Intrinsic Charm Contribution to Double Quarkonium Hadroproduction*

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Double J/ψ production has been observed by the NA3 collaboration in πN and pN collisions with a cross section of the order of 20-30 pb. The $\psi\psi$ pairs measured in π^- nucleus interactions at 150 and 280 GeV/c are observed to carry an anomalously large fraction of the projectile momentum in the laboratory frame, $x_{\psi\psi} \geq 0.6$ at 150 GeV/c and ≥ 0.4 at 280 GeV/c. We postulate that these forward $\psi\psi$ pairs are created by the materialization of Fock states in the projectile containing two pairs of intrinsic $c\overline{c}$ quarks. We calculate the overlap of the charmonium states with the $|\overline{u}dc\overline{c}c\overline{c}\rangle$ Fock state as described by the intrinsic charm model and find that the $\pi^- N \rightarrow \psi\psi$ longitudinal momentum and invariant mass distributions are both well reproduced. We also discuss double J/ψ production in pN interactions and the implications for other heavy quarkonium production channels in QCD.

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Introduction

It is quite rare for two charmonium states to be produced in the same hadronic collision. However, the NA3 collaboration has measured a double J/ψ production rate significantly above background in multi-muon events with π^- beams at laboratory momentum 150 and 280 GeV/c [1] and a 400 GeV/c proton beam [2]. The integrated $\pi^- N \to \psi\psi X$ production cross section, $\sigma_{\psi\psi}$, is 18 ± 8 pb at 150 GeV/c and 30 ± 10 pb at 280 GeV/c, and the $pN \to \psi\psi X$ cross section is 27 ± 10 pb. The relative double to single rate, $\sigma_{\psi\psi}/\sigma_\psi$, is $(3 \pm 1) \times 10^{-4}$ for pion-induced production where σ_ψ is the integrated single ψ production cross section.

A particularly surprising feature of the NA3 $\pi^- N \to \psi\psi X$ events is that the laboratory fraction of the projectile momentum carried by the $\psi\psi$ pair is always very large, $x_{\psi\psi} \geq 0.6$ at 150 GeV/c and $x_{\psi\psi} \geq 0.4$ at 280 GeV/c. In some events, nearly all of the projectile momentum is carried by the $\psi\psi$ system. In contrast, perturbative gg and $q\overline{q}$ fusion processes are expected to produce central $\psi\psi$ pairs, centered around the mean value, $\langle x_{\psi\psi} \rangle \approx$ 0.4-0.5, in the laboratory [3–6].

The average invariant mass of the pair, $\langle M_{\psi\psi} \rangle = 7.4$ GeV, is well above the $2m_\psi$ threshold. In fact, all the events have $M_{\psi\psi} > 6.7$ GeV. The average transverse momentum of the pair is quite small, $p_{T,\psi\psi} = 0.9 \pm 0.1$ GeV, suggesting that $\psi\psi$ pair production is highly correlated [1,2]. The proton events have a somewhat lower invariant mass, $\langle M_{\psi\psi} \rangle \approx 6.8$ GeV. The $x_{\psi\psi}$ distribution for the $pN \to \psi\psi X$ events has not been reported.

There have been attempts to explain the NA3 data within conventional leading-twist QCD. Charmonium pairs can be produced by a variety of QCD processes including $B\overline{B}$ production and decay, $B\overline{B} \to \psi\psi X$ [3] and $\mathcal{O}(\alpha_s^4)$ $\psi\psi$ production via gg fusion and $q\overline{q}$ annihilation [4–6]. Li and Liu have also considered the possibility that a $2^{++}c\overline{c}c\overline{c}$ resonance is produced which then decays into correlated $\psi\psi$ pairs [7]. All of these models predict centrally produced $\psi\psi$ pairs [3–6], in contradiction to the π^- data. In addition, the predicted magnitude of $\sigma_{\psi\psi}$ is too small by a factor of 3-5. If these models are updated using recent branching ratios and current scale-dependent parton distributions, the predicted leading twist cross sections are further reduced [8], suggesting that an additional mechanism is needed to produce fast $\psi\psi$ pairs.

