Phenomenology of $x_F$ Dependence of Quarkonium Production in Proton-Nucleus Interactions

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Abstract
We present a phenomenological study of the $x_F$ dependence of quarkonium production in high-energy proton-nucleus collisions. The $x_F$ dependence of comover contributions is introduced to account for the observed quarkonium suppression at low $x_F$. Combining comover contributions, nuclear shadowing effect, energy loss mechanism and nuclear absorption together we reproduce the overall $x_F$ dependence of E772/E789 data.

I. Introduction
A strong suppression of charmonium ($J/\psi, \psi'$) and bottomonium ($\Upsilon_{1S, 2S+3S}$) production has been observed in p-A collisions on heavy relative to light nuclear targets. Special attention has been paid to the significant suppressions at low (small or negative) and high $x_F$ regions. The suppression at low $x_F$ is usually believed to come from nuclear absorption and comover contributions. The maximum contribution of nuclear absorption to the $J/\psi$ suppression was studied in Ref. [5], and it was found that nuclear absorption alone cannot account for the $J/\psi$ suppression measured in either p-A or A-B collisions. Since at E772 energy most of physical bound states are formed well outside target nucleus due to the Lorentz dilation of the formation time, nuclear absorption can contribute little to the observed suppression at low $x_F$ region. While comovers can continue to interact well outside the nuclear volume, they may in principle play a more important role in proton-nucleus collisions, although the number of comovers in p-A reactions is not so large as in A-B collisions. In the literatures comover contributions are generally estimated in the central rapidity region without $x_F$ dependence. To our knowledge there is no direct explanation of the E772/E789 data at $x_F \approx 0$ and below. In this work we use a simple model to derive the rapidity distribution of comovers for p-A reactions from p-p data, introducing the $x_F$ dependence of comover contributions, to explain the E772/E789 data.

On the other hand, several mechanisms have been proposed to account for the suppression at large $x_F$. Among those, nuclear shadowing effect alone is argued to be unable to explain the data. The intrinsic charm model was expected to explain this $x_F$ dependence. However, E789 data of $J/\psi$ production at very large $x_F$ show no evidence of intrinsic charm contribution. The energy loss mechanism could account for the observed suppression at large $x_F$. Nevertheless, the amount of energy loss needed to explain E772 $J/\psi$ data appears

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to be significantly larger than the value determined from other considerations.\textsuperscript{[11]} In our work, we combine energy loss mechanism together with nuclear shadowing effect, nuclear absorption and comover contributions, and reproduce the large $x_F$ data with a smaller amount of energy loss.

II. Comover Contributions

In the case of quarkonium production, e.g., $J/\psi$ production, in proton-nucleus collisions, comoving secondary particles can scatter with the $c\bar{c}$ pair, and contribute to the observed $J/\psi$ suppression. These comover contributions have been studied in the literatures.\textsuperscript{[8,12–14]} However, since the shape of the rapidity density of the comovers in inclusive $J/\psi$ production for p–A collisions is unknown, comover density is usually estimated in the central rapidity region, and taken as a constant independent of the comover rapidity. In this work we will use a simple model to derive the rapidity distribution of comovers for p–A reactions from p–p data.\textsuperscript{[6]} Assuming that comovers with rapidity close to the rapidity of a $c\bar{c}$ pair can cause the breakup of the $c\bar{c}$ pair, we translate the rapidity distribution of comovers into $x_F$ distribution, and include the resultant $x_F$ dependence of comover contributions to explain the E772/E789 low $x_F$ data. We will follow the works of Refs [8] and [14], and improve the treatment of comover contributions.

Including only the comover contributions, the $x_F$ dependent cross section of $J/\psi$ production in p–A collisions can be expressed as

$$
\frac{d\sigma_{PA}}{dx_F} = \frac{d\sigma_{pp}}{dx_F} \int d^2 b \int_{-\infty}^{+\infty} dz \rho_A(b,z) \exp\left\{- \int_{\tau_0}^{\tau_f} d\tau \sigma_{co} v n(\tau, b) \right\},
$$

(1)

where $\rho_A$ is the nuclear density profile, $\sigma_{co}$ is the $(c\bar{c})$-comover absorption cross section, $\tau_0$ is the formation time of comovers, $\tau_f$ is the effective proper time over which the comovers can interact with $c\bar{c}$ pair, $v$ is the relative velocity of $c\bar{c}$ with the comovers, and $n(\tau, b)$ is the density of comovers at the proper time $\tau$ and impact parameter $b$.

