NOVEL QCD EFFECTS IN THE PRODUCTION AND DECAY OF QUARKONIUM*

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Abstract

There are many outstanding discrepancies comparing the predictions of perturbative QCD and measurements of the rate of production and decay of heavy quark systems. The problems include the $J/\psi \to \rho\pi$ puzzle, leading charmed particle effects, the anomalous behavior of the heavy quark sea components of structure functions, anomalous nuclear target effects, and the large rates observed for single and double quarkonium production at large x_F and large p_T. I argue that these anomalies may be associated with nonperturbative effects in the higher Fock structure of hadron wavefunctions.

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1. Introduction

Heavy quarks act as classical, nonrelativistic color sources, and thus they play an invaluable, simplifying role in illuminating basic features of QCD, such as the nature of hadronic binding and the mechanisms underlying production dynamics. In this talk I will review a number of heavy-quark strong interaction processes which test novel and subtle features of the theory. I also emphasize a number of heavy quark topics in which experiment and theory are apparently discrepant.

2. Quarkonium and the Determination of the QCD Coupling

One of the most important recent developments in the analysis of nonperturbative QCD has been the precise computation of the $c\bar{c}$ and $b\bar{b}$ bound state spectra from lattice gauge theory[1]. In this approach, the exact theory is systematically approximated by an effective Hamiltonian of non-relativistic heavy quarks interacting with the full gauge field. The lattice simulation of the J/ψ and Υ spectrum leads to remarkably precise constraints on the QCD coupling:

$$\alpha_V(8.2\ GeV) = 0.1945(30) \tag{1}$$

from the Υ spectrum, and

$$\alpha_V(8.2\ GeV) = 0.1940(67) \tag{2}$$

from the J/ψ spectrum. Here α_V is the effective coupling defined from the potential for the interaction of two heavy test charges:

$$V(Q^2) = -4\pi\,C_F\,\left(\frac{\alpha_V(Q^2)}{Q^2}\right)\ .$$ (3)

The coupling α_V satisfies the usual QCD renormalization group equation, where the first two perturbative coefficients β_0 and β_1 of the β-function are universal. The running coupling $\alpha_V(Q^2)$ can in turn be used as the basic input to predict other PQCD observable. There are no scale ambiguities when using this coupling since by definition α_V sums all vacuum polarization insertions[2]. Thus this procedure relates observable to observable, eliminating scheme and scale ambiguities. For example, $\alpha_V(\ell^2)$ enters directly into the calculation of the hard scattering amplitude T_H which controls exclusive processes at large momentum transfer, where ℓ^2 is the four-momentum squared carried by the gluons. Another important application is the production of heavy quark systems near threshold[3]. The cross section for the exclusive production $e^+e^- \to Q\overline{Q}$ at low Q-$\overline{Q}$ relative velocities is given by the Born rate multiplied by a Sommerfeld factor

$$S(x) = \frac{x}{1 - e^{-x}}$$ (4)

where

$$x = \pi\,C_F\alpha_V(\vec{p}^{\,2}_{\mathrm{rel}})$$ (5)

is evaluated at the relative momentum $\vec{p}^{\,2}_{\mathrm{ref}} = m_Q^2\,v_{\mathrm{rel}}^2$ of the heavy quarks. The PQCD Sommerfeld factor also leads to a distinctive angular distribution for the $e^+e^- \to c\overline{c}$ and $b\overline{b}$ systems which should be reflected in the θ_{cm} dependence of the corresponding exclusive channels[3].

One can also use the BLM procedure[2] to derive a "commensurate scale relation" [4,1] connecting the effective charge α_V to the standard MS coupling:

$$\alpha_{\overline{MS}}(Q) = \alpha_V(e^{5/6}Q)[1 + (2/\pi)\alpha_V + (0.96 + Cn_F)\alpha_V^2 + \cdots]$$ (6)

The NNLO term has recently been calculated by Lüscher and Weisz[5]. Thus one can use the quarkonium spectrum to predict the MS coupling at any scale; *e.g.,* one finds $\alpha_{\overline{MS}}(M_Z) = 0.117(2)$,[1] assuming that the uncalculated NLO n_F coefficient is zero. This equation also provides an analytic extension of the MS coupling to an effective charge with a quark mass-dependent β-function[6].

