PHYSICAL REVIEW D, VOLUME 64, 071501(R)

Probing for the charm content of B and Υ mesons

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(Received 16 January 2001; revised manuscript received 21 May 2001; published 5 September 2001)

A slow J/ψ bump exists in the inclusive $B\to J/\psi+X$ spectrum, while the softness of the J/ψ spectrum in $\Upsilon(1S)\to J/\psi+X$ decay is in strong contrast to expectations from the color octet mechanism. We propose *intrinsic* charm as the explanation: the former is due to $\bar{B}\to J/\psi D\pi$, with three charm quarks in the final state; the latter is just a small fraction of $\Upsilon(1S)\to(c\bar{c})_{\rm slow}+2$ "jet" events, where the slow moving $c\bar{c}$ system evolves into $D^{(*)}$ pairs. An experimental search for these phenomena at B factories and the Fermilab Tevatron is strongly urged, as the implications go beyond QCD.

DOI: 10.1103/PhysRevD.64.071501 PACS number(s): 12.38.Bx, 12.39.Ki, 13.25.Hw, 14.40.Nd

Owing to its heaviness and narrow width, the J/ψ meson has helped shed much light on the underpinnings of quantum chromodynamics (QCD), the more recent example being the inclusive production of energetic J/ψ's in various processes. Thus, the inclusive spectrum of $B\to J/\psi+X$ decay is largely understood, *except for a slow* J/ψ *bump* observed [1] by CLEO and recently confirmed [2] by the Belle Collaboration [see Fig. 1(a)]. Another intriguing old result from CLEO could be related, namely, the peaking of $p_{J/\psi}$ below 2 GeV for inclusive $\Upsilon(1S)\to J/\psi+X$ decay [3], which is in strong contrast [see Fig. 1(b)] to the hard spectrum expected from the color octet mechanism. In this Rapid Communication we attempt at linking these two soft J/ψ production phenomena and propose specific, testable mechanisms.

We suggest that the *intrinsic* charm (IC) content may be better probed in *heavy* hadrons such as B mesons. Intrinsic, in contrast with extrinsic, charm content of hadrons [4] carries a large momentum fraction and is in the lowest energy configuration as it arises from energy fluctuations. Thus, in the decay of heavy mesons, the production of slow J/ψ and η_c mesons is favored. From the indication that IC in the proton could be $\sim1\%$ [5], we find that IC in B could lead to $\bar{B}\to J/\psi D\pi$ (i.e., $c\bar{c}\bar{c}$ *in the* $\bar{B}$ *decay final state*) at the few $\times10^{-4}$ level and can in principle account for the above excess. From $\Upsilon(1S)\to J/\psi|_{\rm soft}+X$ we argue that $\Upsilon(1S)\to D^{(*)}|_{\rm slow}+X$ could be quite abundant. These modes are rather promising at the B factories [the $\Upsilon(1S)$ especially at CLEO] and at the Fermilab Tevatron, the observation of which would provide strong impetus for establishing intrinsic charm in hadrons. In turn, this would have implications for the flavor program, such as the extraction of V_{cb} from $B\to D^*l\nu$.

Using 1.12 fb^{-1} data on $\Upsilon(4S)$ resonance, CLEO has published the inclusive J/ψ spectrum from B decays [1]. The result, with feed down from $B\to\psi'+X$ ($\psi'\to J/\psi\pi\pi$) and χ_c+X ($\chi_c\to J/\psi\gamma$) subtracted, is reproduced as stars with errors in Fig. 1(a). Evidently there is some activity around $p_{J/\psi}\sim$0.4–0.6 GeV. In 2000, Belle gave preliminary results [2] on inclusive $B\to J/\psi+X$ based on 6.2 fb^{-1} data. Subtracting the $B\to\psi'+X$ and χ_c+X feed down by ourselves, we plot in Fig. 1(a) the result as diamonds without errors, which confirms that there is some activity below 0.8 GeV.

