nuclear medium. We neglect the integration over the momentum transfer in the reaction $\gamma N \Rightarrow \bar{c}cN$, because the transferred momentum can not affect essentially the wave function Ψ_{in} of the compact $\bar{c}c$-system. For the same reason, i.e. due to the smallness of the radius of the $\bar{c}c$-system and its interaction cross section, we ignore in (4) any incoherent final state interactions.

At much higher energies, when $\tau_p \gg R_A$, the pattern of charmonium photoproduction changes drastically. Now the photon converts into the $\bar{c}c$-pair long before the nucleus, as it is shown in fig.1b. The condition $\tau_p \gg R_A$, guaranties simultaneously a smallness of a variation of the transverse size of the $\bar{c}c$-system during propagation through the nucleus. So the influence of the nuclear medium is reduced to a simple attenuation factor, and the nuclear transparency takes a form,

$$\mathrm{Tr} = \frac{\int d^2\mathbf{b}T(\mathbf{b})|\langle\Psi_f|\sigma(\rho)\exp[-\sigma(\rho)T(\mathbf{b})/2]|\Psi_{in}\rangle|^2}{A|\langle\Psi_f|\sigma(\rho)\Psi_{in}\rangle|^2} . \qquad (5)$$

Here $\mathbf{b}$ is an impact parameters of the $\bar{c}c$-pair center of mass; $T(\mathbf{b})=\int_{-\infty}^{\infty}dz\ \rho_A(\mathbf{b},z)$ is the nucleus profile function; $\sigma(\rho)$ is the interaction cross section of the $\bar{c}c$-pair, depending on their relative impact parameter ρ. The integration over ρ is assumed in (5). In analogy to formula (4) we neglect the multiple incoherent interactions of the $\bar{c}c$-pair, as well as the integration over transverse momentum.

It worthwhile emphasizing that the colour transparency phenomenon is not reduced to a simple filtering of point-like $\bar{c}c$-pairs. The nuclear absorption distorts the form of the $\bar{c}c$ wave function. From the phenomenological point of view, this phenomenon is equivalent to the effects of the Gribov's inelastic corrections [14]. The latter are known to bring about an antishadowing [15,16] in some cases, i.e. an increase of the nuclear transparency in comparison with expectations of the Glauber approximation. It is shown below that just this phenomenon takes place for the Ψ' photoproduction on nuclei: in spite of the attenuation in nuclear matter, the yield of Ψ' per nucleon is predicted be higher than on a free nucleon target. So the nuclear transparency, formally defined in (1), is above one in this case.

2. Evolution of $\bar{c}c$-system passing a *nucleus*

Let us go to the c.m. of $\bar{c}c$-pair where a nonrelativistic quantum-mechanical description is appropriate for lowest states. If one represent the evolution operator in the form of functional integral, the influence of nuclear medium will result in a supplementary attenuation factor, $\exp[-1/2\int dl\sigma(\rho)\rho_A(\mathbf{r})]$ for each virtual trajectory, where $\sigma(\rho)$ is the total cross section of $c\bar{c}$ pair interaction with a nucleon, depending on the transverse interquark distance ρ. The integral is taken along the trajectory in the laboratory frame. So the evolution operator can be represented in the form,

$$U = \int D^3\vec{r}\ \exp[i\int dt\ L_{eff}(\vec{r},\dot{\vec{r}},t)] \qquad (6)$$

$$L_{eff}(\vec{\tau},\dot{\vec{\tau}},t) = L(\vec{\tau},\dot{\vec{\tau}}) + \frac{iv\gamma}{2}\,\sigma(\tau_T)\rho_A[\vec{r}(t)]\,. \qquad (7)$$

Here $\vec{\tau}$ is an interquark radius-vector; γ and v are the Lorenz-factor and the velocity of the $\bar{c}c$-pair in the laboratory frame; $L(\vec{\tau},\dot{\vec{\tau}})$ is the vacuum Lagrangian of the $\bar{c}c$-system. We approximate the latter with the harmonic oscillator model:

$$L(\vec{\tau},\dot{\vec{\tau}}) = \frac{\mu\dot{\tau}^2}{2} - \frac{\mu\omega^2\tau^2}{2}\,, \qquad (8)$$

where $\mu=m_c/2$, $m_c=1.5$ GeV. The oscillatory frequency, $\omega=(M_{\psi'}-M_\psi)/2$, is adjusted to the low states of charmonium.