3. Anomalies in Charm Hadroproduction

Although most predictions of PQCD are in reasonable agreement with experiment, a number of processes involving charm hadroproduction appear to be glaring exceptions. The following is a partial list of the empirical anomalies together with a brief discussion of their possible cures:

J/ψ production at large p_T. The cross section for the production of J/ψ's at high transverse momentum at the Tevatron is a factor ~ 30 above PQCD predictions

based on gluon fragmentation to a color-singlet $c\bar{c}\,J/\psi$.[7] The production cross sections for other heavy quarkonium states also show similar anomalies. As discussed by Rothstein[8] at this meeting, a possible cure is the hypothesis that the gluon fragmentation proceeds through $c\bar{c}g$ and $c\bar{c}gg$ Fock components in the charmonium light-cone wavefunction in which the charmed pair is in a color-octet configuration. As noted by Magnago[9], one cannot assume that the fragmentation function is a δ-function at $z = 1$, because $g \to J/\psi\,gg$ fragmentation is softened by the presence of spectator gluons with finite momenta in the quarkonium rest frame. The magnitude of the required color-octet matrix elements thus must be somewhat larger than usually assumed and may be in conflict with other constraints, such as J/ψ photoproduction[10].

An alternative and apparently phenomenologically successful hypotheses is the "color evaporation model" [11]. This is a duality approach, where one simply computes the probability in leading twist QCD for the production of charmed pairs with invariant mass below the open charm threshold. It is postulated that the usual constraints of color conservation for hard processes and fragmentation can be ignored; *i.e.,* it is assumed that color is restored via soft interactions with the spectator partons. An important question is whether this approach is consistent with the hard scattering factorization theorem, and whether the leading order rate for Drell–Yan leptons pairs still requires in this scheme the usual $1/N_C$ factor implied by color conservation.

The charm structure functions $c(x,Q^2)$. The charm structure function of the proton measured by the EMC collaboration[12] is some 30 times larger at $x_{Bj} = 0.47$, $Q^2 = 75\,GeV^2$ than that predicted on the basis of photon-gluon fusion $\gamma^* g \to c\bar{c}$. This remarkable anomaly needs to be confirmed by another large x_{Bj} charm and bottom structure function measurements.

The excess charm signal observed by EMC can be explained by the "intrinsic charm" hypotheses[13] where the charm sea is derived from $c\bar{c}$ contributions to the proton light-cone wavefunction[14] beyond gluon splitting. Any Feynman diagram in which the $c\bar{c}$ is multiply-connected to the valence quarks of the proton produces a source of intrinsic charm (IC) in the hadron wavefunction, in distinction to gluon-splitting $g \to c\bar{c}$ "extrinsic charm" diagrams in which the charm quarks are constituents of the gluon rather than the proton itself. A crucial feature of the IC contribution is the fact that the LC wavefunction $c\bar{c}\,uud$ is maximal when the five quarks have minimal invariant mass and are thus at minimal relative rapidity. The heavy quarks thus tend to be produced with the largest momentum fractions, thus accounting for the EMC anomaly. A recent re-analysis of the EMC data by Vogt, Harris, and Smith[15], indicates that the probability of IC in the nucleon is of order $0.6 \pm 0.3\%$. Thus, in general, one must distinguish two distinct types of quark and gluon contributions to the nucleon sea measured in deep inelastic lepton-nucleon scattering: "extrinsic" and "intrinsic" [13]. The extrinsic sea quarks and gluons are created as part of the lepton-scattering interaction and thus exist over a very short time $\Delta\tau \sim 1/Q$. These factorizable contributions can be systematically derived from the QCD hard bremsstrahlung and pair-production (gluon-splitting) subpro-

cesses characteristic of leading twist perturbative QCD evolution. In contrast, the intrinsic sea quarks and gluons are multi-connected to the valence quarks and exist over a relatively long lifetime within the nucleon bound state. Thus the intrinsic $q\bar{q}$ pairs can arrange themselves together with the valence quarks of the target nucleon into the most energetically-favored meson-baryon fluctuations. The enhancement of the heavy quark sea at large momentum fractions where the relative vapidities between the valence and heavy quarks are minimized has also been observed in solutions of QCD(1+1) with two flavors using the discretized light-cone quantization method [16].

