COMOVER ENHANCEMENT OF QUARKONIUM PRODUCTION

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Abstract
Quarkonium data suggest an enhancement of the hadroproduction rate from interactions of the heavy quark pair with a comoving color field generated in the hard $gg \rightarrow Q\bar{Q}$ subprocess. We review the motivations and principal consequences of this comover enhancement scenario (CES).

1. THE QUARKONIUM THERMOMETER
The production of heavy $Q\bar{Q}$ quarkonia has the potential of offering valuable insights into QCD dynamics, complementary to those given by open heavy flavor production. In both cases, the creation of the heavy quark pair requires an initial parton collision of hardness $O(m_Q)$. Most of the time the heavy quarks hadronize independently of each other and are incorporated into separate hadrons. The QCD factorization theorem exploits the conservation of probability in the hadronization process to express the total heavy quark production cross section in terms of target and projectile parton distributions and a perturbative subprocess cross section such as $\sigma(gg \rightarrow Q\bar{Q})$.

The quarkonium cross section is a small fraction of the open flavor one and is thus not constrained by the standard QCD factorization theorems [1]. Nevertheless, it is plausible that the initial creation of the heavy quarks is governed by the usual parton distributions and hard subprocess cross sections, with the invariant mass of the $Q\bar{Q}$ pair constrained to be close to threshold. Before the quarkonium emerges in the final state there can, however, be further interactions which, due to the relatively low binding energy, can either “make or break” the bound state. Quarkonium studies can thus give new information about the environment of hard production, from the creation of the heavy quark pair until its “freeze-out”. The quantum numbers of the quarkonium state furthermore impose restrictions on its interactions. Thus states with negative charge conjugation ($J/\psi$, $\psi'$) or total spin $J = 1$ ($\chi_{c1}$) require the $Q\bar{Q}$ pair to interact at least once after its creation via $gg \rightarrow Q\bar{Q}$.

Despite an impressive amount of data on the production of several quarkonium states with a variety of beams and targets we still have a poor understanding of the underlying QCD dynamics. Thus quarkonia cannot yet live up to their potential as ‘thermometers’ of $A+B$ collisions, where $A, B = \gamma^{(*)}$, hadron or nucleus. Rather, it appears that we need simultaneous studies and comparisons of several processes to gain insight into the production dynamics.

We will now summarize the successes and failures of the Color Singlet Model [2, 3], which we consider as a guideline for understanding the nature of the quarkonium production dynamics.

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2. SUCCESSES AND FAILURES OF THE COLOR SINGLET MODEL

In the Color Singlet Model (CSM), the $Q\bar{Q}$ pair is directly prepared with the proper quantum numbers in the initial hard subprocess and further interactions are assumed to be absent. The quarkonium production amplitude is then given by the overlap of the non-relativistic wave function with that of the $Q\bar{Q}$ pair.

This model at NLO correctly predicts the normalization and momentum dependence of the $J/\psi$ photoproduction rate \cite{2, 5}. While the absolute normalization of the CSM prediction is uncertain by a factor of $2 - 3$ there appears to be no need for any additional production mechanism, for longitudinal momentum fractions $0.3 \leq x_F \leq 0.9$ and $1 \leq p_T^2 \leq 60 \text{ GeV}^2$. The comparison with leptoproduction data \cite{1} is less conclusive since only LO CSM calculations exist.

The CSM underestimates the directly produced $J/\psi$ and $\psi'$ hadroproduction rates by more than an order of magnitude. This is true both at low $p_T \lesssim m_c$ (fixed target) \cite{2} and at high $p_T \gg m_c$ (collider) \cite{6} data. Similar discrepancies for the $\Upsilon$ states \cite{3, 4, 5} indicate that the anomalous enhancement does not decrease quickly with increasing quark mass.

The inelastic cross section ratio $\sigma(\psi')/\sigma_{\text{dir}}(J/\psi)$ is similar in photoproduction \cite{10} and hadroproduction \cite{11, 12} and consistent with the value $\approx 0.24$ expected in the CSM \cite{14}. The ratio does not depend on $x_F$ in the projectile fragmentation region and is independent of the nuclear target size in $hA$ collisions. The CSM thus underestimates the $J/\psi$ and $\psi'$ hadroproduction cross sections, as well as that of the $\chi_{c1}$ \cite{14}, by similar large factors. The quantum numbers of these charmonium states require final-state gluon emission in the CSM, $gg \to J/\psi g$. This emission is not required for the $\chi_{c2}$ where the CSM cross section $\sigma(gg \to \chi_{c2})$ is only a factor $\sim 2$ below the hadroproduction data \cite{14}.