We also note that strong discrepancies between conventional QCD predictions and experiment have recently been observed for ψ, ψ', and Υ production at large p_T in high energy $p\overline{p}$ collisions at the Tevatron [9]. Braaten and Fleming [10] have suggested that this surplus of charmonium production is due to the enhanced fragmentation of gluon jets coupling to the octet $c\overline{c}$ components in higher Fock states $|c\overline{c}gg\rangle$ of the charmonium wavefunction. However, this explanation does not explain the NA3 $\psi\psi$ fixed target data since the color-octet mechanism still emphasizes central production.

In this paper we shall explore an alternative higher-twist production mechanism in QCD where forward single and double ψ's are created through the materialization of intrinsic $c\overline{c}$ Fock components of the pion or proton projectile [11]. In such states the heavy constituents tend to carry the majority of the projectile momentum since this minimizes the off-shell energy of the wavefunction. We find that the $\psi\psi$ momentum and mass distributions are reasonably well described by the overlap of the charmonium states with the $|\overline{u}dc\overline{c}c\overline{c}\rangle$ Fock configuration postulated in the intrinsic heavy quark model.

The QCD wavefunction of a hadron can be represented as a superposition of quark and gluon Fock states. For example, at fixed light-cone time, $\tau = t + z/c$, the π^- wavefunction can be expanded as a sum over the complete basis of free quark and gluon states: $|\Psi_{\pi^-}\rangle = \sum_m |m\rangle\, \psi_{m/\pi^-}(x_i, k_{T,i}, \lambda_i)$ where the color-singlet states, $|m\rangle$, represent the Fock components $|\overline{u}d\rangle$, $|\overline{u}dg\rangle$, $|\overline{u}dQ\overline{Q}\rangle$, *etc.* The boost-invariant light-cone wavefunctions, $\psi_{m/\pi^-}(x_i, k_{T,i}, \lambda_i)$, needed to compute probability distributions, are functions of the relative momentum coordinates $x_i = k_i^+/P^+$ and $k_{T,i}$. Momentum conservation demands $\sum_{i=1}^n x_i = 1$ and $\sum_{i=1}^n \vec{k}_{T,i} = 0$, where n is the number of partons in a Fock state $|m\rangle$. When the projectile scatters in the target, the coherence of the Fock components is broken, its fluctuations can hadronize, forming new hadronic systems from the fluctuations [12]. For example, intrinsic $c\overline{c}$ fluctuations can be liberated provided the system is probed during the characteristic time, $\Delta t = 2p_{\rm lab}/M^2_{c\overline{c}}$, that such fluctuations exist.

Microscopically, the intrinsic heavy quark Fock component in the π^- wavefunction, $|\overline{u}dQ\overline{Q}\rangle$, is generated by virtual interactions such as $gg \to Q\overline{Q}$ where the gluons couple to two or more projectile valence quarks. The probability for $Q\overline{Q}$ fluctuations to exist in a light hadron thus scales as $\alpha_s^2(m_Q^2)/m_Q^2$ relative to leading-twist production [13]. Therefore, this contribution is higher twist, suppressed by $\mathcal{O}(1/m_Q^2)$ compared to sea quark contributions generated by gluon splitting. In $(1+1)$ QCD the Fock state representation of each hadron can be computed explicitly, including its intrinsic $Q\overline{Q}$ configurations, by diagonalizing a discrete form of the light-cone Hamiltonian [14].

In general, the dominant Fock state configurations are not far off shell and thus have minimal invariant mass, $M^2 = \sum_i m_{T,i}^2/x_i$ where $m_{T,i} = \sqrt{k_{T,i}^2 + m_i^2}$ is the transverse mass of the $i^{\rm th}$ particle in the configuration. Intrinsic $Q\overline{Q}$ Fock components with minimum invariant mass correspond to configurations with equal rapidity constituents. Thus, unlike sea quarks generated from a single parton, intrinsic heavy quarks tend to carry a larger fraction of the parent momentum than the light quarks [11]. In fact, if the intrinsic $Q\overline{Q}$ coalesces into a quarkonium state, the momentum of the two heavy quarks is combined so that the quarkonium state will carry a significant fraction of the projectile momentum. It was shown that large x_F virtual $c\overline{c}$ or lepton pairs can be liberated by a relatively soft interaction with a light quark component of the projectile [12]. For soft interactions at momentum scale μ, the intrinsic heavy quark cross section is suppressed by a resolving factor $\propto \mu^2/m_Q^2$ [13].

