Search for $^1P_1$ charmonium in B decay

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There is no doubt that the $^1P_1$ charmonium h_c exists in the mass range between J/ψ and ψ'. While experiment produced a candidate in the past, it still requires a confirmation. Given the recent progress in the exclusive B decay into charmonia, we now have an opportunity to detect h_c by measuring the final state $\gamma\eta_c$ of the cascade decay $B\to h_cK/K^*\to\gamma\eta_cK/K^*$. Confirmation of h_c may turn out to be much easier in the B decay than at charm factories, although one may have to work a little harder to attain a high precision in the mass determination.

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I. INTRODUCTION

A few measurements suggested the $^1P_1$ charmonium around mass 3526 MeV [1–3]. In particular, the E760 Collaboration [2] studied the resonant production of h_c in $p\bar{p}$ annihilation[1] and quoted the h_c mass at 3526.2 MeV. This value is almost exactly equal to the center of gravity (3525.17 MeV) of the ^3P_J charmonia χ_{cJ} ($J=0,1,2$). However, the result has yet to be confirmed by the E835 Collaboration [5]. No evidence has so far been seen for h_c in e^+e^- annihilation. From the theoretical viewpoint, there is no reason to expect that the h_c mass should be so close to the center of gravity of the ^3P_J masses, since such a relation based on the $\mathbf{L}\cdot\mathbf{S}$ coupling and the tensor force of one-gluon exchange would break down when general spin-dependent interactions are included. Experimentally, the χ_{cJ} mass splitting gives

$$R\equiv\frac{m_{\chi_{c2}}-m_{\chi_{c1}}}{m_{\chi_{1c}}-m_{\chi_{c0}}}\simeq 0.476. \tag{1}$$

The right-hand side would be equal to 2 for the $\mathbf{L}\cdot\mathbf{S}$ coupling alone, 0.8 with all spin-dependent forces of one-gluon exchange, and $0.8\leqslant R\leqslant 1.4$ after including the more general spin-spin interaction arising from the confining potential [6]. Since our knowledge of the spin-dependent charmonium potential is incomplete, there is no accurate theoretical prediction of m_{h_c} relative to $m_{\chi_{cJ}}$ even within the potential model. Furthermore, the E1 transition matrix elements for $\chi_{cJ}\to\gamma J/\psi$ deviate largely from the nonrelativistic values. When relativistic corrections are large for the motion of c and $\bar{c}$, we should be cautious about the accuracy of the potential model approach.

Review of Particle Physics [4] has not yet listed h_c among the confirmed particles. Undoubtedly, much effort will be devoted to the pursuit of h_c at upcoming charm factories overcoming the odds against it. Meanwhile, the recent progress in B physics suggests a new opportunity to search for h_c. The purpose of this Brief Report is to point out that we may be able to observe h_c more easily at the B factories than at future charm factories and in hadron reactions.

Recently the Belle Collaboration discovered that the factorization-forbidden decay $B\to\chi_0K$ occurs as vigorously as the factorization-allowed decays to other charmonia [7]. On the basis of this finding, we expect that another factorization-forbidden decay $B\to h_cK$ may also occur just as abundantly as $B\to\chi_{c0}K$. Since $h_c\to\gamma\eta_c$ is one of the two main decay modes of h_c, the decay $B\to h_cK$ cascades down to the final state $\gamma\eta_cK$ about half of time. The only background for this process at the B factories will be the process $B\to\psi'K\to\gamma\eta_cK$. Since the branching fraction for $\psi'\to\gamma\eta_c$ is minuscule, however, this background is two orders of magnitude smaller than the signal. If one can reconstruct η_c from $K\bar{K}\pi$ or by $\eta\pi\pi$ with 50% efficiency, for instance, 10 million B's translate to roughly 100 events of the signal. Therefore, we have a very good chance to observe h_c through $B\to\gamma\eta_cK$.