In the CSM, $\chi_c$ photoproduction is suppressed by a power of $\alpha_s$ compared to the $J/\psi$ and $\psi'$ production rates. One indeed observes a smaller value of the $\sigma(\chi_{c2})/\sigma(J/\psi)$ ratio in photoproduction \cite{15} than in hadroproduction \cite{16, 19}.

3. THE COMOVER ENHANCEMENT SCENARIO (CES)

The analysis of agreements and discrepancies between the CSM and quarkonium data led to the comover enhancement scenario of quarkonium production \cite{13, 19}. Hadroproduced $Q\bar{Q}$ pairs are created within a comoving color field and form $J/\psi$, $\psi'$ and $\chi_{c1}$ through gluon absorption rather than emission, enhancing the cross section relative to the CSM since the pair gains rather than loses energy and momentum. The $\chi_{c2}$ cross section is not as strongly influenced since no gluon needs to be absorbed or emitted. Most importantly, such a mechanism is consistent with the success of the CSM in photoproduction since no color fields are expected in the photon fragmentation region, $x_F \gtrsim 0.3$.

The effect of a comoving color field is illustrated in Fig. 1. Light charged particles carry gauge fields which are radiated in high energy annihilations into a heavy particle pair. In $e^+ e^- \to \mu^+ \mu^-$ annihilations, the photon fields pass through each other and materialize as forward bremsstrahlung, Fig. 1(a). In $gg \to Q\bar{Q}$, on the other hand, the self-interaction of the color field can also result in the creation of a gluon field at intermediate rapidities, Fig. 1(b). Hadroproduced $Q\bar{Q}$ pairs thus find themselves surrounded by a color field. We postulate that interactions between the $Q\bar{Q}$ pair and this comoving field are important in quarkonium hadroproduction. In direct photoproduction, the incoming photon does not carry any color field and the $Q\bar{Q}$ pair is left in a field-free environment after the collision, Fig. 1(c). The proposed rescattering thus does not affect photoproduction.

The importance of rescattering effects in hadroproduction as compared to photoproduction is also suggested by data on open charm production. Hadroproduced $D\bar{D}$ pairs are almost uncorrelated in azimuthal angle \cite{20}, at odds with standard QCD descriptions. Photoproduced pairs on the other hand, emerge nearly back-to-back \cite{21}, following the charm quarks of the underlying $\gamma g \to c\bar{c}$ process.

Since the hardness of the gluons radiated in the creation process increases with quark mass, the rescattering effect persists for bottomonium. Due to the short timescale of the radiation the heavy quark pair remains in a compact configuration during rescattering and overlaps with the quarkonium wave
function at the origin. The successful CSM result for \( \sigma(\psi')/\sigma_{\text{dir}}(J/\psi) \) \cite{14} is thus preserved.

The \( Q\bar{Q} \) pair may also interact with the more distant projectile spectators after it has expanded and formed quarkonium. Such spectator interactions are more frequent for nuclear projectiles and can cause the breakup (absorption) of the bound state. This conventional mechanism of quarkonium suppression in nuclei is thus fully compatible with, but distinct from, interactions with the comoving color field.

We have investigated the consequences of the CES using pQCD to calculate the interaction between the \( Q\bar{Q} \) and the comoving field. While we find consistency with data, quantitative predictions depend on the structure of the comoving field. Hence tests of the CES must rely on its generic features which we discuss below.

4. GENERIC FEATURES

The CES distinguishes three proper timescales in quarkonium production:

- \( \tau_Q \sim 1/m_Q \), the \( Q\bar{Q} \) pair production time;
- \( \tau_{AP} \), the DGLAP scale over which the comoving field is created and interacts with the \( Q\bar{Q} \) pair;
- \( \tau_\Lambda \sim 1/\Lambda_{\text{QCD}} \), while rescattering with comoving spectators may occur.

In the following we will consider quarkonium production at \( p_\perp \lesssim m_Q \). In quarkonium production at \( p_\perp \gg m_Q \), a large \( p_\perp \) parton is first created on a timescale \( 1/p_\perp \), typically through \( gg \to gg^* \). The virtual gluon then fragments, \( g^* \to Q\bar{Q} \), in proper time \( \tau_Q \). Thus high \( p_\perp \) quarkonium production is also based on the CES \cite{20}.