Asymmetric sea. In conventional studies of the "sea" quark distributions, it is usually assumed that, aside from the effects due to antisymmetrization with valence quarks, the quark and antiquark sea contributions have the same momentum and helicity distributions. However, the ansatz of identical quark and anti-quark sea contributions has never been justified, either theoretically or empirically. Obviously the sea distributions which arise directly from gluon splitting in leading twist are necessarily CP-invariant; *i.e.,* they are symmetric under quark and antiquark interchange. However, the initial distributions which provide the boundary conditions for QCD evolution need not be symmetric since the nucleon state is itself not CP-invariant. Only the global quantum numbers of the nucleon must be conserved. The intrinsic sources of strange (and charm) quarks reflect the wavefunction structure of the bound state itself; accordingly, such distributions would not be expected to be CP symmetric[17]. Thus the strange/anti-strange asymmetry of nucleon structure functions provides a direct window into the quantum bound-state structure of hadronic wavefunctions.

It is possible to consider the nucleon wavefunction at low resolution as a fluctuating system coupling to intermediate hadronic Fock states such as non-interacting meson-baryon pairs. The most important fluctuations are those closest to the energy shell with minimal invariant mass. For example, the coupling of a proton to a virtual $K^+\Lambda$ pair provides a specific source of intrinsic strange quarks and antiquarks in the proton. Since the s and $\bar{s}$ quarks appear in different configurations in the lowest-lying hadronic pair states, their helicity and momentum distributions are distinct. Recently Ma and I[17] and I have investigated the quark and antiquark asymmetry in the nucleon sea which is implied by a light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs. Such fluctuations are necessarily part of any quantum-mechanical description of the hadronic bound state in QCD and have also been incorporated into the cloudy bag model [18] and Skyrme solutions to chiral theories[19]. We have utilized a boost-invariant light-cone Fock state description of the hadron wavefunction which emphasizes multi-parton configurations of minimal invariant mass. We find that such fluctuations predict a striking sea quark and antiquark asymmetry in the corresponding momentum and helicity distributions in the nucleon structure functions. In particular, the strange and anti-strange distributions in the nucleon generally have completely different momentum and spin characteristics. For example, the model predicts that the intrinsic d and s quarks in the proton sea are negatively polarized, whereas the intrinsic $\bar{d}$ and $\bar{s}$ antiquarks

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provide zero contributions to the proton spin. We also predict that the intrinsic charm and anticharm helicity and momentum distributions are not strictly identical. The above picture of quark and antiquark asymmetry in the momentum and helicity distributions of the nucleon sea quarks has support from a number of experimental observations, and we suggest processes to test and measure this quark and antiquark asymmetry in the nucleon sea.

More recently, Ma and I[20] have noted that the hadronic jet fragmentation of the s and c quarks in electron-positron (e^+e^-) annihilation at the Z^0-boson resonance also provides a laboratory for testing the quark/antiquark asymmetries of the nucleon sea. Crossing symmetry implies that the asymmetries of the $s\bar{s}$ and $c\bar{c}$ pairs of the nucleon sea will be reflected in the nucleon/anti-nucleon asymmetries from the hadronic jet fragmentation of s and c quarks into nucleons and anti nucleons. For example, if one has a pure sample of tagged s jets, then one can look for the difference of $D_{p/s}(z)-D_{\bar{p}/s}(z)$ at large z. Here $D_{h/q}(z)$ is the fragmentation function representing the probability for the quark q splitting into the hadron h and z is the momentum fraction carried by the fragmented hadron from the quark jet.