The wide spread approach to the problem of total cross section of hadron interactions is the double-gluon approximation in QCD [1-3]. A $q\bar{q}$-pair with relative impact parameter ρ interacts with a nucleon with the cross section,

$$\sigma(\rho) = \frac{16\alpha_s^2}{3}\int d^2\vec{k}\,\frac{[1-\exp(i\vec{k}\vec{\rho})][1-F(\vec{k})]}{(k^2+m_g^2)^2}\,. \qquad (9)$$

The effective gluon mass, m_g, is introduced to account for the confinement. We fix it at pion mass. The double-quark formfactor $F(k)=\langle N|\exp[i\vec{k}(\vec{r}_1-\vec{r}_2)|N\rangle$ is averaged over the nucleon wave function.

We take into account also the evolution of the QCD coupling, $\alpha_s(q^2)$, which is essential due to smallness of the charmonium radius. According to the usual prescription [17], one should choose a maximal virtuality q^2 of lines on a Feynman diagram entering the vertex. So we put the product $\alpha_s(k^2)\alpha_s[max(k^2, 1/\rho^2)]$ in place of α_s^2 in (9), where $1/\rho^2$ characterizes the virtuality of the c-quark line. We use the one-loop approximation for k^2 behaviour of α_s. However at small values of k^2 the perturbative QCD fails, then we fix $\alpha_s(k^2)$ at a constant value. These two regimes join at some border value of $k=k_o$:

$$\alpha_s(k) = \begin{cases} \dfrac{2\pi}{9\ln(k_o/\Lambda_{QCD})} & \text{if } k<k_o \\[2ex] \dfrac{2\pi}{9\ln(k\ /\Lambda_{QCD})} & \text{if } k>k_o\,. \end{cases}$$

Normalizing $\langle\sigma(\rho)\rangle_\pi=\sigma_{tot}^{\pi N}\approx 24$ mb, we fix $k_o=0.47$ GeV at $\Lambda_{QCD}=0.2$ GeV. The computed in this way $\sigma(\rho)$ well reproduces the EMC data on

q^2-evolution of the nucleon structure function at small x [18].

At small values of $\rho^2 \leq \langle\rho^2\rangle_{\psi,\psi'}$, the cross section (9) is close to a simple behaviour

$$\sigma(\rho) \approx C\rho^2, \qquad (10)$$

used hereafter for the computing of the nuclear transparency. The factor C is fixed by the relation,

$$C = \frac{\sigma_{tot}(\psi N)}{\langle\rho^2\rangle_{\psi}} \approx \frac{\sigma_{tot}(\psi' N)}{\langle\rho^2\rangle_{\psi'}} \quad , \qquad (11)$$

where $\sigma_{tot}(\psi N)$ and $\sigma_{tot}(\psi' N)$ are the average values of $\sigma(\rho)$ weighted with squares of J/ψ and ψ'wave functions respectively. Using the oscillatory model and the double-gluon approximation we find $\sigma_{tot}(\psi N)$=5.75 mb and $\sigma_{tot}(\psi' N)$=12.23 mb. The mean radii are, $\langle\rho^2\rangle_{\psi}=2/m_c\omega$, $\langle\rho^2\rangle_{\psi'}=7\langle\rho^2\rangle_{\psi}/3$. Note that this value of $\langle\rho^2\rangle_{\psi}$ (and consequently $\sigma_{tot}(\psi N)$) obtained in simplified oscillatory model, are close to result of exact calculations with realistic wave function of J/Ψ [19]. At the same time this estimate of $\sigma_{tot}(\psi N)$ is considerably higher than the value extracted from photoproduction data using the vector dominance hypothesis [20]. The latter however is known to fail crudely for J/Ψ [21,22].