4.1 Timescale \( \tau_Q \sim 1/m_Q \): creation of the \( Q\bar{Q} \) pair

The \( Q\bar{Q} \) pair is created in a standard parton subprocess, typically \( gg \to Q\bar{Q} \), at a time scale \( \tau_Q \sim 1/m_Q \). This first stage is common to other theoretical approaches such as the Color Evaporation Model (CEM) \cite{23, 24, 25} and non-relativistic QCD \cite{26, 27}, here referred to as the Color Octet Model (COM).
The momentum distribution of the $Q\bar{Q}$ is determined by the product of projectile ($A$) and target ($B$) parton distributions, such as $g_A(x_1)g_B(x_2)$ where $A, B$ may be a lepton, photon, hadron or nucleus. This production process is consistent with the quarkonium data.

According to pQCD the $Q\bar{Q}$ is dominantly produced in a color octet, $S = L = 0$ configuration, close to threshold. Such a state can obtain the quarkonium quantum numbers through a further interaction which flips a heavy quark spin and turns the pair into a color singlet. The amplitude for processes of this type are suppressed by the factor $k/m_Q$ where $k$ is the momentum scale of the interaction. The various theoretical approaches differ in the scale assumed for $k$.

CSM: Here $k = O(m_Q)$. Thus $J/\psi$ production proceeds via the emission of a hard gluon in the primary process, $gg \rightarrow Q\bar{Q} + g$. The $\chi_{c2}$ is produced without gluon emission, $gg \rightarrow \chi_{c2}$, through a subdominant $S = L = 1$ color singlet production amplitude.

COM: The $Q\bar{Q}$ quantum numbers are changed via gluon emission at the bound state momentum scale $k = O(\alpha_s m_Q)$. This corresponds to an expansion in powers of the bound state velocity $v = k/m_Q$, introducing nonperturbative matrix elements that are fit to data.

CES: Here $k = O(\Lambda_{QCD})$. Soft interactions are postulated to change the $Q\bar{Q}$ quantum numbers with probabilities that are specific for each quarkonium state but independent of kinematics, projectile and target.

CES: The quantum numbers of the $Q\bar{Q}$ are changed in perturbative interactions with a comoving field at scale $k = O(1/\tau_{AP})$, as described below.

4.2 Timescale $\tau_{AP}$: interactions with the comoving field

The scale $\tau_{AP}$ refers to the time in which collinear bremsstrahlung, the source of QCD scaling violations, is emitted in the heavy quark creation process [13]. Thus $1/\tau_{AP}$ characterizes the effective hardness of logarithmic integrals of the type $\int_{\mu_F}^{m_Q} dk/k$ where $\mu_F \ll m_Q$ is the factorization scale. We stress that $1/\tau_{AP}$ is an intermediate but still perturbative scale, $\tau_Q \ll \tau_{AP} \ll \tau_A$, which grows with $m_Q$.

The fact that the $Q\bar{Q}$ pair acquires the quarkonium quantum numbers over the perturbative timescale $\tau_{AP}$ is a feature of the CES and distinguishes it from other approaches. At this time, the pair is still compact and couples to quarkonia via the bound state wavefunction at the origin or its derivative(s). Thus no new parameters are introduced in this transition. However, the interactions of the $Q\bar{Q}$ pair depend on the properties of the comoving color field such as the intensity and polarization. Quantitative predictions in the CES are only possible when the dependence on the comoving field is weak.

Ratios of radially excited quarkonia, such as $\sigma(\psi')/\sigma_{\text{dist}}(J/\psi)$, are insensitive to the comoving field and are thus expected to be process-independent when absorption on spectators at later times can be ignored, see below. The fact that this ratio is observed to be roughly universal [12, 13] is one of the main motivations for the CES. Even the measured variations of the ratio in different reactions agree with expectations, see Ref. [28] for a discussion of its systematics in elastic and inelastic photoproduction, leptoproduction and hadroproduction at low and high $p_{\perp}$.

The ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ is measured to be $0.6\pm0.3$ in pion-induced [23] and $0.31\pm0.14$ in proton-induced [24] reactions. The CSM underestimates this ratio [14] as well as that of $\sigma(J/\psi)/\sigma(\chi_2)$ [14]. The rescattering contribution increases $\sigma(J/\psi)$ and $\sigma(\chi_1)$, enhancing the above ratios.