Assuming Bjorken's hydrodynamics,\textsuperscript{[15]} the comover density varies with the proper time according to

$$
n(\tau) = \tau_0 n(\tau_0)/\tau.
$$

(2)

The comovers consist mostly of $\pi$, $\rho$ and $\omega$ mesons. We relate $n$, the density of comovers, to $n_{ch}$, the density of produced charged particles, by $n = f n_{ch}$. For example, $f \simeq 1.5$ if comovers are all $\pi$'s with equal numbers of $\pi^+$, $\pi^-$ and $\pi^0$.

The charged particle density at $\tau_0$ can be related to rapidity distribution by

$$
n_{ch}(\tau_0, b) = \frac{1}{\sigma_{in}\tau_0} \frac{dN_{ch}^{PA}(b)}{dy},
$$

(3)

where $\sigma_{in} \simeq 30$ mb is the nucleon-nucleon inelastic scattering cross section.

Now we use the so-called independent cluster model\textsuperscript{[16]} to derive the charged particle rapidity distribution for p–A reactions from p–p data.\textsuperscript{[6]}

We fit the data at $\sqrt{s} = 45.2$ GeV, which is close to the E772 energy, in the form,

$$
\frac{dN_{ch}^{pp}}{d\eta} = W \exp\left\{- \frac{(\eta + \eta_0)^2}{\delta} \right\} + W \exp\left\{- \frac{(\eta - \eta_0)^2}{\delta} \right\}
$$

(4)

with $W=1.75$, $\eta_0=1.5$ and $\delta=2.9$.

In the framework of the independent cluster model, we have

$$
\frac{dN_{ch}^{PA}(b)}{d\eta} = \nu(b) W \exp\left\{- \frac{(\eta + \eta_0)^2}{\delta} \right\} + W \exp\left\{- \frac{(\eta - \eta_0)^2}{\delta} \right\},
$$

(5)

where $\nu(b) = \sigma_{in} \int dz \rho_A(b, z)$ is the number of target participants at the impact parameter $b$.

In order to introduce the $x_F$ dependence of comover contributions, we assume that those comovers with rapidity close to the rapidity of a $J/\psi$ can cause the breakup of the $J/\psi$, ...
and we relate the rapidity of $J/\psi$ in the center-of-mass system to $x_F$, which is defined as $x_F = P_{L}^*/(P_{L}^*)_{\max}$, by
\[ y^* = \frac{1}{2} \ln\left[ \frac{(E^* + P_{T}^*)/(E^* - P_{T}^*)}{(E^* + P_{T}^*)/(E^* - P_{T}^*)} \right], \]
where $E^*$ and $P_T^*$ are the energy and longitudinal momentum of $J/\psi$ in the center-of-mass system.

In our approach to the $x_F$-dependent comover density two main parameters are $f$ and $\tau_0$. In Fig. 1 we show the $x_F$ dependence of comover densities for various sets of $f$ and $\tau_0$. Note that the dotted curve with $f = 1.5 \times 0.6$ and $\tau_0 = 0.8$ fm is plotted in view of the argument of Ref. [12], which represents a comover density too low to explain the data. In our further calculations we will fix $f = 1.5$. The comover formation time has been estimated to be about $0.4 \sim 1.2$ fm/c, the time scale of both quark and hadron formation in the early stages of the collision.[17,18] It can be seen from Fig. 1 that the comover density is sensitive to the choice of $\tau_0$. In the next section we will vary $\tau_0$ and $\sigma_{co}$ to attribute the observed suppression at low $x_F$ region to comover contributions.

