Accounting for Slow $J/\psi$ from $B$ Decay

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A slow $J/\psi$ excess exists in the inclusive $B \rightarrow J/\psi + X$ spectrum, and is indicative of some hadronic effect. From color octet nature of $c\bar{c}$ pair in $b \rightarrow c\bar{c}s$ decay, one such possibility would be $B \rightarrow J/\psi + K_g$ decay, where $K_g$ is a hybrid resonance with $s\bar{q}q$ constituents. We show that a $K_g$ resonance of $\sim 2$ GeV mass and suitably broad width could be behind the excess.

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Using 1.12 fb$^{-1}$ data, the CLEO experiment published the inclusive $B \rightarrow J/\psi + X$ spectrum [1]. After subtracting $\chi_{c1}$, $\chi_{c2}$ and $\psi(2S)$ feeddown, there was a hint of excess events around $p_{J/\psi} \sim 0.5$ GeV, where $p_{J/\psi}$ is $J/\psi$ momentum in $\Upsilon(4S)$ frame. With 6.2 fb$^{-1}$ data, the Belle experiment presented [2] the inclusive $B \rightarrow J/\psi + X$ spectrum. After feeddown subtraction, one could also infer [3] an excess for $p_{J/\psi} \lesssim 0.8$ GeV. Recently, the BaBar experiment published [4] similar results based on 20.3 fb$^{-1}$ data, showing clear excess beyond NRQCD expectations [5], of order $10^{-3}$ in rate, for $p_{J/\psi} \lesssim 0.8$ GeV.

As the excess involves slow moving $J/\psi$ mesons, it must have hadronic, rather than perturbative, origins. Various proposals have been advanced. The suggestion of $B \rightarrow J/\psi A_p$ [4] has been studied recently by BaBar [7]; the event rate at $10^{-5}$ order cannot explain the slow $J/\psi$ excess. Intrinsic charm content of the $B$ meson could lead to $B \rightarrow J/\psi D(\pi^\pm)$ final states [6], which can in principle explain the data, but experimental studies are not yet forthcoming. If $B \rightarrow J/\psi D\pi$ dominates, the slow pion does not pair with $D$ to form a $D^*$, and would pose a challenge. Another possibility [6] would be $B \rightarrow J/\psi K_g$, where $K_g$ is a hybrid meson with $s\bar{q}q$ constituents. A recent estimate [4] suggests that the rate could be in the ballpark.

In this note we take a heuristic approach to explore the last possibility. We find the hybrid scenario is indeed viable. We suggest the signature of $B \rightarrow J/\psi + K + n\pi$, where $n$ cannot be more than a few, should be experimentally searched for. If the $K + n\pi$ system tends to peak at some mass, but does not descend from $D$ meson decay, then the hybrid meson picture could be substantiated.

Let us visualize why a hybrid meson recoiling against a $J/\psi$ could be the right picture. In $b \rightarrow c\bar{c}s$ decay, the $c\bar{c}$ pair is dominantly formed in a color octet configuration, hence charmonium production is color-suppressed. Imagine that, upon $b$ quark weak decay, the $c$ and $\bar{c}$ quarks are moving apart with more than $\sim 1$ GeV kinetic energy. Soft “muck” effects cannot change the configuration, and the system would tend to break up into open charm meson pairs, resulting in $D^{(*)}\bar{D}^{(*)}$ or $D\bar{D}K$ final states. But if the $c$ and $\bar{c}$ momenta are relatively collinear, it can be viewed as a “proto-charmonium”. Because of the heaviness of $m_c$, this small, dominantly color octet $c\bar{c}$ system would recoil against the $s$ quark, again relatively unperturbed by the soft “muck”. By the time it separates from the $s$ quark by order 1 fm, strong, non-perturbative effects set in: it has to hadronize. But since this is already a “proto-charmonium”, i.e. the spatial and spin wave-function already maps well onto some physical charmonium state, the only problem is it has to shed color. An effective color octet charge is thus left to neutralize the $s\bar{q}$ system, and the simplest configuration is that of $s\bar{q}g$, which we call an $K_g$ hybrid system.

