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Photoproduction of charm near threshold *

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Abstract

Charm and bottom production near threshold is sensitive to the multi-quark, gluonic, and hidden-color correlations of hadronic and nuclear wavefunctions in QCD since all of the target's constituents must act coherently within the small interaction volume of the heavy quark production subprocess. Although such multi-parton subprocess cross sections are suppressed by powers of $1/m_Q^2$, they have less phase-space suppression and can dominate the contributions of the leading-twist single-gluon subprocesses in the threshold regime. The small rates for open and hidden charm photoproduction at threshold call for a dedicated facility.

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The threshold regime of charmonium and open charm production can provide a new window into multi-quark, gluonic, and hidden-color correlations of hadronic and nuclear wavefunctions in QCD. For example, consider charm photoproduction $\gamma\ p \to J/\psi\ p$ at the threshold energy $E_\gamma^{\rm lab} = 8.20$ GeV. [See Fig. 1.] The available production energy cannot be wasted at threshold, so all three valence quarks of the target nucleon must interact coherently within the small interaction volume of the heavy quark production subprocess. In the case of threshold charm photoproduction on a deuteron $\gamma\ d \to J/\psi\ d$, all color configurations of the six valence quarks will be involved at the short-distance scale $1/m_c$. Thus the exchanged gluons can couple to a color-octet quark cluster and reveal the "hidden-color" part of the nuclear wave function, a domain of short-range nuclear physics where nucleons lose their identity [1, 2, 3].

At high energies the dominant contribution to an inclusive process involving a hard scale Q comes from "leading twist" diagrams, characterized by only one parton from each colliding particle participating in the large momentum subprocess. Since the transverse size scale of the hard collision is $1/Q$, only partons within this distance can affect the process. The likelihood that two partons of the incident hadrons can be found so close to each other is typically proportional to the transverse area $1/Q^2$ and leads to the suppression of higher-twist, multi-parton contributions. However, in contrast to charm production at high energy, charm production near threshold requires all of the target's constituents to act coherently in the heavy quark production process: only compact proton Fock states with a radius of order of the Compton wavelength of the heavy quark can contribute to charm production at threshold. Although the higher-twist subprocess cross sections are suppressed by powers of $1/m_c^2$, they have much less phase-space suppression at threshold. Thus charm production at threshold is sensitive to short-range correlations between the valence quarks of the target, and higher-twist multi-gluon exchange reactions can dominate over the contributions of the leading-twist single-gluon subprocesses.

One can determine the power-law dependence of multi-parton heavy quark production subprocesses using an operator product analysis of the effective heavy quark theory. The heavy quark photoproduction cross section can be computed through the optical theorem from the corresponding cut diagrams of the forward Compton amplitude. Such diagrams factorize into the convolution of two factors: a heavy quark loop diagram connecting the photons to the exchanged gluons, times the gauge invariant matrix element of a product of gluon field strengths $< p|G^n_{\mu\nu}|p >$. Because of the non-Abelian coupling, a single field strength can correspond to one or two exchanged gluons. For heavy quark masses, $m_Q^2 \gg \Lambda_{QCD}^2$ the heavy quark loop contracts to an effective local operator, so that the field strengths in the matrix element are all evaluated at the same local point. The minimal gluon exchange contribution ($n = 2$) gives the leading twist photon-gluon fusion contribution. Since $< p|G^n|p >$ scales as $(\Lambda_{QCD}^2)^{n-1}$, each extra gluon field strength connecting to the heavy quark loop must give a factor of $(1/m_Q^2)$. (Higher derivatives in the matrix element are further suppressed.) Thus one pays a penalty of a factor (Λ^2/m_Q^2) as the number of exchanged

