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Using Nuclei to Probe Hadronization in QCD

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ABSTRACT: The behavior of quasi-exclusive and inclusive ρ and J/ψ photoproduction, electroproduction and hadroproduction in nuclei are discussed for small and large $p_\perp$. In particular we argue that J/ψ production in ion-ion collisions is likely to be suppressed relative to the background lepton pair production, independent of whether or not a QCD plasma is formed. We point out that previous extractions of the J/ψ inelastic cross section do not actually measure the cross section for the interaction of physical J/ψ's with nucleons.

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In this note we would like to point out some qualitative properties of A-dependent effects in which QCD color transparency[1,2] plays an important role. We shall contrast inclusive with exclusive and quasi-exclusive processes, and processes having a hard interaction with those involving only soft interactions. Thus, for example, we shall explicitly consider production of J/ψ particles, at both large and normal values of $p_\perp$, by incident beams of photons, hadrons and ions on a general nuclear target, as well as J/ψ production through proton-anti-proton annihilation using low energy anti-proton beams incident on a nucleus. Similarly we shall consider electroproduction and photoproduction of ρ-mesons at large and small transverse momenta.

For processes involving hard interactions it is convenient to consider two separate time scales, a time of production, $\mathcal{T}_P$ and a time of formation of the measured final state hadron, $\mathcal{T}_F$. We shall generally define these times in a laboratory system having the target, nucleon or nucleus, at rest. $\mathcal{T}_P$ is the time scale over which the hard interaction occurs while $\mathcal{T}_F$ is the time it takes the produced partonic system to reach the normal configuration of the wave function of the hadron. If there is no hard interaction the distinction between $\mathcal{T}_P$ and $\mathcal{T}_F$ is lost. For processes involving a hard collision, and at times after that hard collision less than $\mathcal{T}_F$, one must deal with the partonic system explicitly. Indeed it is only after a time $\mathcal{T}_F$ that it makes sense to talk of a particular hadron as existing.

In a reaction where a final state hadron, H is measured inclusively one puts no restrictions on the final state of the system other than the production of H with a particular momentum. In an exclusive reaction one specifies the final state completely. In a quasi-exclusive reaction one does not give a complete specification of the final state, but particular constraints are imposed requiring the final state to resemble, more or less closely, a particular final state. In our examples we shall sometimes require that no particles be produced in a particular momentum region.

Let us now give estimates[3] of $\mathcal{T}_P$ and $\mathcal{T}_F$ for processes having a hard interaction of momentum transfer Q, where the momentum of the measured outgoing relativistic hadron H is p. Then

$$\mathcal{T}_P \sim \frac{1}{\Delta E} \sim \frac{p}{Q^2}. \tag{1}$$

The time of formation of H is determiend by requiring that

$$v_\perp \mathcal{T}_F = r_H \tag{2}$$

where $v_\perp$ is the transverse velocity of a quark (anti-quark) constituent of H and r_H is the radius of the hadron. Now

$$v_\perp = \frac{\sqrt{\frac{2}{3}}k_H}{E_H} \tag{3}$$

with k_H the typical momentum of the constituent in the rest system of H while E_H is the laboratory energy of H. Equations (2) and (3) give

$$\mathcal{T}_F \sim \frac{r_H}{k_H} E_H. \tag{4}$$

Thus $\mathcal{T}_F \gg \mathcal{T}_P$. For processes involving only soft collisions the distinction between $\mathcal{T}_P$ and $\mathcal{T}_F$ is lost and the single time scale

$$\mathcal{T} \sim \frac{p}{\mu^2}, \tag{5}$$

with $\mu \approx 350$ MeV, occurs.

In general the A-dependence of H, produced in a process having a hard interaction, depends on three factors.

(i) The interaction of the initial projectile system with different nucleons in the nucleus before the hard collision.

(ii) The interaction of the partonic constituents of H with the nucleus or, if $\mathcal{T}_F$ is small enough, the interaction of H itself with the nucleus.

(iii) The interaction of partonic constituents of H with other quarks and gluons, co-moving with the H-system, during times less that $\mathcal{T}_F$. (At times much larger than $\mathcal{T}_F$ all hadronic matter begins to separate from H.)

Since the interaction of co-moving partons with the partons which constitute H is so important for our considerations we shall take a few paragraphs to expand on the physics involved.