Whether a $K_g$ hybrid meson really exists becomes semantical. As visualized above, the leftover color octet charge with the color octet $s\bar{q}$ system is not by perturbative gluon emission [6], but by the fact that two separate color strings extend from the $s$ and the $\bar{q}$ towards the point where the $c\bar{c}$ hadronization took place. It is plausible that this $s-\bar{q}-\bar{q}$ string configuration could resonate and the amplitude gets enhanced, and energy-momentum is exchanged with the departing charmonium. If the $K_g$ resonance is of order 2 GeV in mass, then the $J/\psi$ has to be slow. We have therefore constructed the physical picture whereby slow $J/\psi$ (charmonium in general) can receive enhancement.

Let us illustrate further this picture. The relevant effective weak Hamiltonian is

$$H_W = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{cb} (c_1 \mathcal{O}_1 + c_2 \mathcal{O}_2),$$

$$\mathcal{O}_1(2) \equiv \bar{s}_\alpha \gamma^\mu (1 - \gamma_5) c_{\gamma(\beta)} \bar{\gamma}_{\beta(\alpha)} \gamma^\mu (1 - \gamma_5) b_\beta. \quad (1)$$

The amplitude for $B \rightarrow J/\psi K_g$ decay is

$$A(J/\psi K_g) = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{cb} a_2 \langle J/\psi|\bar{c}\gamma^\mu c|0\rangle \langle K_g|s\gamma^\mu b|B \rangle, \quad (2)$$

where $a_2$ is the effective coefficient governing color-suppressed modes, which in the naive factorization limit is $c_2 + c_1/3$. Fitting data gives $a_2 \gtrsim 0.25$, but factorization calculations tend to give lower values of $a_2 \lesssim 0.2$, suggesting that nonfactorized effects are important.

We now infer from Eq. (2) by analogy the formula for $B \rightarrow J/\psi K_g$. It is well known that

$$\mathcal{O}_1 = 2 \langle \bar{T}^a c \rangle V_{-A} (\bar{T}^a b) V_{-A} + \mathcal{O}_2^2 \frac{3}{3}, \quad (3)$$
where $T^a$ is the color SU(3) generator. A color octet $c\bar{c}$ pair is favored. The “proto-$J/\psi$” would still be produced by a $c\bar{c}$ vector current, but stripping off the extra color as it departs, one is left with a “constituent” gluon in association with the $s\bar{q}$ bilinear. The nonperturbative picture should be two (different colored) strings extending from the point of departure of the $J/\psi$ towards the recoiling $s$ and spectator $\bar{q}$ quarks. Using a factorization language for sake of illustration, the matrix element product, $(J/\psi g)(\bar{T}^a c)_{V-A}(0)\langle [\bar{s} T^a b]_{V-A}|\bar{B}\rangle$, where $g$ is a constituent gluon and $[\bar{s} q]\bar{b}$ is a color octet quark pair, should be nonvanishing. The final state therefore would necessarily have the $J/\psi$ recoiling against a color singlet $s\bar{q}$ configuration, which could form a hybrid $K_g$ meson. We heuristically write the operator $2(\bar{c}T^a c)_{V-A}(\bar{s} T^a b)_{V-A}$ as $\bar{c}\gamma^\mu c[\bar{s} q]_\mu$, which we now take as our Ansatz. Thus, the formula for $B \rightarrow J/\psi K_g$ becomes,

$$A(J/\psi\bar{K}_g) \propto \frac{G_F}{\sqrt{2}} V_{cs} V_{cb} c \langle J/\psi |\bar{c}c^\mu c|0\rangle \langle \bar{K}_g|[\bar{s} q]_\mu|\bar{B}\rangle,$$