There is substantial circumstantial evidence for the existence of intrinsic $c\overline{c}$ states in light hadrons. For example, the charm structure function of the proton measured by EMC is significantly larger than predicted by photon-gluon fusion at large x_{Bj} [15]. Leading charm production in πN and hyperon-N collisions also requires a charm source beyond leading twist [13,16]. The NA3 experiment has also shown that the single J/ψ cross section at large x_F is greater than expected from gg and $q\overline{q}$ production [17]. Additionally, intrinsic charm may account for the anomalous longitudinal polarization of the J/ψ at large x_F [18] seen in $\pi N \to J/\psi X$ interactions.

Over a sufficiently short time, the pion can contain Fock states of arbitrary complexity. For example, two intrinsic $c\overline{c}$ pairs may appear simultaneously in the quantum fluctuations of the projectile wavefunction and then, freed in an energetic interaction, coalesce to form a pair of ψ's. We shall estimate the creation probability of $|n_V c\overline{c}c\overline{c}\rangle$ Fock states, where $n_V = d\overline{u}$ for π^- and $n_V = uud$ for proton projectiles, assuming that all of the double J/ψ events arise from these configurations. We then examine the $x_{\psi\psi}$ and invariant mass distributions of the $\psi\psi$ pairs and the x_ψ distribution for the single ψ's arising from these Fock states.

Intrinsic Charm Fock States

The probability distribution for a general n–particle intrinsic $c\overline{c}$ Fock state as a function of x and $\vec{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\overline{c}})\, \frac{\delta(\sum_{i=1}^n \vec{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2} \; , \tag{1}$$

where N_n normalizes the Fock state probability. In the model, the vertex function in the intrinsic charm wavefunction is assumed to be relatively slowly varying; the particle distributions are then controlled by the light-cone energy denominator and phase space. This form for the higher Fock wavefunctions generalizes for an arbitrary number of light and heavy quark components. The Fock states containing charmed quarks can be materialized by a soft collision in the target which brings the state on shell. The distribution of produced open and hidden charm states will reflect the underlying shape of the Fock state wavefunction.

The invariant mass of a $c\overline{c}$ pair, $M_{c\overline{c}}$, from such a Fock state is

$$\begin{aligned} \frac{dP_{\rm ic}}{dM_{c\overline{c}}^2} &= \int \prod_{i=1}^n dx_i d^2k_{T,i}\, \frac{dx_{c\overline{c}}}{x_{c\overline{c}}}\, d^2k_{T,c\overline{c}}\, \frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}}\, \delta(x_{c\overline{c}} - x_c - x_{\overline{c}}) \\ &\quad \times \delta(\vec{k}_{T,c} + \vec{k}_{T,\overline{c}} - \vec{k}_{T,c\overline{c}})\, \delta\left(\frac{M_{T,c\overline{c}}^2}{x_{c\overline{c}}} - \frac{m_{T,c}^2}{x_c} - \frac{m_{T,\overline{c}}^2}{x_{\overline{c}}}\right) \; , \end{aligned} \tag{2}$$

where $n = 4$ and 5 is the number of partons in the lowest lying meson and baryon intrinsic $c\overline{c}$ Fock states. The probability to produce a J/ψ from an intrinsic $c\overline{c}$ state is proportional to the fraction of intrinsic $c\overline{c}$ production below the $D\overline{D}$ threshold. The fraction of $c\overline{c}$ pairs with $2m_c < M_{c\overline{c}} < 2m_D$ is

$$f_{c\overline{c}/h} = \int_{4m_c^2}^{4m_D^2} dM_{c\overline{c}}^2\, \frac{dP_{\rm ic}}{dM_{c\overline{c}}^2} \Bigg/ \int_{4m_c^2}^{s} dM_{c\overline{c}}^2\, \frac{dP_{\rm ic}}{dM_{c\overline{c}}^2} \; . \tag{3}$$