II. $B\to$ CHARMONIUM $+$ K

The Belle Collaboration reported for the decay $B\to\chi_{c0}K$ [7]

$$\mathrm{B}(B^+\to\chi_{c0}K^+)=(8.0^{+2.7}_{-2.4}\pm1.0\pm1.1)\times10^{-4}. \tag{2}$$

This number should be compared with the recent measurement by the BaBar Collaboration on the B decay into other charmonia [8],

$$\begin{aligned}\mathrm{B}(B^+\to J/\psi K^+)&=(10.1\pm0.3\pm0.5)\times10^{-4},\\ \mathrm{B}(B^+\to\chi_{c1}K^+)&=(7.5\pm0.8\pm0.8)\times10^{-4},\\ \mathrm{B}(B^+\to\psi'K^+)&=(6.4\pm0.5\pm0.8)\times10^{-4}.\end{aligned} \tag{3}$$

Added to these is an earlier measurement on the branching fraction for $B\to\eta_cK$ by CLEO [9],

$$B(B^+\to\eta_cK^+)=(6.9^{+2.6}_{-2.1}\pm0.8\pm2.0)\times10^{-4}. \tag{4}$$

Most recently, however, BaBar gave a preliminary result for this decay as [10]

$$B(B^+\to\eta_cK^+)=(15.0\pm1.9\pm1.5\pm4.6)\times10^{-4}. \tag{5}$$

[1] Although the naming is odd, I refer to the $^1P_1$ charmonium as h_c following the Particle Data tabulation [4].

We should notice here that the decay $B\to\chi_{c0}K$ is forbidden by the factorization while $B\to J/\psi(\psi')K$, $B\to\eta_cK$, and $B\to\chi_{c1}K$ are all allowed. Nonetheless the branching fraction to $\chi_{c0}K^+$ is just as large as those into $J/\psi(\psi')K^+$, η_cK^+, and $\chi_{c1}K^+$. Since no effective decay operator allows $B\to\chi_{c0}K$ in the factorization limit, its decay amplitude must arise from the loop corrections of the energy scale below m_b to the tree-decay operators $O_{1,2}$. The relevant $\bar{c}c$ operator for production of χ_{c0} is generated when the bilocal operator $\bar{c}(x)c(y)$ due to the loop correction is expanded in the series of local operators; $\bar{c}(x)c(y)\to\bar{c}(x)c(x)+\bar{c}(x)(y-x)_\mu\partial^\mu c(x)+\ldots$. If the relevant part of the loop energy is between m_b and m_c, then $|y-x|\simeq 1/m_b\sim 1/m_c$ so that one may keep only the leading term of the expansion. In this case, the QCD coupling α_s/π would suppress the $B\to\chi_{c0}K^+$ decay branching by $(\alpha_s/\pi)^2$ though the suppression relative to the factorization-allowed processes may be somewhat moderated by the color structure. The experimental fact that $B(B^+\to\chi_{c0}K^+)$ is comparable with $B(B^+\to\chi_{c1}K^+)$ indicates that the factorization, even improved with perturbative QCD corrections, is in serious doubt for the B decay into charmonia. In terms of the local expansion of $\bar{c}(x)c(y)$, the magnitude of the relevant $|y-x|$ is as large as $1/\Lambda_{\rm QCD}$ or, in the case of charmonia, could be the charmonium radius $1/\alpha_s m_c$. If so, we must include not only all terms of the local expansion but also all orders of α_s in computation of decay amplitudes. Then a quantitative calculation based on perturbative QCD is intractable.

The decay $B\to h_cK$ is also forbidden by the factorization and has the same chiral structure $(\bar{c}_Lc_R\pm\bar{c}_Rc_L)$ for charmonium as $B\to\chi_{c0}K$. The local operator of the lowest dimension leading to the decay $B\to h_cK$ is $\bar{c}\gamma_5\overleftrightarrow{\partial^\mu}c$ [11]. When the factorization and perturbative QCD fail as proven by the $B\to\chi_{c0}K$ decay rate, it is very likely that the decay $B\to h_cK$ occurs as abundantly as $B\to\chi_{c0}K$ and the factorization-allowed B decays into charmonia.