(4)

where the $[\bar{s} q]$ operator can convert the $\bar{B}$ meson into $\bar{K}_g$, including matching its $J^P$, in analogy with the $\bar{s}\gamma^\mu b$ current converting $\bar{B}$ into $\bar{K}$. Note that the decay amplitude is proportional to $c_1$ rather than $a_2$, but there is some proportionality constant, hopefully of order 1, from the Ansatz we made above. Due to the usual difficulty of hadronic physics and the model dependence that would necessarily arise, we do not attempt at calculating theoretically this proportionality constant, but turn to data for its determination.

The simplest situation would be to have a $K_g$ meson with $J^P = 0^+$ (note that there are no “exotic” kaon hybrids). The contraction of vector current indices should then be very similar between Eqs. (2) and (4), and the $B \rightarrow J/\psi K_g(0^+)$ decay rate is estimated to be

$$\kappa_0 \propto \frac{|c_1|^2}{a_2} \frac{p_{K_g}^3}{p_{K}} |BW|^2 \mathcal{B}(B \rightarrow J/\psi K),$$

(5)

where $\kappa_0$ is related to the aforementioned proportionality factor, but it also contains possible differences in $B \rightarrow K_g$ and $B \rightarrow K$ form factors, and $p_{K_{(g)}}$ is the momentum of $K_{(g)}$ in the $B$ decay frame. Since the hybrid $K_g$ meson is expected to be broad, the decay rate is modulated by the Breit-Wigner factor [11]

$$BW(q^2) = \frac{\sqrt{q^2 \Gamma(q^2)}}{(q^2 - m^2) + i \sqrt{q^2 \Gamma(q^2)}},$$

(6)

where $q^2 = m_{J/\psi}^2 + m_B^2 - 2m_B E_{J/\psi}$ and $E_{J/\psi}$ is the $J/\psi$ energy in the $B$ rest frame. Note that, to account for kinematic dependence [11], a $\sqrt{q^2}$ factor is used instead of $m$. Furthermore,

$$\Gamma(q^2) = \frac{\sqrt{q^2} \Gamma_0}{m},$$

(7)

where $m$, $\Gamma_0$ are the mass and width of $K_g$ at $q^2 = m^2$.

We now make a fit to the inclusive $J/\psi$ spectrum and see whether a single hybrid $K_g$ suffices to account for the observed excess. The direct (feeddown subtracted) $B \rightarrow J/\psi X$ data is taken from Ref. [4]. BaBar uses NRQCD plus $B \rightarrow J/\psi K^{(*)}$ simulation results to fit their data. To simplify, we follow Refs. [2, 8], and use

$$f(p) = N(p - p_{\text{min}})(p - p_{\text{max}}) \exp \left[-\frac{(p - \bar{p})^2}{\sigma_0^2}\right],$$

(8)

to mimic the color-octet NRQCD [3] and $J/\psi K^{(*)}$ [3] components. We find $(N, p_{\text{min}}, p_{\text{max}}, \bar{p}, \sigma_0) = (26, 0, 1.95, 1.21, 0.5)$ and $(180, 1.2, 1.95, 1.65, 0.3)$, with all energy-momentum in GeV, give good accounts of the two contributions, respectively.

Adding now the $B \rightarrow J/\psi K_g$ contribution of Eq. (4), we smear by a Gaussian with rms spread of 0.12 GeV [4] to account for broadening in the $\Upsilon(4S)$ frame. Using $|c_1/a_2| = 5$ for illustration, and the isospin averaged $\mathcal{B}(B \rightarrow J/\psi K) = 0.94 \times 10^{-3}$, and allowing the NRQCD contribution to float in the new fit, we obtain

$$\kappa_0 \sim 2.3, \ m \sim 2.08 \text{ GeV}, \ \Gamma_0 \sim 72 \text{ MeV}. \quad (9)$$

The NRQCD contribution is reduced by 12% with respect to Ref. [4], the fitted $B \rightarrow J/\psi K_g$ branching ratio is $8.5 \times 10^{-4}$, and the spectrum is shown in Fig. 1(a). It is remarkable that a single $0^+$ hybrid $K_g$ meson with mass $\sim 2.1$ GeV and width $\sim 100$ MeV could account for the observed slow $J/\psi$ excess. The fudge factor $\kappa_1 \sim 2.3$ means our inference by analogy is in the right ballpark.

