Probing for the Charm Content of $B$ and $\Upsilon$ Mesons

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

Owing to its heaviness and narrow width, the $J/\psi$ meson has helped shed much light on the underpinnings of Quantum Chromodynamics (QCD), the more recent extension of Quantum Chromodynamics (QCD), the more recent extension of QCD, the more recent extension of QCD, the more recent extension of QCD. The result, with feed-down from $B \to J/\psi + X$ decay is in strong contrast with expectations from color octet mechanism. We propose intrinsic charm as the explanation: the former is due to $B \to J/\psi D\pi$, with three charm quarks in the final state; the latter is just a small fraction of $\Upsilon(1S) \to (c\bar{c})_{\text{slow}} + 2 \text{ "jet" events}$, where the slow moving $c\bar{c}$ system evolves into $D^{(*)}$ pairs. Experimental search for these phenomena at B Factories and the Tevatron is strongly urged, as the implications go beyond QCD.

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FIG. 1. (a) Inclusive $B \to J/\psi + X$ spectrum with $B \to \psi' + X$ and $\chi_c + X$ 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 $\sigma_{\text{max}}$ assuming recoiling $D\pi$. Subtracting the $B \to \psi' + X$ and $\chi_c + X$ 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 and modulate a constant matrix element squared by

$$f(p) = p(p_{\text{max}} - p)/p_{\text{max}}^3 e^{-(p-p_0)^2/\sigma_0^2},$$

where $p_{\text{max}} = 1.95$ GeV is the maximum $J/\psi$ momentum based on 6.2 fb$^{-1}$ data. Subtracting the $B \to \psi' + X$ and $\chi_c + X$ 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.
tum, and \( p_0 \) and \( \sigma_0 \) are adjustable parameters. Taking a simple average (not plotted) of CLEO and Belle data, we adjust \( p_0, \sigma_0 \) 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 \( \times 10^{-4} \), comparable to the rate for \( B \rightarrow J/\psi K_S \).

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 to data above 0.8 GeV. A parton-based model with soft \( b \) quark momentum can also work, albeit less well. In both cases one invokes NRQCD 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 \( B \rightarrow J/\psi D \). Taking into account the broadening from \( B \) motion in \( \Upsilon(4S) \) frame, Belle data might indicate the presence of \( B \rightarrow J/\psi D^* \sim 10^{-4} \). 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 \( B \rightarrow J/\psi D^\pi \sim 4 \times 10^{-4} \) could account for the bump at low \( p_{J/\psi} \).

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 annihilation type. Since nonperturbative \( cc \) 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 \( \tilde{B} \rightarrow DD^- \sim 1\% \), where \( p_{J/\psi}/p_{\max} \sim 1/3 \) comes from phase space. This gives \( \tilde{B}^0 \rightarrow J/\psi D^{(*)0} \sim 10^{-7} \) from Fig. 2(a) alone.

Fig. 2(b) is much harder to estimate, since it involves \( d\bar{d} \rightarrow c\bar{c} \) rescattering. Assuming that this occurs perturbatively via one gluon, we estimate the rate from Fig. 2(b) alone to be no more than \( \zeta_g \times (\alpha_s/\pi)^2 \times 1/3 \) times \( B \rightarrow DD^- \) rate \( \sim 1\% \). Since the rescattering demands energetic \( d \) quark and spectator \( \bar{d} \) quark to produce the heavy \( c\bar{c} \) system, the \( \zeta_g \) factor is expected to be considerably less than one, hence \( \tilde{B}^0 \rightarrow J/\psi D^{(*)0} \) 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 \( ss \) in Figs. 2(a) and 2(b), one already has the limit \( \tilde{B}^0 \rightarrow D^\pi K^- \lesssim 10^{-4} \) from data. This can be viewed as an upper bound on \( \tilde{B}^0 \rightarrow J/\psi D^{(*)0} \) modes, where the limit can be improved at the \( B \) Factories. Similarly, rescatterings such as \( \tilde{B}^0 \rightarrow D^\pi \rightarrow J/\psi D^0 \) (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 charm suppressed modes such as \( D^0 \rightarrow \pi^0 \).

We thus see that, while hard predictions of hadronic \( B \) decays are difficult, there would likely be no plausible explanation for \( B \rightarrow J/\psi D\pi \) if it is observed at \( 10^{-4} \) level or higher.