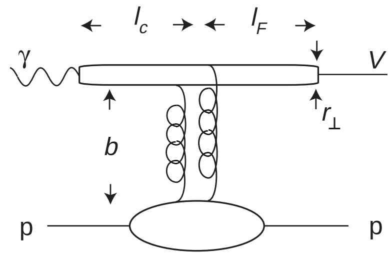

Figure 1: The characteristic scales in elastic J/ψ production on protons near threshold, $E_\gamma^{\rm lab} = 8.20$ GeV. The longitudinal coherence length of the $c\bar{c}$ fluctuation of the photon is short, $l_c \cong 2E_\gamma^{\rm lab}/4m_c^2 = 0.36$ fm. The large mass of the charmed quark also imposes a small transverse size $r_\perp \sim 1/m_c = 0.13$ fm on this fluctuation. The minimum momentum transfer is large, $t_{min} \sim -1.7$ GeV^2. All of the partons of the target wavefunction have to transfer their energy to the charm quarks within their proper creation time $1/m_c$, and must be within this transverse distance from the $c\bar{c}$ and from each other, so that charm production near threshold occurs at small impact distances $b \sim 1/\sqrt{-t} \sim 0.2$ fm.

gluon fields is increased. However, as we shall see, the suppression from the multiple gluon exchange contributions are systematically compensated by fewer powers of energy threshold factors, so that at threshold multi-gluon contributions will dominate. A similar effective field theory operator analysis has been used[4] to estimate the momentum fraction carried by intrinsic heavy quarks in the proton [5, 6].

In this paper, we will use reasonable conjectures for the short distance behavior of hadronic matter inferred from properties of perturbative QCD and effective heavy quark field theory to estimate the behavior of the reaction cross section.

The effective proton radius in charm photoproduction near threshold can be determined from the following argument [7, 8]. As indicated in Fig. 2a, most of the proton momentum may first be transferred to one (valence) quark, followed by a hard subprocess $\gamma q \to c\bar{c}q$. If the photon energy is $E_\gamma = \zeta E_\gamma^{th}$, where E_γ^{th} is the energy at kinematic threshold ($\zeta \geq 1$), the valence quark must carry a fraction $x = 1/\zeta$ of the proton (light-cone) momentum. The lifetime of such a Fock state (in the light-cone or infinite momentum frame) is $\tau = 1/\Delta E$, where

$$\Delta E = \frac{1}{2p}\left[m_p^2 - \sum_i \frac{p_{i\perp}^2 + m_i^2}{x_i}\right] \simeq \frac{\Lambda_{QCD}^2}{2p(1-x)} \tag{1}$$

For $x = 1/\zeta$ close to unity such a short lived fluctuation can be created (as indicated in Fig. 2a) through momentum transfers from valence states (where the momentum is divided evenly) having commensurate lifetimes τ and transverse extension

$$r_\perp^2 \simeq \frac{1}{p_\perp^2} \simeq \frac{\zeta - 1}{\Lambda_{QCD}^2} \tag{2}$$

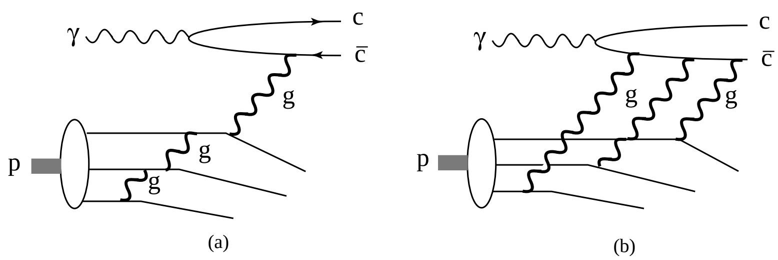

Figure 2: Two mechanisms for transferring most of the proton momentum to the charm quark pair in $\gamma p \to c\bar{c}p$ near threshold. The leading twist contribution (a) dominates at high energies, but becomes comparable to the higher-twist contribution (b) close to threshold.

This effective proton size thus decreases towards threshold ($\zeta \to 1$), reaching $r_\perp^2 \simeq 1/m_c^2$ at threshold ($\zeta - 1 \simeq \Lambda_{QCD}^2/m_c^2$).