We compare behaviour (10) shown in fig.2 by a dashed curve, with the more sophisticated double-gluon approximation. One can see that both curves are very close at small $\rho^2 \leq \langle\rho\rangle^2_{\psi}$.

The absorption term in (7) leads to a modification of the frequency, ω_T, of transverse oscillators [7]:

$$\omega_T = [\omega^2 - i\delta(\vec{r})]^{1/2},$$

where

$$\delta(\vec{r}) = \rho_A(\vec{r})\gamma v\omega\sigma_{tot}(\psi N) \ .$$

To calculate the evolution operator of the $\bar{c}c$ system propagating though a nucleus with varying density function, we changed the latter with a multistep function. Within each slice of constant density one can use the known expression for the evolution operator for a harmonic oscillator with constant frequency [23,7]. For the one-dimension oscillator,

$$\langle y|\hat{U}(t)|x\rangle = \left(\frac{\mu\omega}{2\pi i\sin(\omega t)}\right)^{\frac{1}{2}} \exp\left\{\frac{i\mu\omega}{2\sin(\omega t)}\left[(y^2+x^2)\cos(\omega t)-2xy\right]\right\}, \qquad (12)$$

where x and y are the initial and final coordinates of the oscillator.

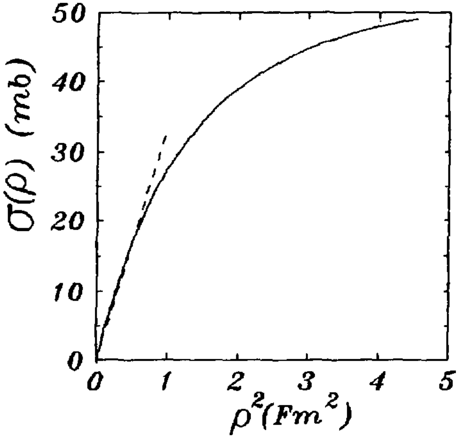


Fig.2. *Interaction cross section of a $\bar{q}q$ pair separated by a relative impact parameter ρ, on a nucleon target. The solid curve corresponds to the double-gluon exchange approximation. The dashed curve shows a simple ρ^2 behaviour (10).*

The evolution operator for the multistep nuclear density can be found using the following convolution relation,

$$\hat{U}(t_{n+1}) = \hat{U}(t_{n+1}-t_n)\circledast\hat{U}(t_n). \tag{13}$$

Here t_i is the moment of passing by the $\bar{c}c$-pair the border between corresponding slices. Note that recurrent sequence (13) can be finished as soon as the nuclear density becomes sufficiently small, because the evolution operator in vacuum provides only a phase factor, unessential for nuclear transparency (4).

After applying expression (12) and relation (13) we get the entire evolution operator, which also has a Gaussian form:

$$\langle y|\hat{U}(t)|x\rangle = A(t)\exp\left\{i\left[\alpha(t)y^2+\beta(t)x^2+\gamma(t)xy\right]\right\}. \tag{14}$$

Here t is the total time of propagation of the $\bar{c}c$-pair along the given trajectory through the nucleus. Values of the factors $A(t)$, $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ can be computed using the following recurrent relations following from (13)

$$A(t_{n+1}) = A(t_{n+1}-t_n)A(t_n)\left[\frac{i\pi}{\alpha(t_n)+\beta(t_{n+1}-t_n)}\right]^{\frac{1}{2}}$$

$$\alpha(t_{n+1}) = \alpha(t_{n+1}-t_n) - \frac{\gamma^2(t_{n+1}-t_n)}{4[\alpha(t_n)+\beta(t_{n+1}-t_n)]}$$

$$\beta(t_{n+1}) = \beta(t_n) - \frac{\gamma^2(t_n)}{4[\alpha(t_n)+\beta(t_{n+1}-t_n)]} \qquad (15)$$

$$\gamma(t_{n+1}) = - \frac{\gamma(t_{n+1}-t_n)\gamma(t_n)}{2[\alpha(t_n)+\beta(t_{n+1}-t_n)]} .$$

The factors A, α, β, γ depending on argument $t_{n+1}-t_n$, are defined according to expression (12).