To bring home the point, some modeling of the inclusive spectrum has to be taken. For simplicity, we adopt the "modified phase space" approach [6] and modulate a constant matrix element squared by

$$f(p)=p(p_{\rm max}-p)/p_{\rm max}^2\,e^{-(p-p_0)^2/\sigma_0^2}, \qquad (1)$$

where $p_{\rm max}$=1.95 GeV is the maximum J/ψ momentum, and p_0 and σ_0 are adjustable parameters. Taking a simple aver-

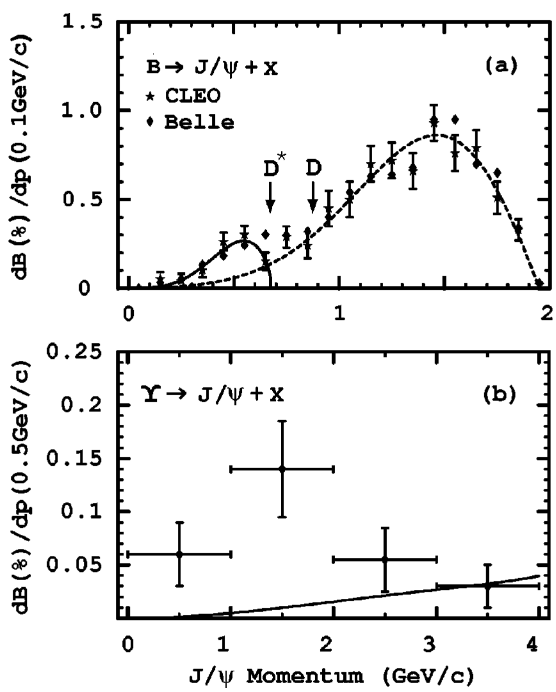

FIG. 1. (a) Inclusive $B\to J/\psi+X$ spectrum with $B\to\psi'+X$ and χ_c+X feed down subtracted. The stars (diamonds) with(out) errors are from Ref. [1] ([2]). The dashed curve is a simple modified phase space fit. The solid line fits below D^* threshold assuming recoiling $D\pi$; D recoil is also indicated. (b) Inclusive $\Upsilon(1S)\to J/\psi+X$ spectrum from CLEO [3]. The curve is from the color octet mechanism.

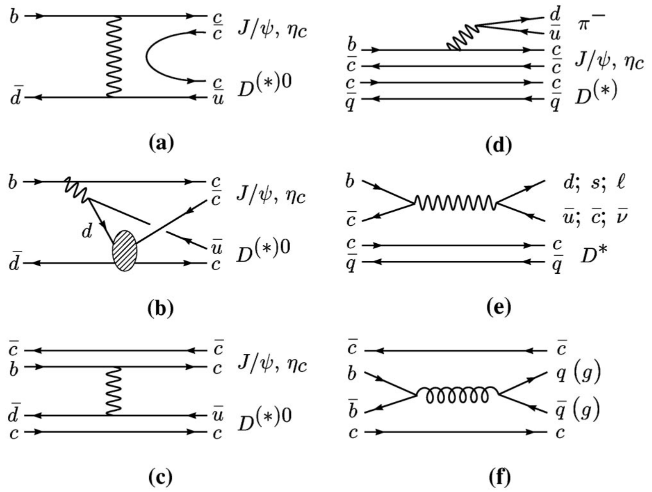

FIG. 2. Standard $\overline{B}^0 \to J/\psi D^{(*)0}$ via (a) exchange and (b) rescattering, $\overline{B} \to J/\psi D^{(*)}(\pi)$ via (c) exchange and (d) spectator from $|b\bar{c}c\bar{q}\rangle$ Fock component, and (e) $b\bar{c}$ annihilation (f) $\Upsilon(1S) \to J/\psi + X$ via $|b\bar{c}c\bar{b}\rangle$ Fock component.

age (not plotted) of CLEO and Belle data, we adjust p_0, σ_0 to 1.9, 0.8 GeV and give the dashed line in Fig. 1(a) as a plausible fit. The apparent excess in 0.3 GeV$\lesssim p_{J/\psi} \lesssim$0.8 GeV is of order 5×10^{-4}, comparable to the rate for $B \to J/\psi K_S$.