The Effect of Co-Movers

Hadrons produced at large transverse momentum collisions, $AB \to H + X$, are described to leading order in $1/p_\perp^2$ by the quark or gluon fragmentation distributions $D_{H/q}(z, p_\perp^2)$ or $D_{H/g}(z, p_\perp^2)$. By QCD factorization these distributions are process-independent and thus independent of effects from the nuclear target or beam.[4] Physically this is due to the long formation time[5] which, for sufficiently large energies E_H, leads to hadron formation outside the nucleus. One can also demonstrate nuclear independence of fragmentation functions as due to coherent cancellation of inelastic processes, such as hard collinear radiation, occurring before and after a soft final state interaction with a nucleon in the nucleus. Soft radiation and multiple elastic scatterings do occur in the nucleus and can give $k_\perp$ smearing of the produced partons and hadrons, but do not affect the inclusive fragmentation functions. This effect is discussed for Drell-Yan processes in Ref. 6.

The inclusive production of heavy quarks from fusion processes, $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$, is predicted by QCD factorization to only depend on the input structure functions.[7] To leading order in the heavy quark mass all effects due to final state interactions are unitary rearrangements of the final state and cannot affect the heavy quark production rate. However, when the heavy quark is produced in the beam direction it can interact strongly with co-moving partons and hadrons, for example the forward-moving spectator partons of the beam hadron or nucleus which have nearly the same velocity as the produced Q or $\bar{Q}$.[8] This interaction can strongly modify the

local momentum distribution of the Q or $\bar{Q}$ relative to the tree-graph calculation. A QED-inspired model which demonstrates this effect is discussed in Ref. 8.

The interaction of the produced Q and $\bar{Q}$ with co-moving hadrons can clearly have a severe effect on the production of *individual* heavy quark states at low $p_\perp$. For example the coalescence of the charm quark with beam spectators can increase the production rate of $c\bar{q}$ or cqq states at the expense of $c\bar{c}$ formation.[9]

Strong final state interaction effects, such as coalescense, occur most strongly when particles have low relative velocity and thus minimum invariant mass.[10] (In the case of QED Coulomb interactions, distributions depend on $\frac{\pi\alpha}{v_{rel}}$.) Kinematically the invariant mass, M^2, of a set of particles $i = 1, 2, \ldots n$ is given by $(P^+ = P^0 + P^z)$

$$\frac{M^2 + P_\perp^2}{P^+} = \sum_{i=1}^{n} \frac{m_i^2 + k_{\perp i}^2}{k_i^+} \tag{6}$$

with $\sum_i k_{\perp i} = P_\perp$ and $\sum k_i^+ = P^+$. M^2 is minimized for

$$x_i = \frac{k_i^+}{P^+} = \frac{m_{\perp i}}{\sum_{j=1}^{n} m_{\perp j}} \tag{7}$$

where $m_\perp^2 = k_\perp^2 + m^2$. Equation (7) corresponds to particles $1, \ldots n$ having equal rapidity. Thus a light quark will interact strongly with a heavy quark if $\frac{x_q}{x_Q} \sim \frac{m_{\perp q}}{m_{\perp Q}}$.

Photo- and Electroproduction of ρ-mesons

We begin by considering a quasi-exclusive ρ-meson electroproduction at large Q^2. By quasi-elastic we mean here that the ρ carries almost all the longitudinal momentum of the incident virtual photon, leaving a large rapidity gap between the ρ and the next fastest particle, in the laboratory system. Then if the incident photon has momentum $q = (\sqrt{\mathbf{q}^2 - Q^2}\, 0, 0|\mathbf{q}|) \approx (q - mx, 0, 0, q)$, with m the nucleon mass and x the usual Bjorken variable, $\mathcal{T}_P = \frac{q}{Q^2} = \frac{1}{2mx}$, while $\mathcal{T}_F \approx (2-3) fm \cdot q$ with q in GeV. Thus at high energy the physical ρ is invariably formed outside the target, even when the target is a large nucleus. Unless x is very small the production of the quark-antiquark pair, which ultimately becomes the ρ, occurs locally in the nucleus. The $(q\bar{q})$ system remains small in transverse size as it passes through the nucleus and expands to the normal size of the ρ far outside the nucleus and far ahead of any of the target fragments which may be produced. Thus we would expect minimal deviations from an A^1-dependence, outside the forward coherent production peak. Small deviations might arise from non-additivity effect in the nucleus such as contribute, for example, to the usual EMC effects.[11] If one neglects these, presumably small, effects and attempts to extract a ρ-nucleon cross section, $\sigma_{\rho N}$, by using the standard[12] eikonal form