Anomalous large x_F J/ψ production. The CERN experiment NA3[21] has reported a number of experimental analyses in the hadroproduction of J/ψ's. The most dramatic feature of the NA3 data is the longitudinal momentum distribution of *pairs* of $J/@$'s as determined from $pA \to \mu^+\mu^-\mu^+\mu^- X$ and $\pi A \to \mu^+\mu^-\mu^+\mu^- X$ events. The NA3 data shows that the X_F^{TOT} distribution peaks at the highest X_F^{TOT} bins, where X_F^{TOT} is the sum of the two J/ψ momentum fractions. The observed distributions, although sparse, are in strong contradiction to the prediction based on PQCD fusion processes which peak at small X_F^{TOT}. The NA3 distributions can be reproduced within the intrinsic charm model, assuming that the J/ψ pair events originate from the diffractive excitation of $|uud\,c\bar{c}\,c\bar{c}\rangle$ intrinsic charm Fock state in the proton[13,22]. In such configurations, the four charmed quarks tend to carry almost all of the momentum of the proton. Only a small momentum transfer to the target is necessary to put the multi-charm state on-shell in a high energy collision. Vogt and I[23] have also presented predictions for J/ψ-Υ and Υ-Υ pairs based on intrinsic bottom and charm higher Fock states.

Anomalous nuclear dependence of J/ψ production. The NA3 experimental also reports an anomalous change in the nuclear-number dependence of the $\pi A \to J/\psi\, X$ and $pA \to J/\psi\, X$ cross sections as x_F varies from the central to forward fragmentation regions. The nuclear dependence A^α is found to be the "diffractive-like" at high x_F with $\alpha \simeq 0.71$ for proton beams and $\alpha \simeq 0.77$ for pion beams, which is characteristic of production on the front surface of the nucleus. This observed A-dependence is much stronger than expected from the shadowing of fusion processes or J/ψ absorption and, in any case, is incompatible with PQCD factorization since the A^α dependence is a function of x_F rather than the target parton momentum fraction[24]. The observed nuclear dependence is naturally explained by the postulate that hadroproduction of J/ψ's at large x_F originates from the diffractive excitation of the IC Fock states in the projectile[25]. Since the interaction on the target is soft, the predicted A-dependence is characteristic of conventional hadron-nucleus

interactions. The strong A-dependence of the J/ψ hadroproduction cross section at large x_F is also consistent with recent Fermilab E789 data[26].

An important test of the IC picture can be carried out at HERA in low momentum transfer electron-proton collisions[25]. If the IC description is correct, then quarkonia as well as open charm will be produced at high longitudinal momentum fractions in the proton fragmentation region. Since the electron can strike a valence quark, the kinematics of the produced charm states will be largely insensitive to the magnitude of the momentum transfer Q^2.

Polarization of the J/ψ. The Chicago-Iowa-Princeton collaboration[27] has measured the polarization of the J/ψ in $\pi N \rightarrow J/\psi X$ interactions. The results are rather remarkable. The J/ψ is found to be unpolarized for almost the entire range of x_F, except for the largest bin at $x_F \cong 0.95$ where the polarization changes to strongly longitudinal. Neither the predictions of the color-singlet model[28] nor the color-octet model[29] can account for the absence of polarization at moderate x_F. The strong longitudinal polarization at $x_F \rightarrow 1$ is similar to the pattern observed in the Drell-Yan reactions $\pi N \rightarrow \mu^+ \mu^- X$[27], which can be readily explained in terms of higher twist subprocesses such as $(q\bar{q}) + q \rightarrow \gamma^* \mu^+ \mu^- q$[30].

Open charm hadroproduction, One of the most controversial areas of charm hadroproduction is the data for leading charmed and bottom baryon production at large x_F. Several experiments at the ISR[22] have reported prominent signals for $pp \rightarrow \Lambda_c X$. Similar signals were also reported by the BIS-2 group at Serpukhov[31]. The ISR group of Basile *et al.* observed Λ_b production at large x_F, measuring two decay channels[32], events which are reported by the Particle Data Group[33]. However, these signals appear to imply very large integrated total cross sections for charm and bottom hadroproduction if one extrapolates the large x_F data to all x_F using the standard $(1 - x_F)^n$ form with $n \geq 0$. However, this assumption may be incorrect. An interesting possibility is that the production cross sections $\frac{d\sigma}{dx_F}(pp \rightarrow \Lambda_c X, \Lambda_b X)$ may not be monotonically falling in x_F but instead have a peaked structure of large x_F reflecting the coalescence of intrinsic charm or bottom with the valence quark. The PYTHIA string acceleration mechanism would also produce such a peak from coalescence of the charm quarks with the valence quarks of the projectile. It should be noted that cross sections such as $(\Xi N \rightarrow \Omega X)$ rise dramatically by two orders of magnitude from $x_F \sim 0$ to $x_F \sim 1$.[34] The possibility of a structured distribution in heavy hadron production is now being examined more carefully by Vogt, Quack, and myself[35].