The ratio $f_{c\overline{c}/\pi}$ is approximately 15% larger than $f_{c\overline{c}/p}$ for $1.2 < m_c < 1.8$ GeV. However, not all $c\overline{c}$'s produced below the $D\overline{D}$ threshold will produce a final-state J/ψ. We include two suppression factors to estimate J/ψ production, one reflecting the number of quarkonium channels available with $M_{c\overline{c}} < 2m_D$ and one for the c and $\overline{c}$ to coalesce with each other rather than combine with valence quarks to produce open charm states. The "channel" suppression factor, $s_c \approx 0.3$, is estimated from direct and indirect J/ψ production, including χ_1 and χ_2 radiative and ψ' hadronic decays. The combinatoric "flavor" suppression factor, s_f, is 1/2 for a $|\overline{u}dc\overline{c}\rangle$ state and 1/4 for a $|uudc\overline{c}\rangle$ state. In Fig. 1 we show the predicted fraction of ψ's produced from intrinsic $c\overline{c}$ pairs,

$$f_{\psi/h} = s_c s_f f_{c\overline{c}/h} \; , \tag{4}$$

as a function of m_c. We take $m_c = 1.5$ GeV, suggesting $f_{\psi/\pi} \approx 0.03$ and $f_{\psi/p} \approx 0.014$.

The nuclear dependence arising from the manifestation of intrinsic charm is expected to be $\sigma_A \approx \sigma_N A^{2/3}$, characteristic of soft interactions. Indeed, in their single J/ψ measurements [17], the NA3 collaboration defined a separate "diffractive" cross section at large x_F scaling like $A^{0.77}$ for πA and $A^{0.71}$ for pA interactions. We thus identify the diffractive cross section with $\sigma_{\rm ic}^{\psi}$, as in our previous study [19]. The intrinsic $c\overline{c}$ production cross section from an $|n_V c\overline{c}\rangle$ configuration,

$$\sigma_{\rm ic}(hN) = P_{\rm ic}\sigma_{hp}^{\rm in} \, \frac{\mu^2}{4\widehat{m}_c^2} \; , \tag{5}$$

was estimated in Ref. [13] to be $\sigma_{\rm ic}(\pi N) \approx 0.5$ μb and $\sigma_{\rm ic}(pN) \approx 0.7$ μb for a beam momentum of 200 GeV. At low x_F, a different, nearly linear, A dependence was observed. The ratio of diffractive to total J/ψ production can then be determined from the NA3 data [17]. The soft interaction scale parameter [21], $\mu^2 \sim 0.2$ GeV^2, is thus fixed by the assumption that the diffractive fraction of the total production cross section is the same for charmonium and charmed hadrons.

The diffractive J/ψ cross section is $(18 \pm 3)\%$ of the total $\pi A \rightarrow J/\psi$ production cross section and $(29 \pm 6)\%$ of the $pA \rightarrow J/\psi$ production [17]. The cross sections in the $J/\psi \rightarrow \mu^+\mu^-$ channel are $B\sigma_\psi(\pi^- N) = 6.5 \pm 0.6$ nb at 150 GeV and $B\sigma_\psi(pN) = 3.6 \pm 0.6$ nb at 200 GeV. Removing the branching ratio [17], then implies $\sigma_{\rm ic}^{\psi}(\pi^- N) = 15.7 \pm 3.0$ nb and $\sigma_{\rm ic}^{\psi}(pN) = 14.3 \pm 3.3$ nb. The proton cross section should be regarded as an upper bound since the bulk of this cross section is at $x_F < 0.2$ where the intrinsic charm contribution is expected to be small. Using the data for $x_F > 0.2$ suggests a lower bound, $\sigma_{\rm ic}^{\psi}(pN) = 5.6 \pm 1.3$ nb. We relate $\sigma_{\rm ic}^{\psi}$ to the intrinsic $c\overline{c}$ production cross section by

$$\sigma_{\rm ic}^{\psi}(hN) = f_{\psi/h}\sigma_{\rm ic}(hN) \; . \tag{6}$$

Using the estimates of $\sigma_{\rm ic}(\pi N)$ from Ref. [13] with the values of $f_{\psi/h}$ in Eq. (4), we find $\sigma_{\rm ic}^{\psi}(\pi^- N) = 15$ nb and $\sigma_{\rm ic}^{\psi}(pN) = 9.8$ nb, in agreement with the NA3 single ψ data[1].