Summarizing, expression (14) and relations (15) solve the problem of determination of the entire evolution operator for a given trajectory of $\bar{c}c$ pair.

3. Choice of initial wave function of $\bar{c}c$-pair

In order to calculate the nuclear transparency using formula (4) one needs also for an initial wave function, Ψ_{in}, of the diffractively produced $\bar{c}c$-pair in the process $\gamma N \to \bar{c}cN$. For the sake of simplicity we restrict ourself with two variants of Ψ_{in}. The first one uses the wave function of the $\bar{c}c$-pair produced in the process $\gamma N \to \bar{c}cN$ at very high energies, when the production time τ_p is considerably higher than a nucleon radius. We assume that this choice of Ψ_{in} can be used at maximal allowed energies (see the Introduction) about 100-150 GeV, where the ratio τ_p/r_N is of the order of 2-3.

In accordance with diffractive mechanism of $\bar{c}c$-pair production shown in fig.1, the asymptotic $\bar{c}c$ wave function is a product of the quark wave function of the photon, and the amplitude of $\bar{c}c$-pair interaction with a nucleon, i.e. $\sigma(\rho)$. The former should be taken for that photon component which has a helicity equal to a sum of helicities of $\bar{c}$ and c, because we are working within the nonrelativistic approach to the charmonium wave function. Using the formula of the noncovariant perturbative theory in the infinite momentum frame

$$|\Psi\rangle = \sum_n \frac{|n\rangle\langle n|\hat{V}|i\rangle}{E_i - E_n} ,$$

we get the wave function in the momentum representation

$$\Psi_\gamma(\alpha, k_T) \propto (m_c^2 + k_T^2)^{-1}, \qquad (16)$$

where α is the light-cone variable of the $\bar{c}c$-pair. Coming back to the ρ-representation we get the transverse part of the photon wave function in the form of the modified Bessel function, $K_0(m_c\rho)$. Gathering all parts together, the transverse part of the $\bar{c}c$ wave function Ψ_{in} [18] *takes the form,*

$$\Psi^T_{in}(\rho) \propto K_0(m_c\rho)\sigma(\rho). \qquad (17)$$

This behaviour shown in fig.3, except the very far tail, is quite exactly reproduced with a simple parameterization

$$\Psi^T_{in}(\rho) \approx Const[\exp(-\rho^2/a^2) - \exp(-\rho^2/b^2)],$$

where a=0.536 Fm, b=0.11 Fm.

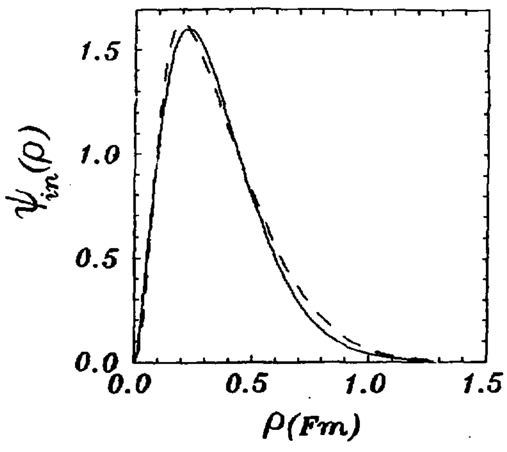


Fig.3. *The input wave function $\Psi_{in}(\rho)$ of $\bar{c}c$ pair photoproduced on a nucleon. The solid curve corresponds to the exact expression (17). The dashed curve is the result of fit with two-Gaussian parameterization.*

