Why Photoproduction of Charmonium on Nuclei Does Not Measure the Charmonium-Nucleon Total Cross Section

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We show that color transparency produces either strong nuclear shadowing or antishadowing, depending on the specific (semi)exclusive photoproduction reaction off nuclei. Neither coherent nor quasielastic diffractive photoproduction of charmonium on nuclei measures the charmonium-nucleon total cross section and the vector-dominance-model interpretation of nuclear photoproduction data cannot be applied. We relate the A dependence of the coherent and quasielastic photoproduction cross sections and derive the energy dependence of shadowing. The results are in good agreement with the New Muon Collaboration data.

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The subject of this paper is the nuclear attenuation (shadowing) in coherent and quasielastic diffractive photoproduction of charmonium off nuclei. The diffractive transition $\gamma N \to VN$ is characterized by the coherence length $l_c = 2\nu/(Q^2+M_V^2)$ (ν and Q^2 are the laboratory energy and squared mass of the photon) [1]. In charmonium photoproduction $l_c \approx 0.04\nu/(1\ \mathrm{GeV})$ fm. The photoproduced $c\bar{c}$ pair recombines into the charmonium states with a formation length $l_f = \gamma/\Delta E_{c\bar{c}} \approx 0.2\nu/(1\ \mathrm{GeV})$ fm [2] ($\Delta E_{c\bar{c}}$ is a typical charmonium level splitting). The relevance of this process was first pointed out by Brodsky and Mueller [2], who suggested that $c\bar{c}$ pairs are produced with small transverse size ρ and have weak nuclear attenuation at $l_c, l_f > R_A$, providing clear-cut evidence of the occurrence of color transparency (CT) [3].

In this paper we discuss a quantum-mechanical treatment of CT effects in charmonium photoproduction. We find that CT gives rise to a strong shadowing for the J/ψ which, due to a certain numerical conspiracy, is close to that predicted by the vector dominance model (VDM) [4]. However, in spite of the larger $\psi' N$ cross section, antishadowing (i.e., nuclear enhancement), whose origin we ascribe to CT, is found for the ψ' [5]. We also derive the energy dependence of the shadowing and find that for the J/ψ it increases with energy, in agreement with the recent New Muon Collaboration (NMC) data [6]. The results obtained using the same approach to get the shadowing corrections to the coherent J/ψ photoproduction off nuclei are also in good agreement with data [7,8].

In order to set the reference frame, let us summarize the VDM predictions for the transparency factor $T_N(V) = d\sigma(\gamma A \to VA^*)/A\,d\sigma(\gamma N \to VN)$. In the low- ($l_c \lesssim R_A$) and high-energy ($l_c \gtrsim R_A$) limits one gets [4,9]

$$T_N(\mathrm{Gl})(l_c \le R_A) = \frac{1}{A}\int d^2b \int_{-\infty}^{+\infty} dz\, n_A(b,z)\exp[-\sigma_{\mathrm{tot}}(VN)t(b,z)] \approx 1 - \frac{1}{2A}\sigma_{\mathrm{tot}}(VN)\int d^2b\, T(b)^2\,, \tag{1}$$

$$T_N(\mathrm{Gl})(l_c \gg R_A) = \frac{1}{A}\int d^2b \int_{-\infty}^{+\infty} dz\, n_A(b,z)\exp[-\sigma_{\mathrm{tot}}(VN)T(b)] \approx 1 - \frac{1}{A}\sigma_{\mathrm{tot}}(VN)\int d^2b\, T(b)^2\,, \tag{2}$$

and shadowing measures the charmonium-nucleon cross section $\sigma_{\mathrm{tot}}(VN)$. Here $\mathbf{r} = (b,z)$ denotes the position of the photon absorption vertex, b is the impact parameter, $n_A(\mathbf{r})$ is the nuclear density, $t(b,z) = \int_z^\infty dz'\, n_A(b,z')$, and $T(b) = t(b,-\infty)$.

The semiclassical treatment of CT [10] leads to the following widely cited predictions. (1) As a result of Lorentz dilation, the higher the energy ν, the slower the expansion of the $c\bar{c}$ pairs and the weaker the nuclear attenuation. (2) At moderate energies, when $l_f \sim R_A$, $c\bar{c}$ pairs have enough time to expand inside the nucleus. Since $\sigma_{\mathrm{tot}}(\psi' N) \approx 2.5\sigma_{\mathrm{tot}}(J/\psi N)$ [5], the attenuation is expected to be stronger for the ψ' than for the J/ψ [see Eq. (1)]. (3) There is always some attenuation, i.e., $T_N = A_{\mathrm{eff}}/A < 1$. None of the above predictions is born out by our quantum-mechanical treatment.