Double J/ψ Production from Intrinsic Charm Fock States

If one assumes that all of the NA3 double J/ψ events arise from intrinsic $|n_V c\overline{c}c\overline{c}\rangle$ Fock states, then the required normalization for this state can be determined from

$$\sigma_{\rm ic}^{\psi\psi}(hN) = f_{\psi/h}^2 \, \frac{P_{\rm icc}}{P_{\rm ic}} \, \sigma_{\rm ic}(hN) = f_{\psi/h} \, \frac{P_{\rm icc}}{P_{\rm ic}} \, \sigma_{\rm ic}^{\psi}(hN) \tag{7}$$

where $P_{\rm icc}$ is the probability to produce a pair of intrinsic $c\overline{c}$ states in the projectile. Then $\sigma_{\psi\psi} \equiv \sigma_{\rm ic}^{\psi\psi}(\pi^- N) \approx 20$ pb [1], requiring $P_{\rm icc} \approx 4.4\%$ $P_{\rm ic}$. If $P_{\rm icc}$ is independent of the projectile, then we predict $\sigma_{\rm ic}^{\psi\psi}(pN) \approx 6$ pb, which is 20% of the measured cross section [2], but consistent with our previous calculations [13]. If, instead, the ratio $\sigma_{\psi\psi}/\sigma_\psi$ [1] is assumed to be independent of the projectile, the cross section increases to 14.6 pb, more compatible with the data and $P_{\rm icc} \approx 10.6\%$ $P_{\rm ic}$. Finally, if we assume $\sigma_{\rm ic}^{\psi\psi}(pN) = 27$ pb, as suggested by the data of Ref. [1], then we require $P_{\rm icc} \approx 20\%$ $P_{\rm ic}$. Note that the probability of making a second intrinsic $c\overline{c}$ pair is relatively easy once one $c\overline{c}$ is present in the Fock state.

The $\psi\psi$ invariant mass distributions measured by NA3 [1,2] are shown in the histograms of Fig. 2. The pair mass distribution predicted from the $|n_V c\overline{c}c\overline{c}\rangle$ Fock state is

$$\begin{aligned} \frac{dP_{\rm icc}}{dM^2_{\psi\psi}} &= \int \prod_{i=1}^n dx_i d^2k_{T,i} \prod_{j=1}^2 \frac{dx_{\psi_j}}{x_{\psi_j}} \, dm^2_{\psi_j} d^2k_{T,\psi_j} \, \frac{dx_{\psi\psi}}{x_{\psi\psi}} \, d^2k_{T,\psi\psi} \, \frac{dP_{\rm icc}}{\prod_{i=1}^n dx_i d^2k_{T,i}} \\ &\times \delta\left(\frac{m^2_{T,\psi_j}}{x_{\psi_j}} - \frac{m^2_{T,c_j}}{x_{c_j}} - \frac{m^2_{T,\overline{c}_j}}{x_{\overline{c}_j}}\right) \delta(\vec{k}_{T,c_j} + \vec{k}_{T,\overline{c}_j} - \vec{k}_{T,\psi_j})\delta(x_{\psi_j} - x_{c_j} - x_{\overline{c}_j}) \\ &\times \delta\left(\frac{M^2_{T,\psi\psi}}{x_{\psi\psi}} - \frac{m^2_{T,\psi_1}}{x_{\psi_1}} - \frac{m^2_{T,\psi_2}}{x_{\psi_2}}\right) \delta(\vec{k}_{T,\psi_1} + \vec{k}_{T,\psi_2} - \vec{k}_{T,\psi\psi})\delta(x_{\psi\psi} - x_{\psi_1} - x_{\psi_2}) \; , \end{aligned} \tag{8}$$

