Search for Missing Charmonium States in B-meson Decays

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Abstract

The recent progress in experiments at B-factories suggests an opportunity to search for the missing charmonium states $\eta_c'(2^1S_0)$ and $h_c(1^1P_1)$. The feasibility of such a search in B-meson decays are discussed.

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1. Introduction

Of the lowest charmonium states with radial quantum number n=1 and 2 below the open charm threshold, two singlet states, the $\eta_c'(2S_0)$ and the $h_c(1P_1)$, are still listed by the Particle Data Group in ref.[1] as missing or needing confirmation.

Much effort has been devoted to search for these states over past two decades. The Crystal Ball experiment claimed the first and also the only observation of a candidate for the $\eta_c'$ in the inclusive photon spectrum of the $\psi'$, with a mass of 3592±5 MeV and a total width of less than 8 MeV (95% C.L.)[2]. This result, however, has never been confirmed by other experiments, such as E760/E835[3], BES[4], DELPHI[5], and L3[6]. No evidence has been found for the $^1P_1$ state of charmonium in $e^+e^-$ annihilation. The discovery of $h_c$ at $\sqrt{s} = 3526.2 \pm 0.15 \pm 0.2$ MeV with a width of less than 1.1 MeV (90% C.L.) once reported by the E760 experiment in $p\bar{p}$ annihilation [7] has not yet been confirmed by more recent higher-statistics studies at the E835 experiment [8], an upgraded continuation of E760.

It was previously deemed that the search for these two singlet states of charmonium poses an unusual experimental challenge since they cannot be resonantly produced in $e^+e^-$ annihilation nor can populated by E1 decay of the $\psi'$ state. However, the unsuccessful experience at the Fermilab Antiproton Accumulator ring [3,8] teaches us that the reason may not merely due to the above difficulties in $e^+e^-$ experiments. In this letter, I will describe a new opportunity to search for these states at the B-factories and will study the feasibility of utilizing a few B-meson decays involving a charmonium meson to that end.

2. Physics of the $\eta_c'$ state

The mass of the $\eta_c'$ is predicted to be somewhere in the range between 3540-3630MeV [9]. The total width of the $\eta_c'$ can be calculated by the relation [10]

$$\frac{\Gamma(\eta_c')}{\Gamma(\eta_c)} \approx \frac{|\Psi(0)|^2}{|\Psi(0)|^2} = \frac{M_{\psi'}^2 \Gamma(\psi' \to e^+e^-)}{M_{J/\psi}^2 \Gamma(J/\psi \to e^+e^-)}$$
Plugging in the appropriate PDG numbers [1] results in \( \Gamma(\eta'_c) \) to be about 7.5 MeV.

Chao, Gu and Tuan [11] deduced a relation between the decay rates for \( \eta'_c \) and \( \eta_c \) to a light hadronic final state as

\[
\frac{B(\eta'_c \to h)}{B(\eta_c \to h)} \approx 1
\]  

(2)

and estimated partial widths for individual decay modes \( \eta'_c \to \eta\pi\pi \), \( \eta'_c \to h_c\gamma \), \( \eta'_c \to J/\psi\gamma \), and \( \eta'_c \to gg \) to be about 140 keV, 11 keV, 5 keV, and 4 MeV, respectively. It is obvious that \( \eta'_c \to gg \) is the dominant mode of the \( \eta'_c \) decays. According to relation (2), \( \eta'_c \to K\bar{K}\pi \), \( \eta\pi\pi \), \( \eta'\pi\pi \), and \( \rho\rho \) are expected to have the largest branching fractions.

However, the relation (2) is not necessarily to be observed for specific exclusive decays. This is a situation similar to the so-called \( \rho\pi \) puzzle in \( J/\psi \) and \( \psi' \) decays[12]. According to the hadron helicity conservation (HHC) theorem of PQCD, the decay of the \( J/\psi \) (\( \psi' \)) into \( \rho\pi \) is first-order forbidden [13]; however, while \( \rho\pi \) is the largest hadronic final state in \( J/\psi \) decay, with a branching fraction 1.27\%, this final state is unobserved for \( \psi' \), with a limit \(< 2.8 \times 10^{-5} \) (90\% C.L.), severely deviating from the ratio of \( \psi' \) to \( J/\psi \) decay rates naively predicted by PQCD[12]. Similarly, the decays of the \( \eta_c \) in two vector mesons (\( \rho\rho \), \( K^*\bar{K} \), \( \phi\phi \) and in \( p\bar{p} \) are also all forbidden by HHC, and yet they are actually observed to occur with relatively large branching fractions[14]. It is not clear whether the analogous decays of the \( \eta'_c \) obey the relation (2) or are suppressed in relation to \( \eta_c \). Therefore, in search for the \( \eta'_c \) state, one has to first choose those decay modes allowed by HHC.