A comment is in order for another factorization-forbidden decay, $B\to\chi_{c2}K$. The decay $B\to\chi_{c2}K$ occurs with $i\bar{c}\gamma^\mu\overleftrightarrow{\partial^\nu}c$. The Belle Collaboration did not see a signal of $B\to\chi_{c2}K$ with a statistical significance [7]. However, since they searched $\chi_{c0,c2}$ by its $\chi_{c0,c2}\to\pi^+\pi^-$ and K^+K^- decay modes, their failure to see a clear signal for $B\to\chi_{c2}K$ may be due to the smaller branching fractions for $\chi_{c2}\to\pi^+\pi^-$ and K^+K^- as compared with $\chi_{c0}\to\pi^+\pi^-$ and K^+K^-. On the other hand the CLEO Collaboration identified χ_{c2} by $\chi_{c2}\to J/\psi\gamma$ and concluded that $B(B\to\chi_{c2}X)$ is significantly less than $B(B\to\chi_{c1}X)$. But they focused on the inclusive decays and the uncertainties were large for the exclusive decays: $0.04<B(B\to\chi_{c2}K/K^*)/B(B\to\chi_{c1}K/K^*)<0.58$ with the 95% confidence level. (See sample B of Ref. [12].) Very recently, however, the Belle Collaboration reported the branching fraction for inclusive χ_{c2} production [13],

$$B(B\to\chi_{c2}X)=(15.3^{+2.3}_{-2.8}\pm 2.6)\times 10^{-4}, \tag{6}$$

where the χ_{c2}'s fed by $\psi'\to\gamma\chi_{c2}$ have been subtracted out. This number is twice as large as the corresponding one of CLEO [12]. In view of this latest Belle measurement, it is possible that $B(B\to\chi_{c2}K)$ will eventually turn out to be comparable with $B(B\to\chi_{c0}K)$.

To summarize the experimental status of $B\to$charmonium, the factorization-forbidden process $B\to\chi_{c0}K$ occurs as strongly as the factorization-allowed processes. The decay $B\to\eta_cK$ shows no sign of suppression for formation of a spin singlet of $\bar{c}c$ relative to a triplet. We therefore expect that the factorization-forbidden decay into another spin singlet, $B\to h_cK$, may also occur with a comparable branching fraction. Since we cannot resort to the factorization method to calculate the branching fraction, we proceed with the tentative assumption

$$B(B\to h_cK)\approx B(B\to\chi_{c0}K). \tag{7}$$

We mean here that two branching fractions are of the same order of magnitude. With this relation as a guideline, we now explore whether search of h_c is feasible or not in B decay. If experiment successfully identifies decay products of h_c in B decay, we can go backward and determine $B(B\to h_cK)$ from an observed cascade branching fraction since the branching fractions of h_c to final states are much better known either theoretically or experimentally.

III. DECAY OF $^1P_1$

Numerous calculations were performed for the properties of charmonia in potential models [6,14]. The decay property of χ_{c1} and h_c was specifically studied by Bodwin *et al.* [15]. Production of h_c through $\psi'\to h_c\pi^0$ in e^+e^- annihilation was also studied [16–18]. However, all that we need for our purpose here can be obtained directly from the experimental numbers for other charmonia if we make the approximation to use a common orbital wave function for the spin singlet and triplet of the same principal quantum number. This approximation is justified for the c and $\bar{c}$ in nonrelativistic motion, and the results are independent of specific bound-state wave functions. Although the nonrelativistic treatment of charmonia is often limited in precision, we do not need much more than that for our discussion below.

The main decay modes of h_c are $h_c\to ggg$ and $h_c\to\gamma\eta_c$. The former is given by perturbative QCD to the leading logarithm of the h_c size [19]. By equating the h_c bound-state wave function at the origin to that of χ_{c1}, we obtain with the experimental value $\Gamma(\chi_{c1}\to ggg)=\Gamma(\chi_{c1}\to\text{hadrons})=640\pm 100$ keV,

$$\begin{aligned}\Gamma(h_c\to ggg)&=\frac{5}{6}\times\Gamma(\chi_{c1}\to ggg),\\ &=530\pm 80\ \text{keV}.\end{aligned} \tag{8}$$

This numerical value does not depend on the magnitude of the fuzzy cutoff variable in the leading logarithmic term nor on specific binding potentials.