Since comovers can interact with the produced heavy quarks $Q$ or $\bar{Q}$ before the quarkonium bound state can be formed, and the interaction is independent of whether or not the heavy quark pair is produced as a color octet or singlet, we expect that for charmonium production the $(cc)$-comover interaction cross section is the same for the $J/\psi$ and $\psi'$ bound states. Furthermore, the comover contributions are expected to be independent of the final hadronic size. As a result, although we expect the occurrence of significant comover absorptions with strong nuclear dependence, the $J/\psi$ and $\psi'$ production would have the same nuclear dependence under comover absorption, which is consistent with the earlier experimental observation.[3]

III. Combination of Mechanisms, Numerical Results and Discussions

In this section we combine comover contributions, nuclear absorption, nuclear shadowing effect and energy loss mechanism to reproduce the overall $x_F$ dependence of E772/E789 data on $J/\psi$ and $\Upsilon$ production.

We will calculate $x_F$ dependence of $\alpha$ for $J/\psi$ and $\Upsilon$ production in the parametrization,
\[ \frac{d\sigma^p}{dx_F} = \frac{d\sigma^{pp}}{dx_F} A^\alpha(x_F). \]
For $J/\psi$ production, we make use of the fact that about 60% of the final $J/\psi$'s are produced directly, about 30% come from intermediate states and the remaining 10% are produced through the decay of $\psi'$. Analogously, about 41% of the final $\Upsilon$'s are produced directly, about 35% and 18% come from the decay of $\chi_b$ and $\chi_b'$, about 5% and 1% are produced through the decay of $\Upsilon_{2S}$ and $\Upsilon_{3S}$.

The cross section of quarkonium production in p-A collisions is

$$\frac{d\sigma^{PA}}{dx_F} = \frac{d\sigma^{PP}}{dx_F} \int d^2b \int_{-\infty}^{+\infty} dz \rho_A(b,z) \exp \{- \int_z^{\infty} dz' \rho_A(b,z') \sigma_{abs}(z'-z)\} \times$$

$$\exp \{- \int_{\tau_0}^{\tau_F} d\tau \sigma_{cnv}(\tau,b)\},$$

where several mechanisms have been included.

The averaged nucleon-nucleon cross section of p-A reactions, $\sigma^{PP}$, in Eq. (8), is the same as the bare nucleon-nucleon cross section except that in $\sigma^{PP}$ the distribution functions of the gluon, quark and antiquark within the target nucleus are nuclear modified. We follow Ref. [20] to incorporate the shadowing effect into $\sigma^{PP}$, and use parameters determined in Ref. [8].

The first exponential in Eq. (8) represents the contribution of nuclear absorption. We take the values of parameters in the following way: the formation time of charmonia and bottomonia, $\tau_0 = 0.89$ fm, $\tau_T = 0.76$ fm, etc., is taken from Ref. [21], the absorption cross section between resonances and nucleon is chosen as

$$\sigma_{RN} = \sigma_{\psi N}(r_N/r_\psi)^2$$

with $\sigma_{\psi N} = 6$ mb, and the radii of resonances $r_N$ taken from Ref. [21]. In particular, we want to point out that with the reason discussed in the first section, the nuclear absorption can contribute very little suppression even with a rather large absorption cross section $\sigma_{\psi N} = 6$ mb, as indicated by the fact that the nuclear dependence of $J/\psi$ and $\psi'$ production is the same within errors.

We follow Ref. [10] to include the contribution of energy loss mechanism in our calculations. In Ref. [10] only energy loss mechanism is taken into account, and an upper bound of energy loss is obtained, $dE/dZ \approx 1.5$ GeV/fm. Moreover, the energy loss contribution in Ref. [10] has not been normalized, which implies an integrated suppression. In our calculations, we complete the normalization in a similar way as in Ref. [22],

$$\frac{d\sigma^{PA}}{dx_F}(x_F) \bigg|_{\text{normal.}} = \frac{1}{\alpha} \frac{d\sigma^{PA}}{dx_F} \left( \frac{x_F}{\alpha} \right),$$

where $\alpha = x_F/(x_F + \Delta x_F)$, and $\Delta x_F$ is the shift of $x_F$ due to the energy loss. Since nuclear shadowing effect can also contribute to the quarkonium production suppression at large $x_F$, in our calculation a value of $dE/dZ \approx 0.5$ GeV/fm is found to be able to fit the data quite well, which is consistent with the value obtained from other considerations.