$$A_{\text{eff}} = \int_0^R 2\pi b\, db\, n \int_{-\sqrt{R^2-b^2}}^{\sqrt{R^2-b^2}} e^{-\sigma_{\rho N}\left[\sqrt{R^2-b^2}+z\right]n}\, dz \tag{8}$$

with $n(b,q)$ the nuclear density and R the radius of the nucleus, one should find $\sigma_{\rho N}$ to be very small, because what passes through the nucleus is not a ρ but a compact, color neutral $q\bar{q}$ pair which interacts very weakly with nuclear matter.

Now let us turn to quasi-exclusive photoproduction (diffraction production) or ρ-mesons at small $p_\perp$. In this case one does not distinguish between $\mathcal{T}_P$ and $\mathcal{T}_F$, and the unique scale over which the ρ is produced is $\mathcal{T} \sim p/\mu^2$. Again the ρ is not formed locally in the nucleus, but now there is no short-distance cross section involved so the system which passes over the nucleus, $(q\bar{q})$, $(q\bar{q}+n \text{ gluons})\cdots$, is strongly interacting. Thus outside of the coherent production peak at very small momentum transfers, $p_\perp \lesssim 1/R$, we expect quasi-exclusive events to be strongly suppressed, with an A-dependence closer to $A^{\frac{1}{3}}$ than to A^1.[12]

If one now allows $p_\perp$ to grow, again in quasi-exclusive photoproduction of ρ's, a hard interaction occurs with $\mathcal{T}_P \approx p/p_\perp^2$ and $\mathcal{T}_F \approx p/\mu^2$ and, so long as $p/\mu \gg 1$, the hadronic system which passes over the nucleus is of small size and interacts weakly. An A-dependence close to A^1 is expected. There are alternative, and equivalent, ways of defining what is meant by quasi-exclusive in this case. One may require absence of a beam jet or one may require that the wide angle produced ρ not have any accompanying high energy particles along the same direction, that is one may require that the ρ form a jet of a single particle.

J/ψ Production on Nuclei

The production of heavy quarkonium states such as J/ψ in collisions involving nuclei can test many fundamental features of QCD. The simplifying features of such reactions is that the underlying production subprocess involves heavy quark pair production at small transverse distances, $r_\perp \lesssim 1/M_Q$. We shall discuss the nuclear dependence of a number of processes ranging from quasi-elastic $p\bar{p} \to J/\psi$ production on nuclei to quasi-exclusive and inclusive photoproduction reactions, to fully inclusive J/ψ production in nucleus-nucleus collisions. This last process has become especially interesting recently because of the suggestion that the attenuation of J/ψ production in ion-ion collisions relative to lepton-pair background might provide a signal for quark-gluon plasma formation.[13] We shall show here that such attenuation is a natural feature of inclusive nuclear reactions independent of the state of the nuclear matter. We[14] also show that the cross section for J/ψ scattering on nucleons cannot be extracted from high energy photoproduction or hadroproduction reactions.

We begin with a description of quasi-elastic J/ψ photoproduction on a nucleus illustrated in Fig. 1. (We assume that the momentum transfer is sufficiently large that coherent production on the nucleus can be neglected.) To leading order in the heavy quark mass the photon couples directly to the heavy quark. As discussed earlier the production time for the $c\bar{c}$ system, in the target rest frame, is quite short

$$\mathcal{T}_P \cong \frac{1}{M}\frac{p_\gamma}{M} \sim 10 \text{ GeV}^{-1} = 2fm \tag{9}$$

even at $p_\gamma \sim 100$ GeV. The formation time required for the cc to separate to a transverse size comparable to the radius of the J/ψ is

$$\mathcal{T}_P \cong \frac{r_{J/\psi}}{v_\perp} \sim \frac{\frac{1}{2}fm}{\frac{1}{2}\text{GeV}/p_\gamma} \sim 1fm\ p_\gamma(\text{GeV}). \tag{10}$$