It is intriguing that a soft \( J/\psi \) problem exists for \( \Upsilon(1S) \) decays as well. Based on \( \sim 7 \times 10^5 \) \( \Upsilon(1S) \) events and \( \sim \Upsilon(1S) \rightarrow \mu^+\mu^- \) candidates, CLEO observed \( \Upsilon(1S) \rightarrow J/\psi + X \sim 1.1 \times 10^{-3} \). The rate is still not sufficiently accounted for by \( \bar{s}s \), but the most striking feature from 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 \( J/\psi \) spectrum (solid curve). Thus, this old CLEO result, if confirmed, would be a major puzzle for the color octet mechanism.

Figs. 1(a) and 1(b) together suggest some additional mechanism that is responsible for soft \( J/\psi \) production from heavy meson decays. We propose one possibility, namely intrinsic charm. IC of hadrons in principle should exist \( \bar{s}s \), and has been suggested to account for charm production in deep inelastic scattering \( \pi^+ \) and \( J/\psi \rightarrow \rho\pi \) decay \( \bar{s}s \). It has also been suggested \( \bar{s}s \) for \( D \) and \( B \) mesons though never pursued.

For the proton, \( |p| = |\Psi_{ud}^P| + |\Psi_{ucd}^P| + \cdots \), the \( |u\bar{c}d\bar{u}| \) component \( \bar{s}s \) is generated by virtual \( gg \rightarrow c\bar{c} \) interactions (so multi-connected to valence quarks), and should scale as \( \alpha_s^2(m_d^2/m_s^2) \) relative to the \( |udd| \) component. Since this higher Fock component arises as a quantum fluctuation, \( \Psi_{ucd}^P \propto 1/(m_d^2 - M^2) \) where \( M^2 \) is the invariant mass of the fluctuation. We show in Fig. 3(a) the distributions in the \( |u\bar{c}d\bar{u}| \) component. One sees that IC carries large momentum fraction \( \bar{s}s \), in contrast to the small \( x \) tendency of usual “sea” (extrin-
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 $|b\bar{c}b\bar{c}|$ component of $\Upsilon(1S)$.

sic) quarks from gluon splitting. Using this feature, there is some evidence from data that IC in proton, $|\Psi_{\text{cud}}^p|^2$, could be at $\sim 0.86\%$ level [1]. Such an analysis, of course, should be done in a more consistent framework [24] and incorporate more data to be conclusive.

For B mesons, one has the differential probability

$$\frac{dP_{B}}{dx_1 \cdots dx_4} \propto \frac{\alpha_{s}^2(m_b^2) \delta(1-\sum_{i=1}^{4} x_i)}{(m_b^2 - m_b^2/x_b - m_c^2/x_c - m_c^2/x_e)^2},$$

in the $|b\bar{c}c\bar{q}|$ Fock component of $|\bar{B}| = \Psi_{b\bar{q}}|b\bar{q}| + \Psi_{b\bar{c}q}|b\bar{c}q| + \cdots$, since $m_b, m_c$ 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 $(x_c) \sim 0.22$ in B, lower than $(x_c) \sim 0.28$ in proton (Fig. 3(a)).

One has no deep inelastic scattering data off B mesons to extract $|\Psi_{\text{bcud}}|^2$. However, $|\Psi_{\text{bcud}}|^2$ may be no less than $|\Psi_{\text{cud}}|^2$, 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 $\sim 1\%$. A heavy quark mass expansion study [13] gives IC in $p \sim 10^{-3}$, which is not inconsistent. As stressed in [13], this study shows that the c$\bar{c}$ pair should be in the color octet configuration, hence the IC component arises from the nonabelian nature of QCD.

To account for the low $p_{J/\psi}$ bump of Fig. 1(a) from the $|b\bar{c}q\bar{c}|$ Fock component, note that $\bar{B} \to J/\psi D^{(*)}a_0$ 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 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 $\Delta E$ to the fifth power. Since $(x_b) \simeq 0.41$ from Fig. 3(b), taking $x_b \simeq 0.41$ to 0.6 gives a rate in the $10^{-3}$ to $5 \times 10^{-2}$ range, shooting up to even 10% for $x_b = 0.65$. We have used $\Delta E \sim m_b - m_c \sim 3.4$ GeV for standard b decay via $|b\bar{q}|$ component, and $\Delta E \sim x_b m_b - 1.3$ GeV via $|b\bar{c}q|$ Fock component of Fig. 2(d). Varying $m_c \sim 1.3$ to 1.4 GeV does not change this range by much. With $x_c, x_\bar{q} \lesssim (x_c) \sim 0.22$ 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 $J/\psi$ or $\eta_c$. 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 $\sim 10^{-2}$ factor times the IC fraction $|\Psi_{b\bar{c}q}|^2$ as a rough estimate. Note that, from duality, the “quark level” decay rate can only feed into $J/\psi D^*$ or $J/\psi D\pi$ final state. In this way, we find that a rate at few $\times 10^{-4}$ level is possible, if IC fraction is not much less than 1%. One should check experimentally whether our suggested signals are there.