As the lifetimes of the contributing Fock states approach the time scale of the $c\bar{c}$ creation process, the time ordering of the gluon exchanges implied by Fig. 2a ceases to dominate higher-twist contributions such as that of Fig. 2b [8]. There are in fact reasons to expect that the latter diagrams give a dominant contribution to charmonium production near threshold. First, there are many more such diagrams. Second, they allow the final state proton to have a small transverse momentum (the gluons need $p_\perp \simeq m_c$ to couple effectively to the $c\bar{c}$ pair, yet the overall transfer can still be small in Fig. 2b). Third, with several gluons coupling to the charm quark pair its quantum numbers can match those of a given charmonium state without extra gluon emission.

The above discussion is generic, and does not indicate how close to threshold the new effects actually manifest themselves. While this question can only be settled by experiment, we rely on a simple model to get an estimate of the cross section.

Near-threshold charm production probes the $x \simeq 1$ configuration in the target, the spectator partons carrying a vanishing fraction $x \simeq 0$ of the target momentum. This implies that the production rate behaves near $x \to 1$ as $(1-x)^{2n_s}$ where n_s is the number of spectators [9]. Perturbative QCD predicts three different gluonic components of the photoproduction cross-section: i) The leading twist $(1-x)^4$ distribution for the process $\gamma q \to c\bar{c}q$, which leaves two quarks spectators (Fig. 2a); ii) Scattering on two quarks in the proton with a net distribution $\frac{(1-x)^2}{R^2\mathcal{M}^2}$, $\gamma qq \to c\bar{c}qq$, leaving one quark spectator; iii) Scattering on three quark cluster (Fig. 2b) in the proton with a net distribution $\frac{(1-x)^0}{R^4\mathcal{M}^4}$, $\gamma qqq \to c\bar{c}qqq$, leaving no quark spectators. Here $x \approx (2m\mathcal{M} + \mathcal{M}^2)/(s - m_p^2)$, where $s = E_{CM}^2$ and $\mathcal{M}$ is the mass of the $c\bar{c}$ pair. The relative weight of scattering from multiple quarks is given by the probability $1/R^2\mathcal{M}^2$ that a quark in the proton of radius $R \simeq 1$ fm is found within a transverse distance $1/\mathcal{M}$ (see Ref. [10]).

The two-gluon exchange contribution produces odd C quarkonium $\gamma gg \to J/\psi$, thus permitting exclusive $\gamma p \to J/\psi p$ production. The photon three-gluon coupling $\gamma ggg \to c\bar{c}$ produces a roughly constant term at threshold in σ/v, where it is expected to dominate (here $v = 1/16\pi(s - m_p^2)^2$ is the usual phase space factor). It produces the $\eta_c p$, $\chi_c p$ and other C even resonances, but also J/ψ.

For elastic charm production (when the proton target remains bound), it is also necessary to take into account the recombination of the three valence quarks into the proton via its form factor, as well as the coupling of the photon to the $c\bar{c}$ pair. For two gluon exchange the cross section of the $\gamma p \to J/\psi p$ takes the form:

$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_{2g}^2(t)(s - m_p^2)^2 \tag{3}$$

while for three gluon exchange it takes the form:

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_{3g}^2(t)(s - m_p^2)^2 \tag{4}$$

where $F_{2g}(t)$ and $F_{3g}(t)$ are proton form factors that take into account the fact that the three target quarks recombine into the final proton after the emission of two or three gluons. While they are analogous to the proton elastic form factor $F_1(t)$, they are not known. In the numerical applications, we have parameterized them as $F^2 = \exp(1.13t)$, according to the experimental t dependency of the cross section [11]. The $(s - m_p^2)^2$ term comes from the coupling of the incoming photon to the $c\bar{c}$ pair and the spin-1 nature of gluon exchange (see, for instance, Ref. [12]). It compensates the same term in the phase space v. The normalization coefficient $\mathcal{N}$ is determined assuming that each channel saturates the experimental cross section measured at SLAC [13] and Cornell [11] around $E_\gamma = 12$ GeV.