[1] We use $B(J/\psi \rightarrow \mu^+\mu^-) \approx 7.4\%$ for consistency with the NA3 measurements. If $B(J/\psi \rightarrow \mu^+\mu^-) \approx 6\%$ is used instead, the single cross sections increase by 20%.

where $n = n_V + 4$ and

$$\frac{dP_{\rm icc}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n[\alpha_s^4(M_{c\overline{c}})]^2 \ \frac{\delta(\sum_{i=1}^n \vec{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2} \ . \tag{9}$$

The delta functions insure conservation of momentum for both J/ψ mesons and the $\psi\psi$ pair. Here, $2m_c < m_\psi < 2m_D$ and $m_c = 1.5$ GeV. In Fig. 2 the predictions for the $\psi\psi$ pair mass distributions are compared with the $\pi^- N$ (a) and pN (b) data and normalized to the data. Without any k_T dependence, the mass distribution is strongly peaked at threshold. The k_T dependence smears out the pair distribution, increasing $\langle M_{\psi\psi}\rangle$ by $0.5 - 1.0$ GeV. We find $\langle M_{\psi\psi}\rangle \approx 7.7$ GeV for the pion beam and $\langle M_{\psi\psi}\rangle \approx 7.4$ GeV for the proton beam. The intrinsic charm model is very successful in reproducing the strongly correlated features of the data. The smaller value of $\langle M_{\psi\psi}\rangle$ in pN interactions also agrees with the trend of the data [1,2].

Although the $\vec{k}_T$ dependence is needed to calculate the mass distributions, it is sufficient to use a mean value of k_T^2 to calculate the x distributions since the shapes of the longitudinal momentum distributions are essentially independent of the transverse momentum. Then the x distributions from an $|n_V c\overline{c}c\overline{c}\rangle$ state, following Eq. (1), can be written as

$$\frac{dP_{\rm icc}}{dx_i \cdots dx_n} = N_n[\alpha_s^2(M_{c\overline{c}})]^2 \ \frac{\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (\widehat{m}_i^2/x_i))^2} \ , \tag{10}$$

where again $n = n_V + 4$ and $\widehat{m}_i = \sqrt{m_i^2 + \langle \vec{k}_{T,i}^2\rangle}$ is the average transverse mass. Assuming $\langle \vec{k}_{T,i}^2\rangle$ is proportional to the square of the constituent quark mass, we adopt the effective values $\widehat{m}_c = 1.8$ GeV and $\widehat{m}_q = 0.45$ GeV, as in our previous work [19,20]. The x_ψ distribution for a single J/ψ in a $|n_V c\overline{c}c\overline{c}\rangle$ state is

$$\frac{dP_{\rm icc}}{dx_{\psi_1}} = \int \prod_{i=1}^n dx_i dx_{\psi_2} \ \frac{dP_{\rm icc}}{dx_1 \ldots dx_n} \ \delta(x_{\psi_1} - x_{c_1} - x_{\overline{c}_1})\delta(x_{\psi_2} - x_{c_2} - x_{\overline{c}_2}) \ . \tag{11}$$

We find $\langle x_\psi\rangle = 0.36$ for the pion projectile and $\langle x_\psi\rangle = 0.33$ for the proton. The number of single J/ψ's is twice the number of $\psi\psi$ pairs. The single J/ψ distributions from the $|n_V c\overline{c}c\overline{c}\rangle$ state have a lower average x_ψ than those from $|n_V c\overline{c}\rangle$ Fock states, where $\langle x_\psi\rangle = 0.62$ for a pion and $\langle x_\psi\rangle = 0.51$ for a proton [17,19]. The pair distribution can be computed from

$$\frac{dP_{\rm icc}}{dx_{\psi\psi}} = \int dx_{\psi_1} \ \frac{dP_{\rm icc}}{dx_{\psi_1}} \ \delta(x_{\psi\psi} - x_{\psi_1} - x_{\psi_2}) \ . \tag{12}$$

The intrinsic charm model predicts $\langle x_{\psi\psi}\rangle = 0.72$ for the pion and $\langle x_{\psi\psi}\rangle = 0.64$ for the proton. We compare the frame-independent calculation to histograms of the combined 150 and 280 GeV data assuming $x_\psi = p_{\rm lab}^\psi/p_{\rm beam}$ in Figure 3. The $\psi\psi$ pair distributions are shown in Fig. 3(a) and 3(c) and the associated the single J/ψ distributions in pair events are shown in Fig. 3(b) and 3(d). Both are normalized to the data with the single J/ψ normalization twice that of the pair.