We stress that more sophisticated models do not change the above result. For example, a Fermi motion model with $p_F \simeq 0.57$ GeV for b quark inside the B meson can give a good fit [7] to data above 0.8 GeV. A parton-based model with a soft b quark momentum can also work, albeit less well. In both cases one invokes nonrelativistic QCD and the color octet mechanism, but one is unable to fit the low $p_{J/\psi}$ excess. In fact, these models have a softer low $p_{J/\psi}$ tail than the simple approach of Eq. (1), making the excess even more striking.

The D and D^* recoil thresholds at $p_{J/\psi}=0.88$ and 0.66 GeV are indicated in Fig. 1(a). There is no apparent excess for $B \to J/\psi D$. Taking into account the broadening from B motion in $\Upsilon(4S)$ frame, Belle data might indicate the presence of $B \to J/\psi D^* \sim 10^{-4}$. Since D^* marks the opening of the $D\pi$ threshold, we adapt Eq. (1) to $p_{\max}$, p_0, $\sigma_0 = 0.66$, 1.4, 1.0 GeV, and fit with the solid curve in Fig. 1(a). It appears that $B \to J/\psi D\pi \sim 4\times10^{-4}$ *could account for the lump at low* $p_{J/\psi}$ [8]. With three charm quarks in the final state, it would be rather distinct and should be searched for. The challenge, however, is to account for such rates.

Two possible diagrams are given in Figs. 2(a) and 2(b). The first involves W exchange and is of the annihilation type. Since nonperturbative $c\bar{c}$ production is exponentially suppressed, the leading mechanism is perturbative and via one gluon. Collecting factors, we estimate that the rate should be suppressed by $(f_B/m_B)^2 \times (\alpha_s/\pi)^2 \times 1/3$ compared to $\overline{B} \to D D_s^- \sim 1\%$, where $p_{J/\psi}/p_{D_s} \sim 1/3$ comes from the phase space. This gives $\overline{B}^0 \to J/\psi D^{(*)0} \sim 10^{-7}$ from Fig. 2(a) alone.

Figure 2(b) is much harder to estimate, since it involves $d\bar{d} \to c\bar{c}$ rescattering. Assuming that this occurs perturbatively via one gluon, we estimate the rate from Fig. 2(b) alone to be no more than $\zeta_{\bar{d}} \times (\alpha_s/\pi)^2 \times 1/3$ times $\overline{B} \to D D_s^-$ rate $\sim 1\%$. Since the rescattering demands an energetic d quark *and* a spectator $\bar{d}$ quark to produce the heavy $c\bar{c}$ system, the $\zeta_{\bar{d}}$ factor is expected to be considerably less than one, hence $\overline{B}^0 \to J/\psi D^{(*)0}$ from Fig. 2(b) should be safely below 10^{-5}. As this is not a firm result, we note that if one replaces $c\bar{c}$ by $s\bar{s}$ in Figs. 2(a) and 2(b), one already has the limit $\overline{B}^0 \to D_s^+ K^- \lesssim 10^{-4}$ from the data [9]. This can be viewed as an upper bound on $\overline{B}^0 \to J/\psi D^{(*)0}$ modes, where the limit can be improved at the B factories. Similarly, rescatterings such as $\overline{B}^0 \to D^+\pi^- \to J/\psi D^0$ [corresponding to two cuts of Fig. 2(b)] should not only suffer from cancellations between the large number of possible diagrams, but can also be firmly bound by searching for color suppressed modes such as $D^0\pi^0$.

We thus see that, while hard predictions of hadronic B decays are difficult, there would likely be no plausible explanation for $B \to J/\psi D\pi$ if it is observed at $\times10^{-4}$ level or higher.