Notice that expressions (3) and (4) are valid in a limited energy range near threshold, where $x \sim 1$. At higher energies one has to rely on the variation of the gluon distribution in the vicinity of $x \sim 0$ to reproduce the steep rise of charm photoproduction [16, 17].

As shown in Fig. 3, the threshold dependence of our conjectured cross sections (3) and (4) is consistent with the scarce existing data [11, 13]. Indeed, there is also evidence [14] that the energy dependence of the J/ψ elastic photoproduction cross section at forward angles is roughly flat up to $E_\gamma \approx 12$ GeV, in contrast to the steep variation observed at higher energies. More accurate measurements of the J/ψ elastic photoproduction cross section up to about 20 GeV are clearly needed.

The existence of five-quark resonances near threshold in the $\gamma p \to pc\bar{c}$ process [15] would modify our picture. However, the qualitative features of the two- and three-gluon-exchange cross sections (which differ by orders of magnitude near threshold) should remain valid.

On few body targets, each exchanged gluon may couple to a colored quark cluster and reveal the hidden-color part of the nuclear wave function, a domain of short-range

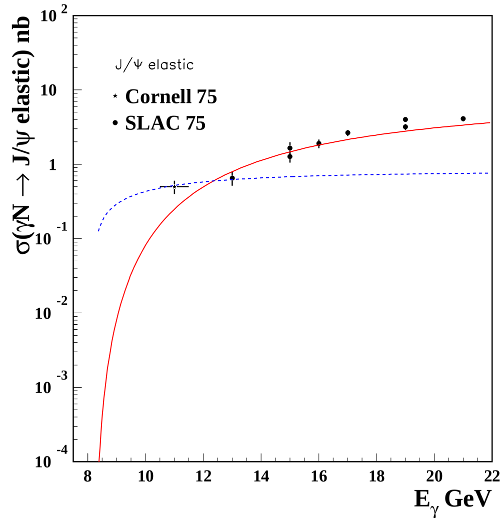

Figure 3: Variation of the J/ψ photoproduction cross section near threshold. Solid line: two gluon exchange (Eqs. 3). Dashed line: three gluon exchange (Eq. 4).

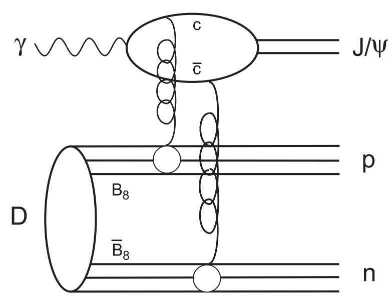

Figure 4: The simplest diagram which reveals a hidden-color state in deuterium [18].

nuclear physics where nucleons lose their identity. The existence of such hidden-color configurations is predicted by QCD evolution equations [3]. It is striking that in $\gamma d \to J/\psi pn$, (Fig. 4), the $|B_8\overline{B_8} >$ hidden-color state of the deuteron couples so naturally via two gluons to the $J/\psi pn$ final state [18], since the coupling of a single gluon to a three-quark cluster turns it from a color octet to a singlet.

When the nucleon is embedded in a nuclear medium, two mechanisms govern the photo- and electroproduction of J/ψ mesons. The first, the quasi-free production mechanism, contributes the following cross section to the $\gamma d \to J/\psi pn$ reaction, when integrated over the angles of the spectator neutron [19]:

$$\frac{d\sigma}{dtd|\,\vec{n}\,|} = \left.\frac{d\sigma}{dt}\right|_{\gamma p \to J/\psi p} 4\pi\vec{n}^2 \rho(|\,\vec{n}\,|) \tag{5}$$