A longitudinal part of the $\bar{c}c$-pair wave function (16) produced in the reaction $\gamma N \Rightarrow \bar{c}cN$, is independent *on* α. So in the c.m. of $\bar{c}c$-pair the intrinsic momentum is distributed in a region of the order of m_c. Then the $\bar{c}c$-pair is located within a region $\Delta z \approx 1/m_c$, of the longitudinal coordinate. A specific choice of the form of the longitudinal part of Ψ_{in} does not play any role for the J/Ψ production because of a factorization of transverse and longitudinal coordinates in the oscillatory model. It doesn't affect considerably the nuclear transparency for ψ' photoproduction also, in spite of the lack of the factorization. We use the Gaussian parameterization, $\Psi^L_{in} \propto \exp(-z^2/d^2)$, with $d=1/2m_c$. We check below an sensitivity of the results to the parameter d.

An additional test of validity of input wave function (17) is calculation of a ratio of yields of J/Ψ to Ψ' on a nucleon target,

$$R = \left| \frac{\langle J/\Psi | \Psi_{in} \rangle}{\langle J/\Psi | \Psi_{in} \rangle} \right|^2 .$$

The computed value R=6.5 nicely agrees with the measured value [24] R=6.8±2.4. Nevertheless we should note that the input wave function (17) is approximate even at asymptotic energies. We used in (16) the free-quark approximation, neglecting the interquark interaction. The latter brings about to the mass of the $\bar{c}c$-system a correction of about 30% at relative distance of $1/m_c$. This effect is important for the absolute value of the photoproduction cross section, but are not essential for the nuclear transparency.

Let us remind that the minimum in ρ-dependence of $\Psi'_{in}(\rho)$ at $\rho=0$ is the result of modulation of the wave function with the factor $\sigma(\rho)$ in (17). It is true only if the transverse coordinates of the $\bar{c}c$-pair are "frozen" during the interaction with a single nucleon. The latter is possible at sufficiently high energy, which provides $\tau_p \gg r_p$. At lower energies, when this condition is crudely violated, a transverse shift of quarks during the interaction with the nucleon, is important. Indeed, $\Delta\rho \approx v_T \tau_p \approx 1/m_c$, where $v_T \approx 2m_c/E_\gamma$ is the velocity of transfer motion of c-quarks in the laboratory frame. Thus the transverse shift of quarks during the interaction is of the order of the quark localization region. As the result, the specific form of the wave function (17) is entirely wiped out. For this reason at low energies we use a simple parameterization of the initial $\bar{c}c$ wave function in the form,

$$\Psi^T_{in}(\rho) \propto \exp(-\rho^2/a^2) . \quad (18)$$

Note that the decreasing of the time of life of the $\bar{c}c$ -pair, τ_p, leads to the reduction of the transverse dimension of the fluctuation, because the hadronic fluctuation of the photon starts from a point. For this reason the parameter a in (18) is not connected directly with the dimension of asymptotic distribution (17). Below we will test a few values of a.

4. Results of calculations

The results of calculation of transparency of nuclei ^9Be, ^{56}Fe and ^{207}Pb with the Saxon-Woods nuclear density, for the photoproduction of J/Ψ and Ψ', are shown in fig.4. We used expression (4) and $\bar{c}c$ initial wave function in the form of (17). Experimental data [13] on J/Ψ photoproduction at the energy $E_\gamma \approx 120$ GeV are depicted in the same picture. Though the calculations were performed in a wide energy interval, we remind that the usage of the asymptotic form of wave function (17) is questionable at low energies. Besides, the results of the Glauber model for photoproduction of J/Ψ and Ψ',