It is intriguing that a soft J/ψ problem exists for $\Upsilon(1S)$ decays as well. Based on $\sim 7\times10^5$ $\Upsilon(1S)$ events and ~ 20 $J/\psi \to \mu^+\mu^-$ candidates, CLEO observed [3] some time ago that $\Upsilon(1S) \to J/\psi + X \sim 1.1\times10^{-3}$. The rate is still not sufficiently accounted for [10], but the most striking feature from the data is the relatively soft $p_{J/\psi}$ spectrum that seemingly peaks below 2 GeV, as shown in Fig. 1(b), compared to $p_{\max} \simeq 4.2$ GeV. Perturbative production predicts a hard J/ψ spectrum [10] (solid curve). Thus, this old CLEO result, if confirmed, would be a major puzzle for the color octet mechanism.

Figures 1(a) and 1(b) together suggest some additional mechanism that is responsible for soft J/ψ production from heavy meson decays. We propose one possibility, namely *intrinsic charm*. IC of hadrons in principle should exist [4], and has been suggested to account for charm production in deep inelastic scattering [5] and $J/\psi \to \rho\pi$ decay [11]. It has also been suggested [12] for D and B mesons though never pursued.

For the proton, $|p\rangle = \Psi^p_{uud}|uud\rangle + \Psi^p_{uc\bar{c}ud}|uc\bar{c}ud\rangle + \cdots$, the $|uc\bar{c}ud\rangle$ component [13] is generated by virtual $gg \to c\bar{c}$ interactions (so multi-connected to valence quarks), and should scale as $\alpha_s^2(m_c^2)/m_c^2$ relative to the $|uud\rangle$ component. Since this higher Fock component arises as a quantum fluctuation, $\Psi^p_{uc\bar{c}ud} \propto 1/(m_p^2 - M^2)$ where M^2 is the invariant mass of the fluctuation. We show in Fig. 3(a) the distributions in the $|uc\bar{c}ud\rangle$ component. One sees that the IC carries a *large* momentum fraction [4], in contrast to the small x tendency of the usual "sea" (extrinsic) quarks from gluon splitting. Using this feature, there is some evidence from the data that the IC in the proton, $|\Psi^p_{uc\bar{c}ud}|^2$, could be at $\sim 0.86\%$ level [5]. Such an analysis, of course, should be done in a more consistent framework [14] and incorporate more data to be conclusive.

For B mesons, one has the differential probability

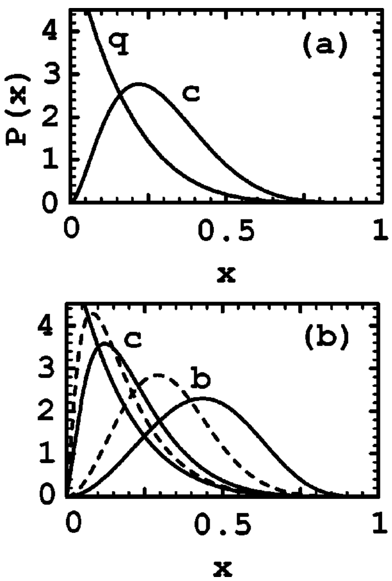

FIG. 3. Intrinsic charm in (a) proton and (b) B meson (b and $\bar{q}$ distributions also shown), with arbitrary normalization. Dashed lines in (b) are for the $|b\bar{c}c\bar{b}\rangle$ component of $\Upsilon(1S)$.

$$\frac{dP^B_{\rm ic}}{dx_1\cdots dx_4}\propto\frac{\alpha_s^2(m_c^2)\,\delta(1-\Sigma_{i=1}^4 x_i)}{(m_B^2-\hat{m}_b^2/x_b-\hat{m}_c^2/x_c-\hat{m}_{\bar{c}}^2/x_{\bar{c}})^2}, \qquad (2)$$

in the $|b\bar{c}c\bar{q}\rangle$ Fock component of $|\bar{B}\rangle=\Psi_{b\bar{q}}|b\bar{q}\rangle+\Psi_{b\bar{c}c\bar{q}}|b\bar{c}c\bar{q}\rangle+\cdots$, since m_B, m_b cannot be ignored. In fact, the heaviness of m_b guarantees that it still carries the largest momentum fraction, as can be seen from Fig. 3(b). We find $\langle x_c\rangle\sim0.22$ in B, lower than $\langle x_c\rangle\simeq0.28$ in the proton [Fig. 3(a)].