### 3. Physics of the \( h_c \) state

The mass of the \( h_c \) is a subject of considerable interest as it has implications for the Lorentz nature of confinement. With scalar confinement the only spin-spin force is the one-gluon-exchange contact interaction, and as a result the \( h_c \) state will lie at spin-weighted center-of-gravity of the \( ^3P_J \) states,

\[
m_{c.o.g.} \equiv \frac{M_{\chi_{c0}} + 3M_{\chi_{c1}} + 5M_{\chi_{c2}}}{9} \simeq 3525\text{MeV}
\]  

(3)
Table 1: Results of $h_c$ decay rates by calculations in different approaches (where $\alpha_M/\alpha_E \approx 1 - 3$)

| $h_c$ Decay Mode          | PQCD            | NRQCD           |
|---------------------------|-----------------|-----------------|
| $\Gamma_{total}$          | $390 \pm 10$keV | $980 \pm 90$keV |
| $B(\gamma \eta_c)$        | $(85 \pm 9)$%   | $(34 \pm 3)$%   |
| B(light hadrons)           | $(11.5 \pm 1.8)$% | $(54 \pm 13)$% |
| $B(J/\psi \pi \pi)$       | $(1.8 \pm 0.2)(\alpha_M/\alpha_E)$% | |
| $B(J/\psi \pi^0)$         | $(0.15 \pm 0.02)(\alpha_M/\alpha_E)$% | |
| B($\gamma + $ light hadrons) | 0.96%           |                 |
| $B(K\bar{K}\pi)$          | $(5.5 \pm 1.7)$% | $(6.5 \pm 3.5)$% |
| $B(\rho\rho)$             | $(2.6 \pm 0.9)$% | $(2.9 \pm 1.8)$% |
| $B(\pi^+\pi^-K^+K^-)$     | $(2.0 \pm 0.7)$% | $(2.2 \pm 1.3)$% |

Alternatively, with vector confinement there is a $1/r$ spin-spin force, and the $h_c$ state is shifted upwards from the $m_{c.o.g.}$ by about $20 MeV/c^2$. A better determination of the mass of the $h_c$ is thus of importance for studies of the nature of confinement, which is one of the most interesting questions in nonperturbative QCD.

It is expected that the $h_c$ has a small width ($< 1$ MeV) and decays predominantly to the $\gamma \eta_c$ final state through an E1 transition. A recent calculation [15] in both conventional PQCD and NRQCD approaches provides a number of important decay rates for $h_c$. Table 1 lists the numerical results in both approaches.

4. Search for $\eta'_c$ and $h_c$ in B meson decays

After two years’ running at the KEKB and PEPII asymmetric energy $e^+e^-$ colliders, both the Belle and BABAR detectors have collected about $30 fb^{-1}$ $\Upsilon(4S)$ data sample, which contains over 30 million $B\bar{B}$ events[15-19]. A number of inclusive and exclusive B-meson decays with a charmonium in the final state have been studied and related branching fractions have been measured, as is shown in Table 2. It is particularly
Table 2: Some branching fractions for inclusive and exclusive decays of B mesons involving charmonium measured at B-factories.