Polarization correlations at the charm threshold. One of the most striking anomalies in QCD is the sudden increase in the polarization correction *ANN* observed by Krisch and his collaborators[36] in large θ_{cm} $pp \rightarrow pp$ elastic scattering at $\sqrt{s} \sim$ 5 *GeV.* Measurements at ANL and BNL show that the rate for elastic scattering at $\theta_{cm} = 90°$ for incident protons polarized parallel and normal to the scattering plane rises to 4 times that for anti-parallel scattering. This seems all the more remarkable since the net correlation of quark felicities with the proton helicity is small when it is determined in inclusive deep inelastic lepton scattering.

A most interesting explanation of the Krisch anomaly is that it reflects the onset

of the charm threshold in the intermediate state[37]. At $\sqrt{s} = 5$ *GeV* there is just enough energy to produce the 8-quark system $uud\,uud\,c\bar{c}$. Since the quarks are all at low relative velocity they can interact strongly. If there is an S-wave resonance of the 8 quarks, it will be produced only if the incident protons have $J = L = S = I.$ In fact, such a state only couples to the incident proton-proton system when the incident proton and polarized parallel are normal to the scattering plane. Guy de Teramond and I[37] have shown that the combination of PQCD quark interchange plus the $uud\,uud\,c\bar{c}$ resonance in the $pp \to pp$ amplitude can account for the Krisch data provided that the cross section for charm production $pp \to c\bar{c}X$ near threshold is of order of 1 μb. A dramatic rise in the asymmetry A_{NN} is also measured in $pp \to pp$ at large θ_{cm} at the strangeness threshold, $\sqrt{s} \cong 3$ *GeV.* This rise again can be accounted for if $\sigma(pp + s\bar{s}X) \sim O(1mb)$ above the strangeness threshold, which is consistent with experiment.

Nuclear-bound quarkonium. The possibility of strong interactions between heavy and light quarks at low relative velocity is undoubtedly a general phenomena in QCD. An important consequence of such attractive forces is nuclear-bound quark-onia[38]; *e.g.,* a bound state of a J/ψ to a nucleus. In fact, Manohar, Luke, and Savage[39] have used the operator product expansion to show that the QCD Van der Waals potential is sufficiently attractive at low relative velocity in the *s*-wave to lead to bound states of the J/ψ with heavy nuclei. It is conceivable that the binding is strong enough to produce bound states of heavy quarkonia with light nuclei or even nucleons.

An interesting place to search for $J/\psi N$ resonances on bound states is in $B \to J\psi\,\overline{\Lambda}$ decays at a *B*-factory[40]. The formation of a $[J/\psi\,p]$ bound state would be signaled by events where the $\overline{\Lambda}$ is produced with a nearly monotonic energy.

4. The Leading Particle Effect in Charm Hadroproduction and the Effect of Parton Coalescence[23]

In leading-twist QCD, the PQCD factorization theorem[41] predicts that the fragmentation functions $D_{H/c}$ *(z, Q)* are independent of the quantum numbers of both the projectile and target. However, strong flavor correlations between the produced particle and the projectile have been reported in charm production [42,43]. For example, in $\pi^-(\overline{u}d)$ interactions with hadrons or nuclei, the $D^-(\overline{c}d)x_f$ distribution is consistently harder than the $D^+(c\overline{d})$ distribution. The D^- and $D^0(c\overline{u})$ are referred to as "leading" charmed mesons while the D^+ and $\overline{D}^0(\overline{c}u)$ are "non-leading". This leading behavior suggests that hadronization at large x_F involves the coalescence of the produced charm or anticharm quarks with the spectator quarks of the projectile, just as in exclusive reactions. The study of this phenomena thus can provide new insights into the coherent mechanisms controlling the formation of hadrons in QCD.