Thus even at $p_\gamma \sim 10$ GeV the J/ψ state is produced outside the nucleus. Since the $c\bar{c}$ system remains a color singlet as it traverses the nucleus, we expect small initial and final state interactions; aside from EMC-type deviations of the structure function one thus predicts

$$A_{\text{eff}} = \frac{\sigma(\gamma A \to J/\psi\ A^*)}{\sigma(\gamma N \to J/\psi\ N^*)} \cong A. \tag{11}$$

Let us contrast this result with the conventional eikonal analysis. There one uses (8), with $\sigma_{\rho N}$ replaced by $\sigma_{J/\psi N}$, corresponding to the J/ψ being created at impact parameter b and longitudinal coordinate z with respect to the center of the nucleus. This formulation assumes that the physical J/ψ particle is produced immediately after the creation of the $c\bar{c}$ pair. In fact the formation time is so long that what passes through the nucleus is not a normal J/ψ and hence the effective cross section, σ, extracted using (8) has little to do with J/ψ scattering on a nucleon. The present photoproduction and hadroproduction experiments have not determined the physical J/ψ-nucleon cross section.[14] J/ψ production experiments from SLAC[15] ($E_{J/\psi} \sim 20$ GeV) and Fermilab ($E_{J/\psi}$ up to about 200 GeV)[16] find $A_{\text{eff}} \sim A^{0.95}$, close to, but below complete additivity. This corresponds to an extracted cross section, using (8), of about 1-2 mb. It is not clear whether there is a significant energy dependence of this cross section.

What then causes $A_{\text{eff}}/A < 1$? The $c\bar{c}$ system, at the time of production, might have a size large enough to account for a cross sewction of about a mb. In the low energy SLAC experiment the c and $\bar{c}$ might separate enough to provide some (additional) attenuation. At the x-values probed in the present experiments shadowing of the initial parton distribution is presumably small. The remaining possibility is final state interactions of the J/ψ with co-moving spectators. Such interactions, described in some detail earlier, could be very important in inclusive J/ψ production, but should be absent in quasi-exclusive production where the requirement of a large rapidity gap eliminates the co-movers.

The effect of co-movers on final state hadronization clearly will be negligible if one studies J/ψ production at high $p_\perp \gtrsim 1-2$ GeV. At high $p_\perp$ we expect $A_{\text{eff}} \sim A^{1.0}$ except for the possible effect of non-additivity of the input gluon distributions. (Also at higher $p_\perp$ the $c\bar{c}$ system is produced with a smaller color dipole moment and should interact more weakly with the nuclear matter it passes through on its way to hadronization.) At low $p_\perp$ the coalescence of the c and $\bar{c}$ with co-moving quarks and gluons could account for the enhancement of large x_F charm hadron production and leading particle correlations at the expense of J/ψ production and other channels.

The effect of co-movers on the production of heavy quarkonium states is clearly enhanced in the case of production by nuclear beams. For example the forward production of J/ψ may be strongly depleted in an ion-ion collision relative to the continuum lepton-pair production because of the increased density of co-moving partons from the beam. In contrast to predictions based on the existence of a quark-gluon plasma, this depletion should occur whether the target be a proton or a nucleus! We urge that heavy ion beam experiments be carried out on hydrogen or light nuclei where plasmas are not expected to be formed. In the end it may be that a plasma is more effective than normal hadronic matter in depleting J/ψ production, but we feel that *if* such is the case it is a *quantitative* rather than a *qualitative* difference and hence will be useful as a plasma formation signal only when quantitative control over hadronic reactions is achieved.

Color Transparency and J/ψ Production in $\bar{p}A$ Collisions

Many novel features of QCD, including color transparency, can be studied by measuring quasi-exclusive J/ψ production by anti-protons on a nuclear target. Unlike J/ψ electroproduction this process could provide direct information on the J/ψ-nucleon cross section. We are particularly interested in the quasi-exclusive annihilation process $\bar{p}A \to J/\psi(A-1)'$ where the nucleus, $A-1$, is left in a ground or excited state, but no extra hadrons are produced. The cross section involves a convolution with the distribution of protons in the nucleus A, $G_{p/A}(y)$, where $y = \frac{p^o+p^z}{p^o_A+p^z_A}$ is the Lorentz-invariant light-cone fractions of momentum carried by the proton. This distribution can be measured in quasi-exclusive lepton-nucleus scattering $\ell A \to \ell p(A-1)'$.