One has no deep inelastic scattering data off B mesons to extract $|\Psi_{b\bar{c}c\bar{q}}|^2$. However, $|\Psi_{b\bar{c}c\bar{q}}|^2$ may be no less than $|\Psi_{u\bar{c}cud}|^2$, because [15] of a larger reduced mass: the B meson is more compact than usual hadrons, hence the IC amplitude could be dynamically enhanced. Thus, IC in B could also be $\sim1\%$. A heavy quark mass expansion study [16] gives the IC in $p\sim10^{-3}$, which is not inconsistent. As stressed in [15], this study shows that the $c\bar{c}$ pair should be in the color octet configuration, hence the IC component arises from the non-Abelian nature of QCD.

To account for the low $p_{J/\psi}$ bump of Fig. 1(a) from the $|b\bar{c}c\bar{q}\rangle$ Fock component, note that $\bar{B}\to J/\psi D^{(*)0}$ decay via Fig. 2(c) is still suppressed by f_B, just like Fig. 2(a). The spectator decay of Fig. 2(d) is more promising. It gives $\bar{B}\to J/\psi D\pi^-$ if one assumes factorization, hence it fits our interpretation of the low $p_{J/\psi}$ bump in Fig. 1(a) rather well. But can we account for the rate?

The quark level 3-body spectator decay is very sensitive to x_b as it scales with the available energy ΔE to the fifth power. Since $\langle x_b\rangle\simeq0.41$ from Fig. 3(b), taking $x_b\simeq0.41$ to 0.6 gives a rate in the 10^{-3} to 5×10^{-2} range, shooting up to even 10% for $x_b=0.65$. We have used $\Delta E\simeq m_b-m_c\sim3.4$ GeV for standard b decay via $|b\bar{q}\rangle$ component, and $\Delta E\simeq x_b m_B-1.3$ GeV via $|b\bar{c}c\bar{q}\rangle$ Fock component of Fig. 2(d). Varying $m_c\sim1.3$ to 1.4 GeV does not change this range by much. With $x_c\lesssim\langle x_c\rangle\sim0.22$ and $x_{\bar{q}}$ at its peak near zero, $b\to d\bar{u}c$ decay leads to the configuration $(d\bar{u})c\bar{c}(c\bar{q})$, where we have indicated color singlet pairings. The remaining $c\bar{c}$ is also color singlet and plausibly evolves into J/ψ or η_c. With all quarks having low momenta, there is ample time for them to redistribute energy and momentum, including $J/\psi D^+\pi^-\to J/\psi D^0\pi^0$. It is sensible then that one can take the above $\sim10^{-2}$ factor times the IC fraction $|\Psi_{b\bar{c}c\bar{q}}|^2$ as a rough estimate. Note that, from duality, the "quark level" decay rate can only feed into the $J/\psi D^*$ or $J/\psi D\pi$ final state. In this way, we find that a rate at few $\times10^{-4}$ level is possible, *if* the IC fraction is not much less than 1%. *One should check experimentally whether our suggested signals are present.*

It is useful to identify other effects where the IC of B can make an important impact. Since the $b\bar{c}$ forms a color singlet in $|b\bar{c}c\bar{q}\rangle$ Fock component, $b\bar{c}\to s\bar{c}$, $d\bar{u}$, and $l\nu$ annihilation can proceed without helicity suppression in the vector channel, as illustrated in Fig. 2(e). They in general complement standard channels and hence would not be easy to distinguish. However, the energy fluctuation argument suggests that the *vector* $b\bar{c}$ system would have near maximal mass, and the accompanying $c\bar{q}$ would end up in the lowest energy-momentum state available, that is, a slow moving D^*. Indeed, we find that $\langle x_c\rangle+\langle x_{\bar{q}}\rangle$ is right at the D^* mass. One therefore expects the most significant impact to be on $B\to D^*l\nu$ near the zero recoil region, where a distortion in spectrum *would affect the program of* $|V_{cb}|$ *extraction*. Thus, if the IC in B is truly sizable, there would be new systematics to $|V_{cb}|$ determination, hence the importance is beyond QCD.