Let us investigate the case for $K_g$ meson with $J^P = 1^+$. Replacing $K$ by $K^*$ in Eq. (2), we estimate, in analogy to Eq. (8), the $B \rightarrow J/\psi K_g(1^+)$ decay rate to be

$$\kappa_1 \frac{|c_1|^2}{a_2} \frac{p_{K^*}}{p_{K}} |BW|^2 \mathcal{B}(B \rightarrow J/\psi K^*),$$

(10)

where $\kappa_1$ is analogous to $\kappa_0$, but now the $B \rightarrow K_g$ and $B \rightarrow K^*$ form factor ratio can be rather complicated, because of two possible helicity configurations. Absorbing all of this into $\kappa_1$, we retain linear momentum dependence corresponding to longitudinally polarized component, which is expected to be dominant from usual form factor models, as well as in the heavy quark limit.

Performing a fit as before using isospin averaged $\mathcal{B}(B \rightarrow J/\psi K^*) = 1.35 \times 10^{-3}$, we obtain

$$\kappa_1 \approx 0.6, \ m \approx 2.05 \text{ GeV}, \ \Gamma_0 \approx 70 \text{ MeV}. \quad (11)$$

The NRQCD contribution is reduced by 11% with respect to Ref. [4], and the fitted $\mathcal{B}(B \rightarrow J/\psi K_g(1^+))$ is $7.9 \times 10^{-4}$. The spectrum is shown in Fig. 1(b), which is similar to Fig. 1(a) since mass and width are almost the same. Note that the fudge factor $\kappa_1 \approx 0.6$ appears even more reasonable than the $0^+$ case.

Fig. 1 suggests that the fits may not yet be optimized for $p_{J/\psi}$ between 0.9–1.5 GeV. As we have allowed some freedom in the strength of the NRQCD contribution [3],
we now allow its peak position to float as well. Fitting again, we find for $0^+$ case
\begin{equation}
\kappa_0 \simeq 2.0, \ m \simeq 2.08 \text{ GeV}, \ \Gamma_0 \simeq 147 \text{ MeV}, \tag{12}
\end{equation}
with the NRQCD contribution reduced by 13% with respect to Ref. \cite{4}, and the parameter $\bar{p}$ shifted by 100 MeV to 1.31 GeV. The fitted $B \to J/\psi K_g$ branching ratio becomes $12.9 \times 10^{-4}$. For $1^+$ case, we find
\begin{equation}
\kappa_1 \simeq 0.5, \ m \simeq 2.03 \text{ GeV}, \ \Gamma_0 \simeq 103 \text{ MeV}, \tag{13}
\end{equation}
with NRQCD contribution reduced by 10% with respect to Ref. \cite{4}, $\bar{p}$ shifted from 1.21 GeV to 1.29 GeV, and fitted $B(B \to J/\psi K_g(1^+)) \simeq 10.5 \times 10^{-4}$. The fitted spectrum is shown in Fig. 2. The remaining slight “discrepancy” can be attributed to the difference between a perturbative vs. hadronic approach, e.g. summing over $J/\psi K_1$, $J/\psi K_2$, etc. modes.