4.3 Nuclear target dependence

The quarkonium cross section can be influenced by rescattering effects in both the target and projectile fragmentation regions. For definiteness, we assume the charmonium is produced in the projectile fragmentation region, $x_F > 0$.

The nuclear target dependence is usually parametrized as $\sigma(hA \rightarrow J/\psi + X) \propto A^\alpha$. It turns out that $\alpha < 1$ and obeys Feynman scaling, i.e., $\alpha$ decreases with $x_F$ rather than with the momentum fraction $x_2$ of the target parton [31, 32]. The comparison with lepton pair production in the Drell-Yan process
shows that the $J/\psi$ nuclear suppression cannot be attributed to shadowing of parton distributions in the nucleus [13]. The $A$-dependence is thus difficult to explain in the CSM, COM and CEM approaches.

In the Feynman scaling regime, we may assume that the $Q\bar{Q}$ pair energy is high enough to remain compact while traversing the target. The relative transverse momentum of the $Q$ and $\bar{Q}$ could increase as a result of rescattering in the target, thus suppressing the binding probability. However, this explanation is unlikely in view of the absence of nuclear suppression in photoproduction [13].

In the CES, the nuclear target suppression is ascribable to absorption of the comoving color field in the target nucleus. This field is emitted by a projectile parton with transverse size $\tau_{AP}$, larger than the size, $\sim 1/m_Q$, of the $Q\bar{Q}$ pair. Due to Lorentz time dilation, the field is emitted long before reaching the target and reinteracts with the $Q\bar{Q}$ long after passing the target. Absorption of the comoving field in the target implies suppression of $J/\psi$ production in the CES. At high energies, we have $x_1 \simeq x_F$, which explains the Feynman scaling of this effect. Moreover, as $x_F$ increases, less energy is available to be radiated to the gluon field which therefore becomes softer, further increasing its absorption in the target and thus the nuclear suppression.

This explanation is consistent with the fact that the nuclear target suppression of the $J/\psi$ and the $\psi'$ is found to be the same for $x_F \gtrsim 0.2$ [32]. It also predicts that the suppression will be similar for $\chi_{c1}$ production. On the other hand, the nuclear target suppression should be reduced for $\chi_{c2}$ since a substantial fraction is directly produced without a comoving field. A measurement of $\sigma(hA \to \chi_c + X)$ in the projectile fragmentation region would thus constitute an important test of the CES.

In a Glauber picture of the nuclear suppression, a relatively large value for the absorption cross section is required, $\sigma_{abs} \sim 5 \text{ mb}$. We interpret this value as the joint cross section of the $Q\bar{Q}$ pair and the comoving field, thus of order $\tau_{AP}^2 \gg 1/m_Q^2$. Since $1/\tau_{AP}$ scales with $m_Q$, we expect less nuclear absorption for the $\Upsilon$ states than for the $J/\psi$, as observed experimentally [34, 35].

### 4.4 Timescale $\tau_\Lambda \sim 1/\Lambda_{QCD}$: interactions with comoving spectators

By the time, $\tau_\Lambda \sim 1 \text{ fm}$, that the $Q\bar{Q}$ pair encounters comoving projectile spectators, the pair has already expanded and is distributed according to the quarkonium wave function. The spectator rescattering effects are thus independent of the quarkonium formation process. Larger and more loosely bound charmonia are more easily broken up by secondary scattering. Hence the $\chi_c$ and $\psi'$ cross sections should be depleted compared to that of the $J/\psi$. Likewise bottomonium is generally less affected by spectator interactions than charmonium.

Spectator interactions at large enough $x_F$ are likely to be unimportant for hadron projectiles judging from the approximate universality of the $\sigma(\psi')/\sigma_{dir}(J/\psi)$ ratio in photo- and hadroproduction. The lower ratio seen in nucleus-nucleus collisions [34], on the other hand, is most naturally explained by absorption on spectators. It would be important to confirm this by also measuring the ratio in $Ah$ scattering.

### 5. SUMMARY

Data on quarkonium production have proved challenging for QCD models. The richness of the observed phenomena indicates that quarkonium cross sections are indeed sensitive to the environment of the hard QCD scattering. We may, however, only be able to decipher its message through systematic experimental and theoretical studies of several species of quarkonia produced with a variety of beams and targets in a range of kinematic conditions.

It is thus useful to begin by asking fairly general questions about the production mechanism before fitting detailed models to data. This is the spirit of the comover enhancement scenario that we have discussed here, motivated by apparent regularities of the data and general theoretical constraints.
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