The asymmetry between leading and non-leading charm, has been measured by the WA82[44] and E769[45] collaborations. Both experiments find that the measured asymmetry $\mathcal{A}(x_f)$, integrated over p_T, increases from ~ 0 for x_f near zero to ~ 0.5

around $x_f = 0.65$. However, the asymmetry $\mathcal{A}(p_T^2)$, integrated over all x_f, is found to be small in the range $0 < p_T^2 < 10 \text{ GeV}^2$.[45] These facts are consistent if the leading charm asymmetry is localized at large x_F, involving only a small fraction of the total cross section.

Perturbative QCD at leading order predicts that c and $\bar{c}$ quarks are produced with identical distributions. Next-to-leading order calculations do give rise to a small charge asymmetry ($\sim 10\%$ for $x_f \sim 0.8$) between $\bar{c}$ and c production due to qg and $q\bar{q}$ interference[46,47]. However, this charge asymmetry should result in an increase of D^-, D production over D^+ and D^0 at high x_f, not a separation between D^-, D^0 and $D^+, \overline{D}^0$.

How can one explain the origin of leading charm asymmetry within the context of QCD? It is clear that the produced charm (or anticharm) quark must combine with a projectile valence quark. Ordinary jet fragmentation (e.g., Peterson fragment at ion [48]) cannot produce a leading particle asymmetry since it is independent of the initial state and thus the projectile valence quarks. This is an essential property of leading-twist factorization. However, one expects on physical grounds that a charm quark produced by fusion may coalesce with a comoving spectator valence quark[49,50,51,52,23]. For example, in QED, leptons of opposite charge moving with similar velocities can be captured into neutral atoms[53]. Since the capture is significant only at small relative rapidity, Δy, the effect on the total rate is higher twist.

In leading-twist QCD heavy quarks are produced by the fusion subprocesses $gg \rightarrow Q\overline{Q}$ and $q\bar{q} \rightarrow Q\overline{Q}$. The heavy Q or $\overline{Q}$ normally fragments independently; however, there is a finite probability that it will combine with a spectator valence quark in the final state to produce a leading hadron. Coalescence is expected to dominate when the valence quark and the produced heavy quark have the same velocity. The coalescence amplitude should be largest at small relative rapidity since the invariant mass of the $\overline{Q}q$ system is minimal and the binding amplitude of the heavy meson wavefunction is maximal. This picture of coalescence is also consistent with "heavy quark symmetry" [54,55]. A similar final-state coalescence mechanism is contained in PYTHIA, a Monte Carlo program based on the Lund string fragmentation model[56]. Its string mechanism produces some charmed hadrons with a substantially larger longitudinal momentum than the charmed quarks originally produced by the fusion processes. At large x_f and low invariant string masses, the produced D^- or D^0 inherits all the remaining projectile momentum while D^+, $\overline{D}^0$ production is forbidden. However, PYTHIA substantially overestimates the observed asymmetry, $\mathcal{A}(x_f)$, particularly at low x_f. It also results in $\mathcal{A}(p_T^2) \sim 0.3$ for $0 < p_T^2 < 10 \text{ GeV}^2$, overestimating the effect seen in the x_f-integrated data. This larger asymmetry produced by PYTHIA is due to a general excess of D^- compared to D^+ production, presumably arising from differences in c and $\bar{c}$ quark fragmentation and is not a general feature of final-state coalescence models.

In the usual picture of leading charm hadroproduction and in PYTHIA, it is implicitly assumed that coalescence is strictly a final-state phenomenon. In fact, the

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coalescence of the charm quark and a projectile valence quark may also occur in the initial state. For example, the π^- can fluctuate into a $|\bar{u}dc\bar{c}\rangle$ Fock state. The most important fluctuations occur at minimum invariant mass $\mathcal{M}$ where all the partons have approximately the same velocity. Characteristically, most of the momentum is carried by the heavy quark constituents of these Fock states. As viewed from the target rest frame, the intrinsic charm configurations can have very long life-times, of order $\tau = 2P_{\mathrm{lab}}/\mathcal{M}^2$ where P_{lab} is the projectile momentum. Intrinsic charm hadroproduction occurs dominantly when the spectator quarks interact strongly in the target[25], explaining why large x_f charm production on nuclear targets is observed to have a strong nuclear dependence, similar to that of the inelastic hadron-nucleus cross section. Since the charm and valence quarks have the same rapidity in an intrinsic charm Fock state, it is easy for them to coalesce into charmed hadrons and produce leading particle correlations at large x_f where this mechanism can dominate the production rate.