We do not commit ourselves to what should be the lightest $K_g$ hybrid state, or how large is the splitting for further excitations. It is gratifying, however, that the fitted masses of order 2–2.1 GeV is close to expectations \cite{10}. The width of 70–150 MeV may seem narrow, but kaonic hybrids have not been widely discussed in the literature, and the relative narrowness would make experimental identification easier. As for decay modes, we remark that flux tube models suggest \cite{14} hybrids decay into final states with one excited meson. Thus, one should consider reconstructing $K_g$ in $K_{0,1,2}^0(\pi, \rho)$, $K^+ f_{0,1,2}$, maybe also $K^+ f''$ final states. It would be fascinating if a heavy kaon resonance is found to be dominating the slow $J/\psi$ excess from $B$ decay.

We note that the $K_g$ width is larger for the improved fit of Fig. 2. We have checked that $\Gamma_0 \sim 250$ MeV is possible, if the “peak position” parameter $\bar{p}$ is allowed to shift slightly higher, to 1.34 GeV and 1.31 GeV, respectively, for the $0^+$ and $1^+$ cases. Thus, the narrowness of $\Gamma_0 \sim 70$ MeV of Eqs. (9) and (11) may be an artefact of trying to mimic the NRQCD result of Ref. \cite{4}. The latter work subtracted $B \to J/\psi K$ and $J/\psi K^*$, an approach BaBar adopted, but it was done before the Belle measurement \cite{12} of $B(B \to J/\psi K_1(1270)) \simeq 1.55 \times 10^{-3}$ (isospin averaged), which is comparable to $B \to J/\psi K$ and $J/\psi K^*$. An update of Ref. \cite{4} would be helpful.

The $0^-$ and $1^-$ hybrid quantum numbers allow us to make some insight into the possible cause of sizable non-factorizable contributions to $B \to J/\psi K^{(*)}$, $J/\psi K_1$ decay. The physical $K^{(*)}$ state may have a hybrid Fock component, $|K \rangle = c_0 |K_0 \rangle + s_0 |K_2 \rangle$. One then finds
\begin{equation}
a_2^{\text{eff}} = a_2^{\text{fac}} \left( c_0 + \frac{c_1}{a_2 \kappa_0 s_0} \right), \tag{14}
\end{equation}
where $a_2^{\text{fac}}$ is from factorization calculations, typically of order 0.15–0.2. One sees from our fitted $\kappa$ values that a hybrid admixture of a few % to no more than 10% in the $K^{(*)}$ wavefunction can suffice to account for the
large $a_2^{\text{eff}} \sim 0.25$–0.3 extracted from data, in large part because of gaining the $c_1/a_2$ factor.

We comment on a recent proposal that slow $J/\psi$ from $B$ decay could arise from $cq\bar{q}\bar{c}$ four quark states \[14\]. The physical picture would be that the color octet $c\bar{c}$ picks up a color octet $q\bar{q}$ pair as it hadronizes. Ref. \[14\] gave some arguments for why $J/\psi$ may end up slow. It may not be so easy to distinguish this proposal from the present one, as both lead to $J/\psi + K + n\pi$ final states, and in fact both mechanisms may well be at work concurrently. To distinguish the two mechanisms, one would have to check whether the charmonium system is resonating with some of the recoil hadrons. For $K_g$ mechanism, it would be helpful if $K_{0,1,2}^{*}(\rho)$, $K_{0,1,2}^{*}(\rho)$, $K_{0,1,2}^{*}(\rho)$, $K_{0,1,2}^{*}(\rho)$ configurations.

In summary, we have illustrated that a single hybrid $K_g$ state recoiling against a $J/\psi$ could explain the slow $J/\psi$ excess observed in $B$ decay with rate at $10^{-3}$ order. The fitted $K_g$ mass is of order 2.05–2.1 GeV, with width of order 70–150 MeV, but could be broader. Experimental signature would be to reconstruct $K_g \rightarrow K + n\pi$, probably in $K_{0,1,2}^{*}(\rho)$, $K_{0,1,2}^{*}(\rho)$, $K_{0,1,2}^{*}(\rho)$ configurations.

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