The radiative decay $h_c\to\gamma\eta_c$ is an allowed E1 transition similar to $\chi_{cJ}\to\gamma J/\psi$. We can eliminate the E1 transition matrix element $\langle f|\mathbf{r}|i\rangle$ between the $1P$ and the $1S$ state by relating $h_c\to\gamma\eta_c$ to $\chi_{c1}\to\gamma J/\psi$:

$$\Gamma(h_c\to\gamma\eta_c)=\left(\frac{|\mathbf{p}|}{|\mathbf{p}'|}\right)^3\Gamma(\chi_{c1}\to\gamma J/\psi),$$
$$=520\pm 90\ \ \text{keV}. \tag{9}$$

The central value of Eq. (9) is about 15% higher than the value computed by Bodwin *et al.* [15] while the value 530 ± 80 keV of Eq. (8) coincides with theirs. The rates for other modes such as $h_c\to J/\psi\pi^0$ and $\gamma\chi_{c0}$ are of $O(1)$ keV. Therefore we obtain from the ggg and $\gamma\eta_c$ decay modes the $h_c\to\gamma\eta_c$ branching fraction,

$$B(h_c\to\gamma\eta_c)=0.50\pm 0.11. \tag{10}$$

In this estimate the uncertainty is entirely due to those of the measured values for $\Gamma_{tot}(\chi_{c1})$ and $B(\chi_{c1}\to\gamma J/\psi)$. The value of Eq. (10) is a firm number up to relativistic corrections and higher-order QCD corrections, though the former corrections may turn out to be larger than we imagine.

Combining $B(h_c\to\gamma\eta_c)$ of Eq. (10) with Eqs. (2) and (7), we obtain the cascade branching fraction for $B\to h_cK\to\gamma\eta_cK$,

$$B(B^+\to h_cK^+\to\gamma\eta_cK^+)=(4.0^{+1.6}_{-1.5}\pm 0.5\pm 0.6)\times 10^{-4}. \tag{11}$$

It should be remembered that the number in the right-hand side is based on the tentative assumption made in Eq. (7). If η_c is searched by $K\bar{K}\pi$ or $\eta\pi\pi$ (the branching fraction $\simeq 5\%$ each), the cascade branching fraction is

$$B(B^+\to h_cK^+\to\gamma\eta_cK^+\to\gamma(K\bar{K}\pi)K^+)\simeq 2\times 10^{-5} \tag{12}$$

for $B(B\to h_cK)\simeq B(B\to\chi_{c0}K)$. When 10 million B mesons are accumulated, there will be about 100 events of the $\gamma\eta_cK^+$ signal just from $K\bar{K}\pi$ or from $\eta\pi\pi$ alone in the case in which the reconstruction efficiency of h_c is 50% for these decay modes. One can increase statistics by including $B^\pm\to h_cK^{*\pm}$ and by combining $B^0/\bar{B}^0$ with $B^\pm$. There will be a sufficient number of the cascade $B\to h_cX\to\gamma\eta_cX$ events to search for h_c if $B(B\to h_cK)$ is as large as $B(B\to\chi_{c0}K)$. Even if $B(B\to h_cK)$ happens to be one-tenth of $B(B\to\chi_{c0}K)$, search of h_c will be possible with 100 million B's, i.e., long before BaBar and Belle experiments come to a close. Once we obtain a number for the cascade branching of Eq. (12) from experiment, we should use it to determine $B(B\to h_cK)$, which we have equated temporarily to $B(B\to\chi_{c0}K)$ in our discussion above,

$$B(B^+\to h_cK^+)=(36\pm 14)\times B[B^+\to h_c(\to\gamma\eta_c\to\gamma K\bar{K}\pi)K^+], \tag{13}$$

where the numerical factor on the right-hand side is the inverse of $B(h_c\to\gamma\eta_c)B(\eta_c\to K\bar{K}\pi)$.

Let us compare Eq. (12) with the corresponding number in the h_c search through $\psi'\to h_c$ at charm factories. According to the calculation by Kuang, Tuan, and Yan [16] and more recently by Kuang [20], who included *S-D* mixing of ψ', the branching fraction for $\psi'\to h_c\pi^0$ is at the level of 1×10^{-3} at most, for $m_{h_c}=3526.2$ MeV. Taking account of the low reconstruction efficiency of the soft $\pi^0\to\gamma\gamma$, Kuang estimates that detection of h_c through $\psi'\to h_c\pi^0$ requires 30 million ψ''s at charm factories. While h_c can be produced only through $\psi'\to h_c\pi^0$ at charm factories, the h_c production occurs in the B decay in conjunction with K^* or a higher strange meson as well as with K. Furthermore, the production in conjunction with K^* tends to be stronger than that with K in the $B\to$charmonium decay. By and large, the search of h_c will be quite competitive with the search at charm factories, if not superior to it.