The leading charm asymmetry must be a higher-twist effect or it would violate PQCD factorization. Final-state coalescence is higher twist since only a small fraction of the fusion-produced heavy quarks will combine with the valence quarks. Intrinsic heavy quark production is also higher twist because the virtual configurations in the projectile wavefunction must be resolved during their limited lifetime. The cross section decreases with extra powers of $1/m_Q$ relative to leading-twist fusion. From a general quantum-mechanical standpoint, both types of higher-twist mechanisms, coalescence of fusion-produced charm in the final state and coalescence of the intrinsic charm configurations in the initial state, must occur in QCD at some level. Recently Vogt and I[23] have computed the asymmetry within a two-component model: parton fusion with coalescence, and intrinsic charm with valence-quark recombination[57]. In this model the coalescence mechanism is treated simply as a probabilistic process where the momenta simply add to form the charmed hadron. More recently Quack, Vogt and I[35] have treated coalescence at the amplitude level as a quantum mechanical process.

The effects of coalescence can also explain the qualitative features of J/ψ suppression seen in heavy ion[58] and pA collisions[59]. When charm quarks are produced they will often coalesce with comoving partons to produce open charm hadrons, thus reducing the probability of quarkonium production[60]. The magnitude of the suppression of quarkonium production is enhanced in the nuclear fragmentation regions or in events with high transverse energy when the nuclear target produces a high density of co-movers. Vogt and I[23] have shown that this effect can explain the main features of J/ψ and Υ nuclear suppression observed in the NA38 and E772 experiments.

5. Anomalous Charm Decays

Another unusual feature of charmonium physics is the pattern of exclusive two body decays of the J/ψ and ψ'. For example, the branching ratio $BR(J/\psi \to \rho\pi) = 1.28(\,10)10^{-2}$ whereas there is only an upper limit for the $\psi' : BR(\psi' \to \rho\pi) <$

8.3 10^{-5} at 90% confidence level. Normally one would expect that the branching ratios for any two-body hadronic channel would proceed through three-gluon intermediate states. The magnitude is controlled by the charmonium wavefunction at small $c\bar{c}$ separation and thus should track with the lepton pair rates; *i.e.,* the ψ' rate should be 15% that of the J/ψ. For most decays this appears to be true; however, hadron helicity conservation at the perturbative QCD level predicts that vector-pseudoscalar channels should be strongly suppressed[61]. Thus the suppression of $\psi' \to \rho\pi$ *is* expected, but the large rate for $J/\psi \to \rho\pi$ is truly anomalous. A good account of this physics and a review of the latest data from BES[62] is given by Olsen in these proceedings[63].

The simplest explanation for the large $J/\psi \to \rho\pi$ decay rate is the postulate that the J/ψ *is* mixed with a nearby glueball state with the same 1^{--} quantum numbers. Such a glueball, called the Omicron, $\mathcal{O}$, could decay preferentially to vector-pseudoscalar channels[64]. This explanation[64,61] also would imply that an increase in $e^+e^- \to \rho\pi$ should be observable over background at the mass and width of the $\mathcal{O}$. Thus far the sensitivity of the experiments has not been sufficient to detect the presence the $\mathcal{O}$ if its width is greater than 10 MeV[63]. The possible effect of color-octet multigluon Fock states in the charmonium wavefunction on its decay also needs further exploration.

6. Channels and Its Production at Large p_T

As I have discussed in this brief review, there are a remarkable number of anomalies associated with the production and decay of heavy quark systems. A common thread in the proposed explanations for the anomalies within QCD are non-perturbative and higher Fock state effects which can cause mixing of hadronic states and enhanced interactions near threshold and at low relative velocities. There are other important consequences which require experimental verification, including nuclear-bound quarkonia, intrinsic heavy quark contributions to structure functions and target fragmentation, anomalous spin correlations, enhanced rates near heavy quark thresholds, leading particle effects, and unusual nuclear target dependencies.

7. ACKNOWLEDGEMENTS

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