$$\int \rho(|\,\vec{n}\,|) d\vec{n} = 1 \tag{6}$$

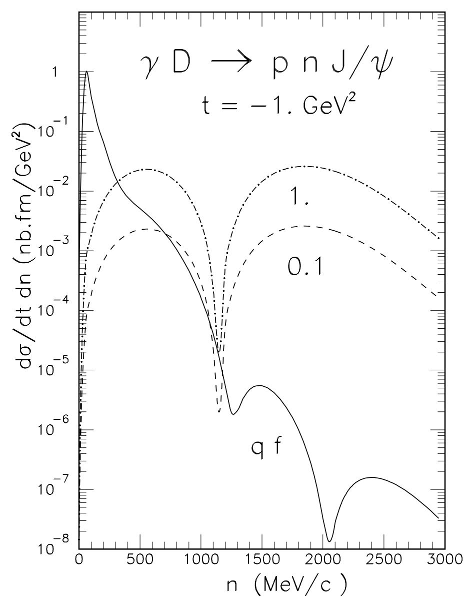

Figure 5: The variation of the cross-section of the reaction $\gamma D \to pnJ/\psi$ against the neutron momentum $|\vec{n}|$, at fixed t. Solid line: quasi-free contribution. Dashed line: contribution of a hidden-color component when its probability is 0.1%. Dash-dotted curve: the same for a probability of 1%.

where $|\ \vec{n}\ |$ is the momentum of the spectator neutron. The nucleon momentum distribution $\rho(|\ \vec{n}\ |)$ in deuterium decreases very quickly [19] with increasing neutron momentum. Consequently, by selecting high neutron momenta one can suppress quasi-free production and measure inherently nuclear effects. The quasi-free contribution in Fig. 5 has been computed with the Paris wave function [20] of the deuterium.

The second contribution comes from coupling the two gluons to separate color octet 3-quark clusters. This contribution is expected to have a flatter momentum distribution, since the recoil momentum is shared between two nucleons. The corresponding cross section can be roughly estimated as :

$$\frac{d\sigma}{dtd|\ \vec{n}\ |} = \left.\frac{d\sigma}{dt}\right|_{\gamma p \to J/\psi p} 4\pi \vec{n}^2 \left[\varphi_{cc}(\frac{\vec{n}}{2})\right]^2 \frac{F_1^4(\frac{t}{4})}{F_1^2(t)} \tag{7}$$

where the fourth power of the nucleon form factor comes from the fact that two nucleons have to recombine, each at the momentum transfer $t/4$ [18, 21]. We assume that the form factor of the transition between a colored cluster and the nucleon does not differ too much from the nucleon form factor [22] and that the recoil momentum is equally shared between the two colored clusters whose relative wave function is $\varphi_{cc}(\frac{\vec{n}}{2})$. This component of the deuterium wave function has not been measured and few predictions are available. As an example and to set the order of magnitude, the hidden-color contribution in Fig. 5 has been obtained using the Fourier transform of the wave function depicted in Fig. 11 of Ref. [23]. Since it exhibits a node around 500 MeV/c, a node appears in the cross-section around $n \simeq 1\ GeV/c$. In a more elaborate calculation the sum over the nucleon internal momentum would wash out this node. Anyway, this rough estimate shows that the hidden-color component contribution dominates the cross-section above 0.5 GeV/c. The calculation reported in [23] predicts a probability of finding a hidden-color component in the deuterium wave function of the order of 0.1%. Fig. 5 also shows what one may expect for a probability around 1%.

Scattering on colored clusters may dominate subthreshold production, since the high momentum of the struck nucleon suppresses the quasi free mechanism. On deuterium the threshold for J/ψ production is $\sim$ 5.65 GeV, while on heavy nuclei the threshold is simply the J/ψ mass 3.1 GeV.

Let us close this note with two remarks. At threshold, the formation length (during which the $c\overline{c}$ pair evolves into a J/ψ, after its interaction with a nucleon)

$$l_F \cong \frac{2}{m_{\psi'} - m_{J/\psi}} \left[\frac{E_{J/\psi}}{2m_c}\right] \cong 0.22 \text{ fm } E_\gamma/\text{GeV} \tag{8}$$

is around 1 fm, considerably smaller than the size of a large nucleus. It is thus possible to determine the scattering cross section of a full sized charmonium on a nucleon using nuclear targets, in contrast to the situation at higher energies where the nuclear interaction of a compact $c\overline{c}$ pair is measured. The study of the A dependence of the J/ψ photoproduction cross section at SLAC at 20 GeV [24] gave $\sigma_{J/\psi} = 3.5 \pm 0.8 \pm 0.5$ mb. However, a large calculated background was subtracted and the lack of information on the J/ψ kinematics prevented a separate measurement of coherent and incoherent photoproduction. A new measurement of J/ψ photoproduction on several nuclei around $E_\gamma \approx 10$ GeV, with good particle identification and a determination of the J/ψ momentum is clearly called for.