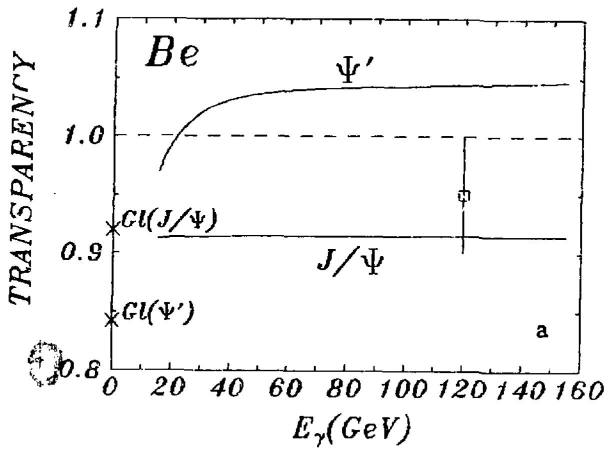
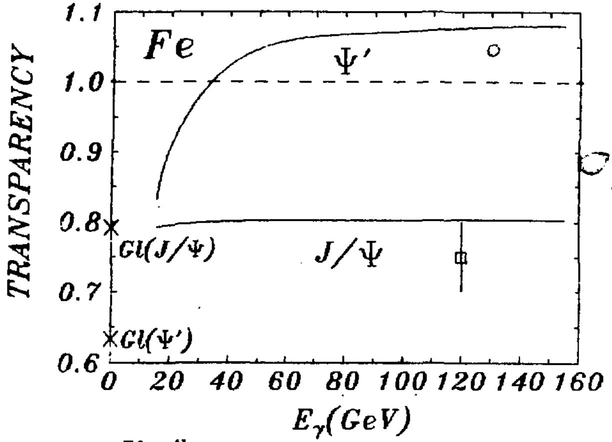
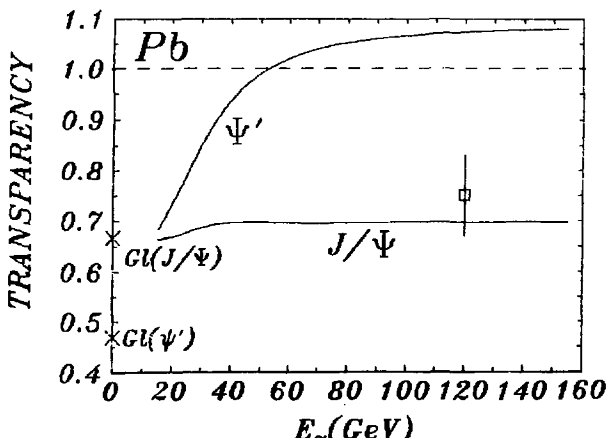


Fig.4. Energy-dependence of J/Ψ and Ψ' photoproduction cross sections on ^9Be (a), ^{56}Fe (b) and ^{207}Pb (c), computed with the asymptotic input wave function (17). The crosses depicted on the y-axis are the predictions of the Glauber approximation (19), independent on energy.



Fe
Ψ'
J/Ψ
Gl(J/Ψ)
Gl(Ψ')
TRANSPARENCY
1.1
1.0
0.9
0.8
0.7
0.6
0
20
40
60
80
100
120
140
160
$E_\gamma(GeV)$

Fig.4b



Pb
Ψ'
J/Ψ
Gl(J/Ψ)
Gl(ψ')
TRANSPARENCY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
20
40
60
80
100
120
140
160
$E_\gamma(GeV)$

Fig.4c

$$Tr_{(Gl)}=\frac{1}{A}\int d^2\mathbf{b}\int_{-\infty}^{\infty}dz\;\rho_A(\mathbf{b},z)\,\exp\left[-\sigma_{tot}(\Psi N)\int_z^{\infty}dz'\rho_A(\mathbf{b},z')\right], \qquad (19)$$

are also depicted in fig.4 with crosses.

One can see that the transparency for J/Ψ photoproduction is nearly energy-independent and is close to the Glauber model prediction. At high energy, where this variant of calculations is most justified, our predictions well agree with the experimental data [13].

On the contrary, the photoproduction of Ψ' displays some peculiarities. First, at high energies the transparency is considerably higher than the Glauber predictions, so inelastic corrections play an important role. Second, the transparency for J/Ψ is higher than for Ψ' production, in spite the fact that $\sigma_{tot}(\psi'N)$is more than two times higher than $\sigma_{tot}(\psi N)$. At last the transparency exceeds unity at energies higher than 40-60 GeV, i.e. nuclei enhance the yield of Ψ'. This means that the nuclear transparency defined in (1) can not be interpreted in accordance with an intuitive understanding, as a simple attenuation in the nuclear medium. This result shows also that the distortion of the $\bar{c}c$ wave function during propagation through the nucleus plays a more important role than the nuclear attenuation. Of course the total yield of $\bar{c}c$ is shadowed. Note that the possibility of positive contribution of inelastic corrections was discussed earlier in Refs.15,16.