Turning to $\Upsilon(1S)\to J/\psi+X$ decay, it is clear that IC of $\Upsilon(1S)$ naturally gives a soft J/ψ spectrum as given in Fig. 1(b). Since the $b\bar{b}$ in the $|b\bar{c}c\bar{b}\rangle$ Fock component should be the color octet [16], it decays via $b\bar{b}\to g^*\to q\bar{q}$, gg, as shown in Fig. 2(f) ($b\bar{b}\to gg$ has an extra t-channel contribution), while the accompanying $c\bar{c}$ is color octet and carries minimal energy. Thus, one expects the underlying process $\Upsilon(1S)\to(c\bar{c})^{\rm soft}_{\rm octet}+2$ "jets," where $(c\bar{c})^{\rm soft}_{\rm octet}$ evolves into slow moving $D\bar{D}X$ or $J/\psi(\eta_c)X$, in contrast with $D^{(*)}$ production by leading particle effects from c jets, or from $g^*\to c\bar{c}$ splitting.

The rate is easier to estimate than the B meson weak decay case. We estimate $\Upsilon(1S)\to q\bar{c}c\bar{q}$ rate via the IC component as

$$\Gamma_{q\bar{c}c\bar{q}}=\frac{\Gamma_{q\bar{c}c\bar{q}}}{\Gamma_{ee}}\times\Gamma_{ee}\sim6\left(\frac{\alpha_s}{\alpha}\right)^2|\Psi_{b\bar{c}c\bar{b}}|^2\times1.3\ \ \text{keV}, \qquad (3)$$

for a single quark flavor q, where 6 is from the ratio of color and electric charges. Counting 3 (u, d, and s) flavors and roughly $N_C=3$ colors for $b\bar{b}\to gg$, one gains an additional factor of 6. Understandably, the process of Fig. 2(f) *is rather fast*. We should certainly demand that $\Gamma_{q\bar{c}c\bar{q}}<50\%\times\Gamma_{\Upsilon(1S)}$, which implies that the IC fraction $|\Psi_{b\bar{c}c\bar{b}}|^2\lesssim10^{-3}$. This is not in conflict with $|\Psi_{b\bar{c}c\bar{q}}|^2\sim$ 1% since the $\Upsilon(1S)$ is basically a nonrelativisitic bound state and hence lacks high frequency components. But it does mean that, if the IC is relevant at all, $\Upsilon(1S)\to(\bar{c}c)^{\rm slow}_{\rm octet}+q\bar{q}$ *could easily be* 10% (or 5 keV) of $\Upsilon(1S)$ rate.

It is remarkable that the last statement is consistent with all known facts. Very few hadronic decays of $\Upsilon(1S)$ have been reconstructed so far, while the strong α_S^3 dependence of $\Upsilon(1S)\to ggg$ rate certainly allows $\Upsilon(1S)\to(\bar{c}c)^{\rm slow}_{\rm octet}+\bar{q}$ $\sim 10\%$. This is also consistent with the observed $\Upsilon(1S)\to J/\psi+X\sim 1.1\times 10^{-3}$, since J/ψ formation should be just a small fraction of $(\bar{c}c)^{\rm slow}_{\rm octet}$, while the softness of observed J/ψ spectrum is also explained. The main part of $(\bar{c}c)^{\rm slow}_{\rm octet}$ evolves into $D^{(*)}\bar{D}^{(*)}+X$ where the $D^{(*)}$ mesons are slow, accompanied by two ''jets'' from the $q\bar{q}$ and gg with 5–6 GeV total energy. We note that the ARGUS Collaboration has set a bound of [17] $\Upsilon(1S)\to D^{*-}X<1.9\%$ for $p_{D^*}>0.86$ GeV. This is not yet constraining after adjusting for D^* fraction, and in particular, one must loosen the cut on p_{D^*} to be sensitive to the IC induced decays. It is rather exciting that CLEO would be running on Υ resonances soon [18], where we may learn about the relative abundance of $\Upsilon(1S)\to(\bar{c}c)^{\rm slow}_{\rm octet}+2$ ''jet'' events. Note that $\sim$1/6–1/10 of these ''jets'' would be charm jets.