IV. POSSIBLE BACKGROUND EVENTS

The only decay mode that feeds $\gamma\eta_cK$ with the $\gamma\eta_c$ invariant mass close to m_{h_c} is the cascade decay $B\to\psi'K\to\gamma\eta_cK$. Since $\psi'\to\gamma\eta_c$ is a hindered M1 transition with the branching fraction $(2.8\pm 0.6)\times 10^{-3}$, this cascade branching fraction is tiny,

$$B(B\to\psi'K^+\to\gamma\eta_cK^+)=(1.8\pm 0.4\pm 0.2)\times 10^{-6}. \tag{14}$$

It is more than two orders of magnitude smaller than the signal of Eq. (11). We can therefore choose a wide bin for $(p_\gamma+p_{\eta_c})^2$ in reconstruction of h_c without concern about the ψ' contamination in $\gamma\eta_c$. This is fortunate from the viewpoint of raising the precision in mass determination. Since there is no competing decay process, we may fix the invariant mass of $K\bar{K}\pi$ or $\eta\pi\pi$ to m_{η_c} once we find a cluster of candidate events. Although we certainly do not expect to determine the h_c mass to an accuracy anywhere close to its width ($\Gamma_{h_c}\simeq 1$ MeV), it will be easy to notice if the h_c mass is located substantially off the center of gravity of χ_{cJ}.

It will be challenging to identify h_c directly by its hadronic decay modes. Since h_c is G-parity odd, the simplest decay mode is $h_c\to\pi\pi\pi$, then $K\bar{K}\pi$. The branching fractions to $\pi\pi\pi$ and $K\bar{K}\pi$ are no larger than at the level of 1% if we make a guess by rescaling the corresponding decays of J/ψ. Then the cascade branching fraction is most likely of the order

$$B(B\to h_cK\to\pi^+\pi^-\pi^0K)=O(1)\times 10^{-5}. \tag{15}$$

After multiplying it with the reconstruction efficiency of $\pi^0\to\gamma\gamma$, it does not appear competitive with $B\to h_cK\to\gamma\eta_cK$. Although one can distinguish h_c from χ_{c1} by G-parity of the decay products, one can separate h_c from ψ' only by the mass resolution when one searches h_c by its hadron decays. There are clear advantages for studying the radiative cascade decay $B\to h_cK\to\gamma\eta_cK$.

V. SUMMARY

Nobody disputes the existence of h_c. Our real interest is in the values of its parameters. For this purpose the cascade decay process $B \to h_c K/K^* \to \gamma\eta_c K/K^*$ deserves a careful study at the B factories. The search of h_c through the B decay is very competitive with the search at charm factories and presumably superior to it. It will either confirm the controversial $^1P_1$ charmonium at the center of gravity of χ_{cJ} or discover it away from the mass suggested by $p\bar{p}$ annihilation. We should keep in mind that theory does not require that the h_c mass should be so close to the center of gravity of χ_{cJ}.

We shall obtain the product of the branching fractions, $B(B \to h_c K) \times B(h_c \to \gamma\eta_c)$, from the proposed B decay measurement. Since the value of $B(h_c \to \gamma\eta_c)$ given in Eq. (10) is a fairly firm number, measurement or nil measurement of the process $B \to h_c K \to \gamma\eta_c K$ will provide us with a meaningful number or a tight upper bound for $B(B \to h_c K)$. If we should end up with a nil result for $B \to h_c K \to \gamma\eta_c K$ at completion of the current B factory experiments, it would set an upper bound on $B(B \to h_c K)$ at a level of an order of magnitude or more lower than $B(B \to \chi_{c0} K)$. We think that this is very unlikely. Whatever the experimental outcome, information on h_c will provide us with an opportunity to examine all of $B \to$ charmonium decays together and will advance theoretical understanding of how or if the factorization plays a role in the B decay into charmonia.

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