Although the $c\overline{c}$ pair is created with rather high momentum at threshold, it may be possible to observe reactions where the pair is captured by the target nucleus, forming "nuclear-bound quarkonium" [15]. This process should be enhanced in subthreshold reactions. There is no Pauli blocking for charm quarks in nuclei, and it has been estimated that there is a large attractive Van der Waals potential binding the pair to the nucleus [25]. The discovery of such qualitatively new states of matter would be very important.

In this paper we have shown that charm production near threshold has strong sensitivity to the multi-quark, gluonic, and hidden-color correlations of hadronic and nuclear wavefunctions in QCD. Although multi-parton subprocess cross sections are suppressed by powers of $1/m_c^2$, they have correspondingly less phase-space suppression and thus can dominate the contributions of the leading-twist single-gluon subprocesses in the threshold regime. Such processes will therefore add to our understanding of the short-range structure of nucleons and nuclei. A new dedicated facility, such as CEBAF12 or ELFE, with high intensity and duty factor, will make possible the experiments needed to explore this QCD frontier.

References

[1] V. A. Matveev and P. Sorba, Lett. Nuovo Cim. **20**, 435 (1977).

[2] V. A. Matveev and P. Sorba, Nuovo Cim. **A45**, 257 (1978).

[3] S. J. Brodsky, C. Ji and G. P. Lepage, Phys. Rev. Lett. **51**, 83 (1983).

[4] M. Franz, M. V. Polyakov and K. Goeke, hep-ph/0002240.

[5] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys. Lett. **B93**, 451 (1980).

[6] B. W. Harris, J. Smith and R. Vogt, Nucl. Phys. **B461**, 181 (1996)

[7] P. Hoyer, Nucl. Phys. **A622** (1997) 284c.

[8] S.J. Brodsky, P. Hoyer, A.H. Mueller and W.-K. Tang, Nucl. Phys. **B369** (1992) 519.

[9] S. J. Brodsky, M. Burkardt and I. Schmidt, Nucl. Phys. **B441**, 197 (1995)

[10] E.L. Berger and S.J. Brodsky, Phys. Rev. Lett. **42** (1979) 940.

[11] B. Gittelman et al., Phys. Rev. Lett. **35** (1975) 1616.

[12] J.M. Laget, Phys. Lett. **B489** (2000) 313.

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

[14] R. Anderson et al., SLAC-PUB-1741 *Invited talk presented at Int. Conf. on Production of Particles with New Quantum Numbers, Wisconsin U., Madison, Apr. 22-24, 1976.*

[15] S.J. Brodsky, G.F. de Teramond and I.A. Schmidt, Phys. Rev. Lett. **64** (1990) 1924.

[16] S.J. Brodsky et al., Phys. ReV. **D50** (1994) 3134.

[17] D. Kharzeev et al., Eur. Phys. J. **C9** (1999) 459.

[18] J.M. Laget and R. Mendez-Galain, Nucl. Phys. **A581** (1995) 397.

[19] J.M. Laget, Phys. Rep. **69** (1981) 1.

[20] M. Lacombe *et al.*, Phys. Lett. **B101** (1981) 139.

[21] S. J. Brodsky and J. R. Hiller, Phys. Rev. **C28**, 475 (1983).

[22] This is a conservative estimate, since a color 3-quark cluster is probably more compact than a singlet nucleon; hence the form factor should be larger.

[23] Y. Yamauchi and Wakamatsu, Nucl. Phys. **A457** (1986) 621.

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

[25] M. Luke, A.V. Manohar and M.J. Savage, Phys. Lett. **B288** (1992) 355.