The comover contributions are included in the second exponential in Eq. (8). We take the effective proper time $\tau_F = r_0/c_s$, where $r_0$ is the projectile radius taken the value to be 1.2 fm, and $c_s \approx 1/\sqrt{3}$ (Ref. [8]).

The results of our calculations are compared to E772/E789 data for $J/\psi$ production at 800 GeV/c in Figs 2 and 3, with different sets of $\sigma_{co}$ and $\tau_0$. We find that $\sigma_{co} = 4.0$ mb and $\tau_0 = 0.8$ fm/c are the best fit which correspond to a comover density with maximal value about 6 fm$^{-3}$. Figure 2 shows that a lower density (larger $\tau_0$) is not sufficient to explain the data. In Fig. 3 we see that a comover absorption cross section $\sigma_{co}$ smaller than 4.0 mb is also insufficient to fit the data. Note that the dot-dashed curve in Fig. 3 corresponds to the case without comover contributions. The curve illustrates a very small contribution of nuclear absorption at low $x_F$, as we expected. One can find in Fig. 3 that although the number of comovers is not very large in p-A reactions, comover interactions have a much more important
effect than nuclear absorption.

![Graph](image1)

**Fig. 2.** $x_F$ dependence for $J/\psi$ production from E772/E789. The curves compare our calculations to the data, with a fixed $\sigma_{co} = 4.0$ mb and various values of $T_0$.

![Graph](image2)

**Fig. 3.** $x_F$ dependence for $J/\psi$ production from E772/E789. The curves compare our calculations to the data, with a fixed $T_0 = 0.8$ fm/c and $\sigma_{co} = 4.0$ mb, 2.0 mb. The dot-dashed line corresponds to the case without comover contributions.

A comparison of our calculations for $\Upsilon$ production with the E772 data is shown in Fig. 4. The dashed curve with $\sigma_{co} = 4.0$ mb and $T_0 = 0.8$ fm/c is somehow lower than the experimental points at $x_F \approx 0.3$. This may imply our over-estimate of comover contributions when we fit the data at low $x_F$ region.

In the literatures studies of nucleus-nucleus reactions indicated that the comover density at an early stage of the collision is very high, possibly from 1 to 5 fm$^{-3}$. In our work, a comover density with a maximum $\sim 6$ fm$^{-3}$ is used when we fit the E772/E789 data at low $x_F$. With such a high density one would rather think of these comovers as light quarks and antiquarks than as pions and low-mass resonances.[14] However, whether it is possible to obtain such a high density in proton-nucleus collisions seems to be questionable. Presumably some new mechanism might also contribute at low $x_F$ region.

According to Ref. [23], absorption in confined hadronic matter is excluded as a possible cause of the $J/\psi$ suppression observed in nucleus-nucleus collisions. Since at low $x_F$ region neither energy loss nor nuclear shadowing effect is important, it seems difficult to understand the low $x_F$ suppression in proton-nucleus collisions, in which no deconfined matter is expected. Our work shows that comover interactions play an important role at the low $x_F$ region, and a comover absorption cross section as large as 4 mb is needed to confront the E772/E789 data. In addition, a recent work observed that nuclear antishadowing leads to enhanced $J/\psi$ production at low $x_F$, which is in contradiction with the E772/E789 data.[24] These issues suggest that the low $x_F$ suppression in p-A reactions deserves careful studies, and possibly requires some new mechanisms.

To summarize, we have reproduced the overall $x_F$ dependence of quarkonium production in proton-nucleus collisions, by combining comover contributions, nuclear shadowing effect, nuclear absorption and energy loss mechanism together. In particular, by including the $x_F$ dependence of comover distribution we show that comover interactions have a very important effect when one attempts to explain the observed quarkonium suppression, especially at low $x_F$ region, in proton nucleus collisions. However, our work indicates that a fairly high density
of comovers is needed to explain the E772/E789 low $x_P$ suppression, which might imply some new mechanisms occurring in this region as well.

![Graph](image)

**Fig. 4.** Our calculations of $x_P$ dependence for bottomonium production with different sets of $\sigma_{co}$ and $\tau_0$ are compared to the E772 data.

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