Some further remarks are in order. First, the lump below $p_{J/\psi}<0.9$ GeV cannot be due to feed down from additional $\bar{c}c$ states, since such spectrum would in general extend beyond 1 GeV, as can be seen from the data [1,2] for $B\to\psi'+X$ and η_c+X. There is no evidence for excess above 0.9 GeV. Second, the low $p_{J/\psi}$ excess could be due to $\bar{B}\to J/\psi\Lambda\bar{N}$ [6], but then a large baryon production probability is needed near the threshold, which is not more plausible. Third, for intrinsic strangeness, one can have analgous signatures such as $\bar{B}\to\phi D^{(*)}$ by making simple changes to Figs. 2(a)–2(d). While these signals should be searched for, they are less distinct since strangeness production is less suppressed, and multi-particle final states may be preferred since available energy is more than 2 GeV. An earlier suggestion [12] of $D^0\to\phi\bar{K}^0$ as evidence for intrinsic strangeness in D mesons suffers from large rescattering at m_D scale. We mention, however, the possibility of $B\to J/\psi\phi K+X$, since CLEO recently observed [19] $B\to J/\psi\phi K\sim 10^{-4}$. Whether it is from intrinsic strangeness or final state rescattering, this possibility should be studied further. Fourth, analagous signatures for B_c mesons and b baryons are $B_c\to J/\psi J/\psi(\pi)$, $J/\psi\eta_c\pi$, and $\Lambda_b\to J/\psi\Lambda_c(\pi)$.

We emphasize that the $\bar{B}\to J/\psi D^+\pi^-$, $J/\psi D^0\pi^0$, and $J/\psi D^{*0}$ signals can be searched for *right away* at B factories and at the Fermilab Tevatron with relative ease. The two environments complement each other, with excellent π^0 detection at B factories but with a larger cross section and higher boost at Fermilab Tevatron, where a large number of J/ψ events have been recorded. The $B\to D_s^{(*)}K^{(*)}$ modes should be searched for as a control on rescattering diagrams.

In conclusion, we propose the following study plan. B factory and Fermilab Tevatron experiments should scan low momentum J/ψ events for $\bar{B}\to J/\psi D\pi$, $J/\psi\phi\bar{K}+X$, and $J/\psi\Lambda\bar{N}$. If $\bar{B}\to J/\psi D\pi$ (and perhaps $J/\psi D^*$) is established above 10^{-4} level, while $D_s^{(*)}K^{(*)}$ modes are found to be far less, one then has a good case for intrinsic charm in B. CLEO should run on $\Upsilon(1S)$ and collect at least 1 fb^{-1} data, reconfirm $\Upsilon(1S)\to J/\psi(\eta_c)+X$, and search for $\Upsilon(1S)\to D^{(*)}+X$. Slow moving J/ψ or $D^{(*)}\bar{D}^{(*)}$ in an otherwise jetty event from $\Upsilon(1S)$ decay would indicate, perhaps more unequivocally, the existence of intrinsic charm. The discovery of intrinsic charm in B and Υ mesons would not only add another twist to hadron structure, it would have implications on V_{cb} extraction from $\bar{B}\to D^*l\nu$ decay as well.

This work is supported in part by NSC 89-2112-M-002-063 and 89-2112-M-003-021, the MOE CosPA Project, and as part of the NCTS Topical Program on B Physics and CP Violation. We thank Andrzej Bozek, Stan Brodsky, Tom Browder, and Henryk Palka for inspiration.

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