Consider first the high-energy limit of $l_c > R_A$, $l_f \gg R_A$. In this case the transverse size of the pair $\vec{\rho}$ is a frozen, diagonal parameter of the scattering matrix and the interaction of the $c\bar{c}$ pair with nucleons and nuclei can be cast in quantum-mechanical form using the diffraction eigenstate reformulation [11] (see also [3]) of Gribov's theory of inelastic shadowing [12]. The forward γN

$\to VN$ and forward coherent $\gamma A \to VA$ amplitudes read as

$$\Sigma(\gamma\to V) = \langle V|\sigma|\gamma\rangle = \int d^2\rho \langle V|\rho\rangle \sigma(\rho)\langle\rho|\gamma\rangle\,, \tag{3}$$

$$\Sigma(\gamma A\to VA)_{t=0} = \int d^2b\,dz\,n_A(b,z)\langle V|\sigma\exp[-\tfrac{1}{2}\sigma t(b,z)]|\gamma\rangle\,, \tag{4}$$

where $\sigma(\rho) = \langle\rho|\sigma|\rho\rangle$ is the cross section of a $c\bar{c}$ pair of transverse size ρ and $\langle\rho|\gamma\rangle,\langle\rho|V\rangle$ are the wave functions (WF) of the $c\bar{c}$ fluctuation of the photon and the charmonium state V, respectively. The forward (excluding the coherent peak region) quasielastic production cross section on the nuclear target is [11]

$$16\pi\left.\frac{d\sigma(\gamma A\to VA^*)}{dt}\right|_{t=0} = \int d^2b\,dz\,n_A(b,z)|\langle V|\sigma\exp[-\tfrac{1}{2}\sigma T(b)]|\gamma\rangle|^2\,. \tag{5}$$

The leading shadowing term in Eq. (5),

$$T_N = 1 - \frac{1}{A}\frac{\langle V|\sigma^2|\gamma\rangle}{\langle V|\sigma|\gamma\rangle}\int d^2b\,T(b)^2\,, \tag{6}$$

is quite different from the one in the VDM formula [Eq. (2)].

The WF of the $c\bar{c}$ fluctuation of the photon and the cross section $\sigma(\rho)$ are calculable within perturbative QCD. In the case of photoproduction, i.e., when $Q^2=0$, charmonium can be treated nonrelativistically, and [5,13]

$$\langle\rho|\gamma\rangle \propto m_c K_0(m_c\rho)\,, \tag{7}$$

where $K_0(x)$ is the Bessel function. The numerical value of the transparency T_N crucially depends on the CT property of the cross section,

$$\sigma(\rho)\propto\rho^2\alpha_S(\rho)\log[1/\alpha_S(\rho)] \tag{8}$$

at small ρ [3,9,13], which is a fundamental consequence of the color gauge invariance [$\alpha_S(\rho)$ is the QCD coupling]. $\sigma(\rho)$ saturates at large ρ, beyond the confinement radius R_c [13]. Notice that neither $\langle\rho|\gamma\rangle$ nor $\sigma(\rho)$ depends on the longitudinal separation between the quarks. The overlap integrals in Eqs. (3)-(5) are controlled by the product $\sigma(\rho)K_0(m_c\rho)$, shown in Fig. 1. CT makes it peaked at $\rho\approx\rho_{\rm in}=0.25$ fm $> 1/m_c$. In Fig. 1 we also show the J/ψ and ψ' WF's integrated over the longitudinal size.

In the case of J/ψ photoproduction, there is a certain numerical conspiracy: The product $\sigma(\rho)\langle\rho|\gamma\rangle$ is dominated by a fairly large $\rho\sim\rho_{\rm in}$, $\rho_{\rm in}$ being smaller than $R_{J/\psi}$ (Fig. 1). However, because of CT [Eq. (8)], the matrix element of σ^2 is dominated by a larger $\rho\sim R_{J/\psi}$, so that

$$\frac{\langle J/\psi|\sigma^2|\gamma\rangle}{\langle J/\psi|\sigma|\gamma\rangle}\sim\sigma_{\rm tot}(J/\psi N) = \langle J/\psi|\sigma|J/\psi\rangle\,, \tag{9}$$

yielding a value of $T_N(J/\psi)$ marginally similar to the one given by the Glauber formula [Eq. (2)]. In this instance CT predicts strong shadowing.