The results of calculations with the second variant (18) of Ψ_{in} more appropriate at low energies are shown in fig.5 versus value of the parameter a. This choice of the initial wave function essentially modifies the nuclear transparency: first, in the case of J/Ψ production a strong energy dependence appears. Second, the relation between yields of J/Ψ and Ψ' is found to be sensitive to the size of the initial $\bar{c}c$ system: the larger is the parameter a, the higher is the relative yield of Ψ'. Within the uncertainty of the parameter a, the results well agree with the measurements at SLAC at E_γ=20 GeV [25]. The measured value of ratio $R=Tr(^9Be)/Tr(^{180}Ta)=1.21\pm0.08$ should be compared with prediction ranged from 1.25 to 1.27 for parameter $a=(1-3)/m_c$.

Now let us proceed to another energy region where both τ_p and τ_F are much higher than the nuclear radius R_A. Under these conditions the relative impact parameter ρ of the $\bar{c}c$-pair is "frozen" during the propagation through the nucleus, so one can use asymptotic expressions (5), for the transparency, and (14) for the $\bar{c}c$-pair wave function. The results of calculations are collected in table 1.

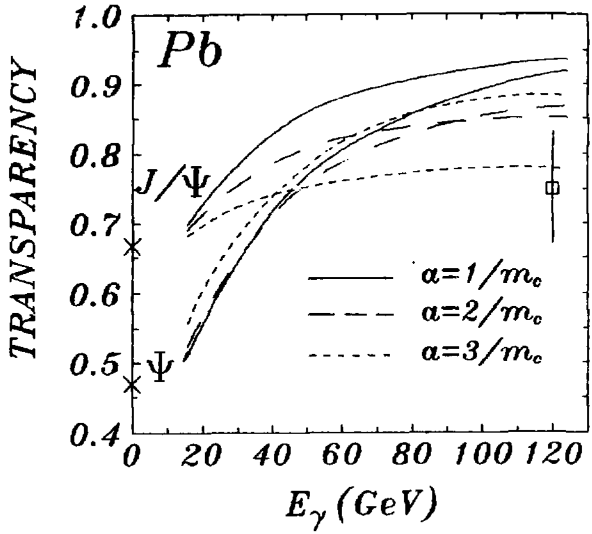


Fig.5. *Energy-dependence of J/Ψ and Ψ' photoproduction cross sections on ^{207}Pb computed with the low-energy input wave function (18), v.s. value of parameter a.*

Table 1.

Nuclear transparency for J/Ψ and Ψ' at asymptotic energies

A	Be	Fe	Pb
J/Ψ	0.85	0.72	0.5
Ψ'	1.08	1.12	1.08

Note that the asymptotic values of the transparency are lower for J/Ψ and a little higher for Ψ' than those at intermediate energies, depicted in fig.4. Consequently the growth of the transparency at intermediate energies should turn to a fall at higher energies. The reason is obvious: in the latter case a path covered by the hadronic fluctuation inside a nucleus is longer. As the result the influence of the nucleus at asymptotic energies is stronger, but we have found out that it manifests itself as the shadowing for J/Ψ and the antishadowing for Ψ'.

5. Conclusions

Let us summarize the main conclusions of present paper.

- Quantum effects for a quark system propagating through nuclear medium are very important. The nuclear absorption causes not only an attenuation but distorts also the quark wave function.

- Nuclear transparency essentially depends on the wave function of the quark system at a moment of its creation. Figs.4 and 5 illustrate the sensitivity to the choice of wave function. We conclude that the nuclear shadowing of the charmonium production in hadron-nucleus interaction is uncertain up to the initial $\bar{c}c$ wave function which depends on a production mechanism.