| Channel | Branching fraction \((10^{-3})\) | Reference |
|---------|-----------------------------------|-----------|
| \(B^+ \to \eta_c K^+\) | 1.50 ± 0.19 ± 0.15 ± 0.46 | [16] |
| \(B^+ \to J/\psi K^+\) | 1.01 ± 0.03 ± 0.05 | [17] |
| \(B^+ \to \chi_{c0} K^+\) | 0.60^{+0.21}_{-0.18} ± 0.11 | [18] |
| \(B^+ \to \chi_{c1} K^+\) | 0.75 ± 0.08 ± 0.08 | [17] |
| \(B^+ \to \psi' K^+\) | 0.64 ± 0.05 ± 0.08 | [17] |
| \(B^+ \to J/\psi K^{*+}\) | 1.37 ± 0.09 ± 0.11 | [17] |
| \(B^0 \to \eta_c K^0\) | 1.06 ± 0.28 ± 0.11 ± 0.33 | [16] |
| \(B^0 \to J/\psi K^0\) | 0.83 ± 0.04 ± 0.05 | [17] |
| \(B^0 \to \chi_{c1} K^0\) | 0.54 ± 0.14 ± 0.11 | [17] |
| \(B^0 \to \psi' K^0\) | 0.69 ± 0.11 ± 0.11 | [17] |
| \(B^0 \to J/\psi K^{*0}\) | 1.24 ± 0.05 ± 0.09 | [17] |
| \(B \to \chi_{c2} X\) | 3.32 ± 0.22 ± 0.34 | [19] |
| \(B \to \chi_{c2} X\) | 1.53^{+0.23}_{-0.28} ± 0.27 | [19] |

Interesting to observe the factorization-forbidden decay \(B \to \chi_{c0} K\), which has a rate comparable to those for the factorization-allowed \(B \to J/\psi K\) and \(B \to \chi_{c1} K\) decays [18], and a statistically significant inclusive \(\chi_{c2}\) production in B-meson decays, which is also a factorization-forbidden process[19]. The experimental progress at B-factories suggests a good opportunity to search for the missing charmonia in B-meson decays.

In comparison with the BES experiment and the proposed CLEO-c program which take data on the \(\psi'\) resonance, the B-factory experiments will have significant advantages in looking for the \(\eta_c'\) and \(h_c\). In respect of detector performance, both Belle and Babar are modern detectors, while the CLEO-c is similar to them but will not have any superiority over them, and the BES is modeled on MARKIII, which was built two decades ago. In respect of statistics, Belle and Babar will each have about 400\(fb^{-1}\) of \(\Upsilon(4S)\) in a few years, corresponding to about 400 million \(B\bar{B}\) events, an unprece-
dent huge data sample compared to both BES (14 million \( \psi' \)'s at present in store) and CLEO-c (50-100 million \( \psi' \)'s tentatively planned after 2003).

Moreover, it would be intrinsically difficult to find an \( \eta'_c \) signal in \( \psi' \) decays when the mass of the \( \eta'_c \) is closed to that of the \( \psi' \). As is known, the rate of \( \psi' \rightarrow \gamma \eta'_c \) decays can be determined directly from the \( J/\psi \rightarrow \gamma \eta_c \) rate. Assuming identical \( 1^-\) and \( 0^+ \) spatial wavefunctions, these simply scale as \( k_\gamma^3 \) of the photon, therefore

\[
\Gamma(\psi' \rightarrow \gamma \eta'_c) = \left( \frac{(M_{\psi'}^2 - M_{\eta'_c}^2)/2M_{\psi'}}{(M_{J/\psi}^2 - M_{\eta_c}^2)/2M_{J/\psi}} \right)^3 \Gamma(J/\psi \rightarrow \gamma \eta_c) \quad (4)
\]

For an \( \eta'_c \) mass of 3630 MeV/c\(^2\) one expects a partial width \( \Gamma(\psi' \rightarrow \gamma \eta'_c) \) of about 0.1 keV or \( \Gamma(\psi' \rightarrow \gamma \eta'_c) \sim 5 \times 10^{-4} \). Clearly this rate falls rapidly and the photon from the M1 transition would be too soft to detect as the \( \eta'_c \) mass approaches the \( \psi' \) mass. It is obvious that this kind of difficulty would not occur in case of \( B \) decays into final states containing a charmoinum meson.

5. Signal and background estimation

It is seen from Table 2 that all four factorization-allowed decays \( B \rightarrow \eta_c K, B \rightarrow J/\psi K, B \rightarrow \chi_{c1} K \) and \( B \rightarrow \psi' K \) have comparable branching fractions. One may thus expect that the branching fraction of \( B \rightarrow \eta'_c K \) is just as large as those measured values. Taking \( B(B^+ \rightarrow \eta'_c K^+) = 0.64 \times 10^{-3} \) and assuming \( B(\eta'_c \rightarrow K_s^0 K^+\pi^-) \cong B(\eta_c \rightarrow K_s^0 K^+\pi^-) = (1.5 \pm 0.4) \times 10^{-2} \), the cascade branching fraction is

\[
B(B^+ \rightarrow \eta'_c K^+) \rightarrow (K_s^0 K^+\pi^- + c.c.) K^+ \rightarrow (\pi^+\pi^- K^+\pi^- + c.c.) K^+) \cong 6.6 \times 10^{-6} \quad (5)
\]