It is useful to identify other effects where IC of B can make important impact. Since the $b\bar{c}$ forms a color singlet in $|b\bar{c}q\bar{c}|$ Fock component, $b\bar{c} \to c\bar{c}, d\bar{u}$ and $\ell\nu$ annihilation can proceed without helicity suppression in the vector channel, as illustrated in Fig. 2(e). They in general complement standard channels hence would not be easy to distinguish. However, the energy fluctuation argument suggest 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 $(x_c) + (x_\bar{q})$ is right at the $D^*$ mass. One therefore expects the most significant impact to be on $B \to D^*\ell\nu$ near the zero recoil region, where a distortion in spectrum would affect the program of $|V_{cb}|$ extraction. Thus, if 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 soft $J/\psi$ spectrum as given in Fig. 1(b). Since the $b\bar{b}$ in the $|b\bar{c}b\bar{c}|$ Fock component should be color octet [24], 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 $\Upsilon(1S) \to (c\bar{c})_{\text{octet}} + 2 "jets"$, where $(c\bar{c})_{\text{octet}}$ evolves into slow moving $D\pi X$ 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 $\Upsilon(1S) \to q\bar{c}q\bar{c}$ rate via IC component as,

$$\Gamma_{q\bar{c}q\bar{c}} = \frac{\Gamma_{\Upsilon(1S)}}{\Gamma_{ee}} \sim 6 \left(\frac{\alpha}{\alpha_{0}}\right)^2 |\Psi_{b\bar{c}q}|^2 \times 1.3 \text{ keV},$$

for a single quark flavor $q$, where 6 is from 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 $\Gamma_{q\bar{c}q\bar{c}} < 50\% \times \Gamma_{\Upsilon(1S)}$, which implies that the IC fraction $|\Psi_{b\bar{c}q}|^2 \lesssim 10^{-3}$. This is not in conflict with $|\Psi_{\text{bcud}}|^2 \sim 1\%$ since the $\Upsilon(1S)$ is basically a nonrelativistic bound state hence lacks high frequency components. But it does
mean that, if IC is relevant at all, Υ(1S) → (c̅c)_{octet} + q̅q could easily be 10% (or 5 keV) of Υ(1S) rate.

It is remarkable that the last statement is consistent with all known facts. Very few hadronic decays of Υ(1S) have been reconstructed so far, while the strong α_{S} dependence of Υ(1S) → ggg rate certainly allows Υ(1S) → (c̅c)_{octet} + q̅q ≈ 10%. This is also consistent with the observed Υ(1S) → J/ψ + X ≈ 1.1 × 10^{-3}, since J/ψ formation should be just a small fraction of (c̅c)_{octet} while the softness of observed J/ψ spectrum is also explained. The main part of (c̅c)_{octet} evolves into D^{(*)} + X where the D^{(*)} mesons are slow, accompanied by two “jets” from the q̅q and gg with 5 − 6 GeV total energy. We note that the ARGUS Collaboration has set a bound of 165 Υ(1S) → D^{−}X < 1.9% for pD^{−} > 0.86 GeV. This is not yet constraining after adjusting for D^{−} fraction, and in particular, one must loosen the cut on pD^{−} to be sensitive to IC induced decays. It is rather exciting that CLEO would be running on Υ environments complement each other, with excellent n_{T} detection at B Factories but larger cross section and higher boost at Tevatron, where a large number of J/ψ events have been recorded. The B → D^{(*)}K^{(*)} modes should be searched for as control on rescattering diagrams.

In conclusion, we propose the following study plan. B Factory and Tevatron experiments should scan low momentum J/ψ events for B → J/ψDπ, J/ψφK + X, and J/ψΛN. If B → J/ψDπ (and perhaps J/ψD^{*}) is established above 10^{-4} level, while D^{(*)}K^{(*)} modes are found to be far less, one then has a good case for intrinsic charm in B. CLEO should run on Υ(1S) and collect at least 1 fb^{-1} data, reconfirm Υ(1S) → J/ψ(q\bar{q}) + X, and search for Υ(1S) → D^{(*)} + X. Slow moving J/ψ or D^{(*)}D^{(*)} in an otherwise jetty event from Υ(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 B → D^{+}ℓν decay as well.

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