The relative yields of different final states considerably vary depending on their wave functions. The exciting prediction of this paper is the nuclear antishadowing of the Ψ' photoproduction in spite of the nuclear absorption.

- On the contrary to naive expectation of the Glauber approach, the nuclear transparency for the photoproduction of Ψ' is higher than for J/Ψ, in spite of the larger absorption cross section of the former. This result might explain the experimentally observed high yield of Ψ' in hadron-nucleus interactions [26].

At asymptotic energies the nuclear effects are enhanced, both the shadowing for J/Ψ and the antishadowing for Ψ'.

Summarizing, the colour transparency phenomenon is analyzed in present paper in a simple and clear case of the heavy quarkonium photoproduction. The theoretical expectations well agree with the available experimental data on nuclear enhancement of the J/Ψ photoproduction cross section. Nevertheless more precise measurements in a wide energy range, as well as data for Ψ', are desirable to have more definite confirmation of the colour transparency phenomenon. It would be of high interest to have also data for a photoproduction of $\bar{b}b$ quarkonia where the present approach can be used.

References

1. F.Low, Phys.Rev. **D12**(1975)163
2. S.Nussinov, Phys.Rev.Lett. **34**(1975)1286
3. Y.F.Gunion, H.Soper, Phys.Rev. **D15**(1977)2617
4. A.Mueller, in Proc. of XVII Recontre de Moriond, Les Arcs, France, 1982, edited by J.Tran Thanh Van (editions Frontieres, Gif-sur-Yvette,1982) p.13
5. S.J.Brodsky, in Proc. XIII Int. Symp. on Multiparticle Dynamics, eds. W.Kittel, W.Metzger and A.Stergiou (World Scientific, Singapore 1982) p.963
6. B.Z.Kopeliovich, B.G.Zakharov, Yad.Fiz. **46**(1987)1535
7. B.Z.Kopeliovich, B.G.Zakharov, Preprint of the Inst. of Exper. Phys., Slovak Academy of Sciences, UEF-03-90, Kosice, 1990
8. A.S.Carroll et al. Phys.Rev.Lett., **61**(1988)1698
9. J.P.Ralston, B.Pire. Phys Rev.Lett., **61**(1988)182
10. S.J.Brodsky, G.F.De Teramond. Phys.Rev.Lett., **60**(1988)1924
11. S.J.Brodsky, A.H.Mueller. Phys.Lett. **206B**(1988)685
12. G.N.Farrar, H.Liu, L.L.Frankfurt, M.I.Strikman, H.Liu, Phys.Rev.Lett.,**61**(1988)686
13. M.D.Sokoloff et al., Phys.Rev.Lett. **57**(1986)3003
14. V.N.Gribov, JETP, **56**(1979)892
15. B.Z.Kopeliovich, L.I.Lapidus, S.V.Mukhin, A.B.Zamolodchikov, JETP, **77**(1979)461
16. N.N.Nikolaev, JETP, **81**(1981)814
17. Yu.L.Dokshitzer, D.I.Diakonov, S.I.Troyan, Phys.Rep., ser.C, **58**(1980)269
18. N.N.Nikolaev, B.G.Zakharov, Preprint OUTP-90.23.P, Oxford Univ., 1990
19. M.Eichten et al., Phys.Rev., **D21**(1980)203
20. M.Binkley et al., Phys.Rev.Lett., **48**(1982)73
21. K.G.Boreskov, B.L.Ioffe, Yad.Fiz.,**25**(1977)623
22. J.Pumplin, Phys.Rev., **D28**(1983)2741
23. R.Feynman, A.R.Hibbs. *Quantum mechanics* and path integrals. McGraw-Hill Book company, NY, 1965
24. U.Camerini et al., Phys.Rev.Lett., **35**(1975)483
25. R.Anderson, Phys.Rev.Lett., **38**(1977)263
26. E772 Collaboration, D.M.Alde et al., FERMILAB-Pub-90/156-E, 1990

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