The situation is reversed for the ψ'. Since $\sigma_{\rm tot}(\psi' N)\approx 2.5\sigma_{\rm tot}(J/\psi N)$ [14], the VDM formulas equations (1) and (2) predict $T_N(\psi') < T_N(J/\psi)$. However, as a result of the same CT suppression of the small-ρ contribution to the overlap integral and to the presence of a node in $|\psi'\rangle$, the second moment $\langle\psi'|\sigma^2|\gamma\rangle < 0$ and $T_N(\psi') > 1$, as was found numerically in [5]. In terms of the ψ' overlap integral in Eq. (5), antishadowing comes from the strong suppression of the contribution from ρ above the node due to the factor $\exp[-\sigma(\rho)T(b)/2]$, which proves to be more important than the overall attenuation. The node in $\langle\rho|\psi'\rangle$ also plays a relevant role in determining the ratio $d\sigma(\gamma N\to\psi' N)/d\sigma(\gamma N\to J/\psi N)$, whose calculated value is 0.16 [5]. The agreement between this result and the measured value $0.20\pm0.05({\rm stat})\pm0.07({\rm syst})$ [7] indicates that the cancellation mechanism is properly handled within the present approach. Both the ψ' suppression on nucleons and its enhancement (antishadowing) on nuclei are direct consequences of CT.

In the photoproduction of the light-quark mesons, $\langle\rho|\gamma\rangle_{u\bar{u}+d\bar{d}}$ will have a normal hadronic size [13], and the same numerical conspiracy makes the correct quantum mechanical treatment of photoproduction of the low-lying ρ,ω,ϕ mesons marginally similar to the VDM treatment. But for the first radial excitation, ρ', the cancellation mechanism in the overlap integral may also lead to very weak production of the ρ' on nucleons and to very strong enhancement of the nuclear production [14].

The predicted pattern of shadowing in coherent photoproduction is similar. The coherent cross section reads

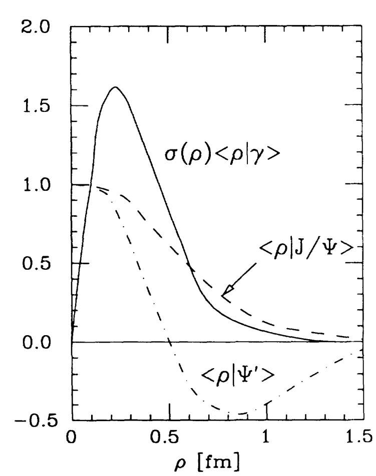

FIG. 1. The impact-parameter structure of the overlap integrals for the J/ψ and ψ' photoproduction amplitudes (arbitrary units).

$$\sigma(\gamma A \to VA) = 4\int d^2b |\langle V|\{1-\exp[-\tfrac{1}{2}\sigma T(b)]\}|\gamma\rangle|^2 \approx \langle V|\sigma|\gamma\rangle^2 \int d^2b\, T(b)^2 \left[1 - \frac{1}{2}\frac{\langle V|\sigma^2|\gamma\rangle}{\langle V|\sigma|\gamma\rangle} T(b)\right], \tag{10}$$

and we predict shadowing for the J/ψ and antishadowing for the ψ'. Nuclear effects in the coherent and quasielastic production can easily be related to each other.

In the intermediate energy range of $l_c \lesssim R_A$ the amplitudes for photoproduction on different nucleons i will differ by the phase factor $\exp(i\kappa_L z_i)$, where $\kappa_L = M_\psi^2/2\nu = 1/l_c$. Because of the strong inequality $l_c \ll l_f$, the analogous phases associated with the off-diagonal transitions between charmonium states can safely be neglected. The factor $\exp(i\kappa_L z)$ emerges in the integrand of (4), so that the coherent cross section will be proportional to $F_{\mathrm{ch}}(\kappa_L)^2$, $F_{\mathrm{ch}}(q)$ being the charge form factor of the target nucleus. Incidentally, a similar form factor effect dominates the energy dependence of J/ψ photoproduction on nucleons.

The recent New Muon Collaboration data [7] give the limiting high-energy ratio

$$R_{\mathrm{coh}}(\mathrm{Sn/C}) = \sigma(\gamma\mathrm{Sn} \to J/\psi\mathrm{Sn})/\sigma(\gamma\mathrm{C} \to J/\psi\mathrm{C}) = 2.15 \pm 0.10\,,$$

to be compared to 2.28 from Eq. (10) [2.76 without the shadowing term in (10)]. The Fermilab E691 experiment [8] gives $R_{\mathrm{coh}}(\mathrm{Fe/Be}) = 2.28 \pm 0.32$ and $R_{\mathrm{coh}}(\mathrm{Pb/Be}) = 3.47 \pm 0.50$, compared to 2.41 and 3.52 from Eq. (10) [2.82 and 4.79 without the shadowing term in (10)].