Other Tests of the Intrinsic Heavy Quark Mechanism

The intrinsic charm model provides a natural explanation of double J/ψ hadroproduction and thus gives strong phenomenological support for the presence of intrinsic heavy quark states in hadrons. While the general agreement with the intrinsic charm model is quite good, the excess events at medium $x_{\psi\psi}$ suggests that intrinsic charm may not be the only $\psi\psi$ QCD production mechanism present or that the model parameterization with a constant vertex function is too oversimplified. The $x_{\psi\psi}$ distributions can also be affected by the A dependence. Additional mechanisms, including an update of previous models [3–7], will be presented in a separate paper [8].

The intrinsic heavy quark model can also be used to predict the features of heavier quarkonium hadroproduction, such as $\Upsilon\Upsilon$, $\Upsilon\psi$, and $(\overline{b}c)(\overline{c}b)$ pairs. Using $\widehat{m}_b = 4.6$ GeV, we find that the single Υ and $\Upsilon\Upsilon$ pair x distributions are similar to the equivalent $\psi\psi$ distributions. The average mass, $\langle M_{\Upsilon\Upsilon}\rangle$, is 21.4 GeV for pion projectiles and 21.7 GeV for a proton, a few GeV above threshold, $2m_\Upsilon = 18.9$ GeV. The $x_{\Upsilon\psi}$ pair distributions are also similar to the $\psi\psi$ distributions but we note that $\langle x_\Upsilon\rangle = 0.44$ and $\langle x_\psi\rangle = 0.30$ from a $|\overline{u}dc\overline{c}b\overline{b}\rangle$ configuration and $\langle x_\Upsilon\rangle = 0.39$ and

$\langle x_\psi \rangle = 0.27$ from a $|uudc\overline{c}b\overline{b}\rangle$ configuration. Here $\langle M_{\Upsilon\psi} \rangle = 14.9$ GeV with a pion projectile and 15.2 GeV with a proton, again a few GeV above threshold, $m_\Upsilon + m_\psi = 12.6$ GeV.

It is clearly important for the double J/ψ measurements to be repeated with higher statistics and also at higher energies. The same intrinsic Fock states will also lead to the production of multi-charmed baryons in the proton fragmentation region. It is also interesting to study the correlations of the heavy quarkonium pairs to search for possible new four-quark bound states and final state interactions generated by multiple gluon exchange [7]. It has been suggested that such QCD Van der Waals interactions could be anomalously strong at low relative rapidity [22,23].

There are many ways in which the intrinsic heavy quark content of light hadrons can be tested. More measurements of the charm and bottom structure functions at large x_F are needed to confirm the EMC data [15]. Charm production in the proton fragmentation region in deep inelastic lepton-proton scattering is sensitive to the hidden charm in the proton wavefunction. The presence of intrinsic heavy quarks in the hadron wavefunction also enhances heavy flavor production in hadronic interactions near threshold. More generally, the intrinsic heavy quark model leads to enhanced open and hidden heavy quark production and leading particle correlations at high x_F in hadron collisions with a distinctive strongly-shadowed nuclear dependence characteristic of soft hadronic collisions.

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Figure Captions

Figure 1. The fraction of intrinsic $c\overline{c}$ states below the $D\overline{D}$ threshold that produce J/ψ's is given as a function of charmed quark mass for pion (solid) and proton (dashed) projectiles.

Figure 2. The calculated $\psi\psi$ mass distributions, Eq. (8), are compared with histograms of the NA3 data [1,2] from $\pi^- N$ (a) and pN (b) production. The calculations are normalized to the total number of $\psi\psi$ events.

Figure 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.