In first approximation $\bar{p}p \to J/\psi$ involves $qqq + \bar{q}\bar{q}\bar{q}$ annihilation into three gluons as shown in Fig. 2. The transverse momentum integrations are controlled by the charm mass scale and thus only the Fock state of the incident anti-proton which contains three anti-quarks at small impact separation can annihilate. Since this state has a relatively small color dipole moment it should have a longer than usual mean-free path in nuclear matter. This is the central idea of "color transparency." Thus, unlike traditional expectations, QCD predicts that the $\bar{p}p$ annihilation into charmonium is not restricted to the front surface of the nucleus.[17] The exact nuclear dependence also depends on the formation time for the physical $\bar{p}$ to couple to the small $\bar{q}\bar{q}\bar{q}$ configuration,

$$\tau \sim \frac{r_p}{k_p} E_p.$$

It may be possible to study the effect of finite formation time by varying the beam energy, E_p, and using the Fermi-motion of the nucleon to stay at the J/ψ resonance energy.

Since the J/ψ is produced at non-relativistic velocities in this low energy experiment, the J/ψ is formed inside the nucleus. The study of the A-dependence of this quasi-exclusive reaction can thus be used to determine the J/ψ-nucleon cross section at low energies. For a normal hadronic reaction $\bar{p}A \to HX$ one expects $A_{\rm eff} \sim A^{\frac{1}{3}}$ corresponding to absorption in the initial and final state. In the case of $\bar{p}A \to J/\psi x$ one

expects $A_{\rm eff}$ to be closer to A^1 if color transparency is fully effective and if $\sigma(J/\psi, N)$ is small.

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FIGURE CAPTIONS

Figure 1: A schematic picture of J/ψ production in a nucleus indicating with he production time, τ_p, and formation time, τ_F, indicated.

Figure 2: The dominant mechanism for $p\bar{p}$ exclusive annihilation into J/ψ.

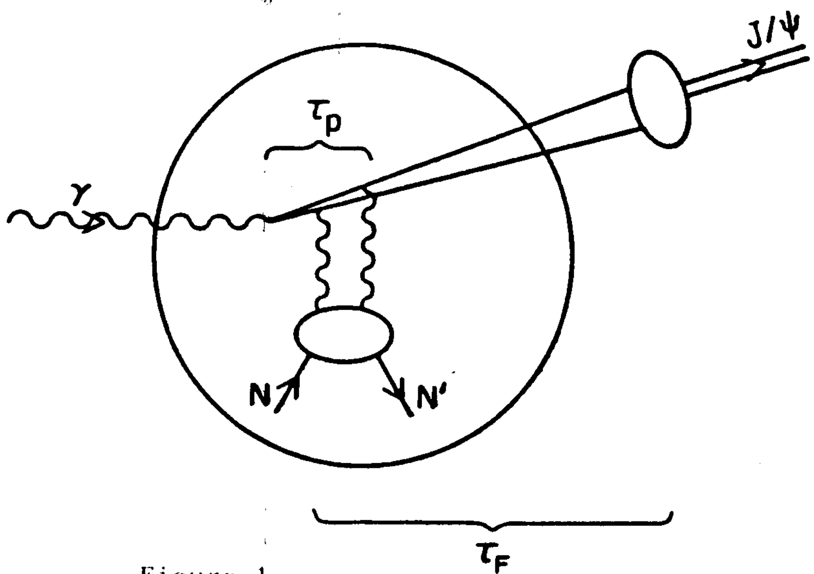

Figure 1

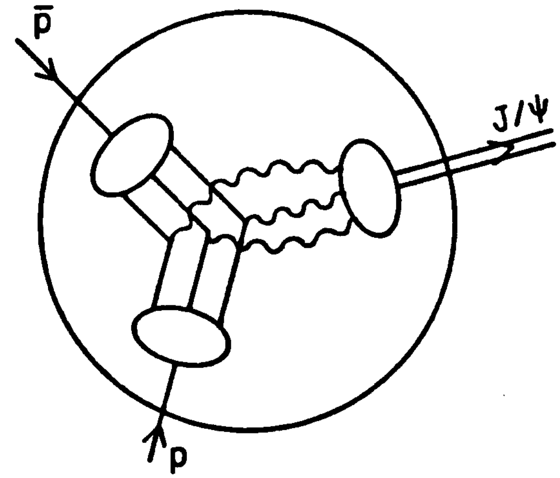

Figure 2