The antishadowing in ψ' production leads to an increase of the ratio of the ψ' to J/ψ production cross sections for heavy nuclei: We find $R_{\mathrm{coh}}(\psi'/(J/\psi),\mathrm{Sn/C}) = 1.25$.

In the quasielastic case a careful treatment of the interference terms associated with production on different nucleons is needed. The detailed derivation will be presented elsewhere [15], here we just sketch the basic ideas. In quasielastic scattering one sums over all excitations of the final-state nucleus, and has to evaluate the nuclear matrix element of $\sum_{ik} A_i^* A_k \exp[i\kappa_L(z_k - z_i)]$, where A_i is the production amplitude on the ith nucleon. If the coherence length is much smaller than the nuclear radius R_A, the interference terms vanish upon z integration. The nuclear cross section will then be given by Eq. (5) with the substitution $T(b) \to t(b,z)$. Up to the leading term, the resulting attenuation is half of that given by Eq. (6).

The interference contribution to the leading shadowing term is $\propto F_{\mathrm{ch}}(\kappa_L)^2$ and leads to the energy dependence of the transparency:

$$T_N = 1 - \frac{1+F_{\mathrm{ch}}(\kappa_L)^2}{2A} \frac{\langle V|\sigma^2|\gamma\rangle}{\langle V|\sigma|\gamma\rangle} \int d^2b\, T(b)^2 . \tag{11}$$

This prediction of a rise of J/ψ shadowing with energy agrees perfectly with the recent NMC data [6] (see Fig. 2). The bump in the low-energy end of Fig. 2 is due to the more rapid rise of shadowing in carbon. Within the semiclassical treatment of Ref. [10] the opposite energy dependence is predicted: At lower energies the shadowing is stronger, as the $c\bar{c}$ system has time to expand inside the nucleus. The transparency for J/ψ photoproduction in the two limiting cases, corresponding to low and very high photon energy, has been evaluated in [5].

In order to emphasize the nontrivial effects of CT in the shadowing matrix elements, in the above equations we only show the leading shadowing corrections. The evaluation of the higher-order terms is straightforward and is presently being carried out. The preliminary results indicate that the corrections are small and the present estimates are fairly accurate (see [15]).

The VDM formula [Eq. (1)] is applicable in the very-low-energy domain only, when $l_f < R_A$ (for a review see [16]). Therefore, the SLAC determination of $\sigma_{\mathrm{tot}}(J/\psi N) = 3.5 \pm 0.8$ mb from the Ta/Be quasielastic cross-section ratio at $\nu = 20$ GeV [17] can be regarded as a reliable one. The QCD calculations predict $\sigma_{\mathrm{tot}}(J/\psi N) \approx 5$ mb [5]. For the same reason (i.e., due to the inequality $l_f < R_A$), the nuclear attenuation of the J/ψ's produced in $\bar{p}A$ annihilation measures the J/ψ-nucleon cross section [2].

In conclusion, the property of CT in QCD can be quantified in terms of $\sigma(\rho)$. The understanding of the consequences of CT in a specific (semi)exclusive nuclear process requires the quantum-mechanical evaluation of the relevant amplitudes and of the interference terms coming from interactions with different nucleons in the target nucleus. Our analysis clearly demonstrates the perils of the semiclassical treatment of CT and of the

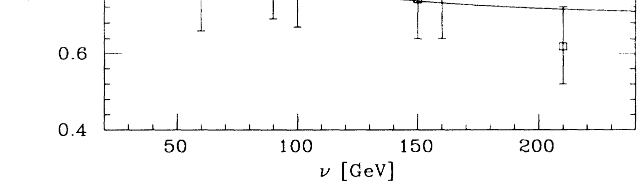

FIG. 2. QCD prediction [Eq. (11)] (solid line) and semiclassical prediction of Farrar *et al.* [10] (dashed line) for the ratio of transparency in quasielastic J/ψ photoproduction on tin and carbon, as a function of the photon energy, vs the NMC data [6].

VDM interpretation of charmonium photoproduction on nuclei. A signal of the relevance of quantum-mechanical effects in charmonium propagation in nuclei is also provided by the Fermilab E772 data for forward J/ψ and ψ' production in pA collisions [18]: In spite of the very different free-nucleon cross sections, J/ψ and ψ' have strong and identical nuclear attenuation. With the only exception of quasielastic production at low energies, corresponding to $l_f \lesssim R_A$, photoproduction of charmonium on nuclei does not measure the charmonium-nucleon cross section.

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