Given the accumulated number of B mesons \( N_B = 1 \times 10^8 \) (a goal to be achieved within the year), and the signal efficiency determined for \( B^+ \rightarrow \eta_c K^+, \eta_c \rightarrow K_s^0 K^+\pi^- + c.c., \epsilon \cong 10\%[16] \), there will be 66 events of the \( \eta'_c \) from \( K_s^0 K^+\pi^- + c.c. \).

As for the \( h_c \), the decay \( B \rightarrow h_c K \) should be also forbidden by the factorization just as the decay \( B \rightarrow \chi_{c0} K \) and \( B \rightarrow \chi_{c2} K \). Based purely on experimental information, since the measured \( B(B \rightarrow \chi_{c0} K) \) is comparable with \( B(B \rightarrow \chi_{c1} K) \), and \( B(B \rightarrow \eta'_c K) \) is...
\chi_{c2}K)/B(B \to \chi_{c1}K) \cong 0.5, as is seen from Table 2, it would be rather safe to assume
B(B \to \eta_cK) \cong B(B \to \chi_{c2}K) \cong 0.4 \times 10^{-3}. If \eta_c is searched by \gamma \eta_c, which is the
main exclusive decay mode of \eta_c, the cascade branching fraction is

$$B(B^+ \to \eta_cK^+ \to \gamma \eta_c K^+ \to \gamma(K_\pi^0 K^+ \pi^-+c.c.)K^+ \to \gamma(\pi^+ \pi^- K^+ \pi^-+c.c.)K^+) \cong 3.5 \times 10^{-6}$$

(6)

When \(N_B = 1 \times 10^8\), and \(\epsilon = 10\%\), there will be about 35 events of the \eta_c.

There are still room for increasing statistics with increased \(N_B\) and by including
other channels, such as \(\eta_c' K^{**}\) or \(\chi_{c2} K^{**}\), and by combining \(B^0/B^0\) with \(B^\pm\). One
may also carry out the search in other \(\eta_c'\) and \(\eta_c\) decay modes as well as in inclusive B
decays.

The dominant source of background in most cases of exclusive B decays into two-
body final states containing a certain charmonium is found to be other B decays that
include charmonia in the final state[17]. For the cascade decay \(B^+ \to \eta_c' K^+\), \(\eta_c' \to K_\pi^0 K^+ \pi^-\), the possible competing process is \(B^+ \to \chi_{c2} K^+\), \(\chi_{c2} \to K_\pi^0 K^+ \pi^-\). Since
there is only an upper limit set for \(\chi_{c2} \to K_\pi^0 K^+ \pi^-\) to date, it may not be a serious
background source when one searches for \(\eta_c'\) in B decays. As is also shown by the
measurement of the decay \(B^+ \to \eta_c K^+\) with \(2.7 \times 10^6\ B \bar{B}\) events \[16\], the fitted
combinatorial background with the peaking background together accounts for about
one-sixth of the raw yield for the \(\eta_c \to K_\pi^0 K^+ \pi^-\) mode. Hopefully a similar scenario
will happen at \(\eta_c'\).

At present there is not any result of data analysis which provides a basis for the
discussion of the background problem in \(\eta_c\) search in B decays; also it seems unlikely
that any decay process would compete with \(\eta_c \to \gamma \eta_c\) and contaminate it significantly.
For example, \(B \to \psi' K \to \gamma \eta_c K\) is a decay process with the invariant mass of \(\gamma \eta_c\)
most close to the \(\eta_c\) mass, but the branching fraction of the hindered M1 transition
\(\psi' \to \gamma \eta_c\) [1] is expected to be two orders of magnitude smaller than that of \(\eta_c \to \gamma \eta_c\)
calculated either by PQCD or NRQCD[15].
6. Conclusion

The feasibility of searching for the $\eta_c'$ and $h_c$ states at B-factories has been discussed based on information from recent experiments and calculations. It is shown that there is a good opportunity to observe these states through some B-meson decays before the BEPC upgrade or CLEO-c program come true.

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