B to charmonium - mini-summary

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1 Introduction

I summarize recent experimental results on $B$ to charmonium decays. Decays of $B$ meson to final states that include charmonium states play an important role in the study of CP violation at B-factories. The decay modes $B_{CP} \rightarrow J/\psi K_S$, $\psi(2S)K_S$, $\chi_c K_S$, $\eta_c K_S$, $J/\psi K_L$ and $J/\psi K^{*0}(K^{*0} \rightarrow K_S \pi^0)$ have been used for $\sin 2\phi_1$ measurements [1] [2] [3] [4] [5]. These two-body decay modes are dominated by the color suppressed $b \rightarrow c$ transition. Other CP eigenstates of the neutral $B$ meson, e.g. $J/\psi \rho^0$, may also be useful for the CP measurements. Meanwhile, the branching fractions for the $B \rightarrow$ charmonium decays can provide valuable information on their decay mechanism.

2 Non-factorizable decay modes

In the factorization approximation, the production of $\chi_{c0}$ and $\chi_{c2}$ are not allowed by angular momentum and vector-current conservation. However, these decays can occur if factorization is broken by an exchange of soft gluons between the quarks.

2.1 Observation of $B^+ \rightarrow \chi_{c0} K^+$

Using a data sample containing 31.3 million $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider, the Belle collaboration has made the first observation of $B^+ \rightarrow \chi_{c0} K^+$ [6].

The $\chi_{c0}$ candidates are reconstructed from $\chi_{c0} \rightarrow \pi^+\pi^- \text{ and } K^+K^-$. Two kinematic variables, the beam-constrained mass, $M_{bc} = \sqrt{E_{beam}^2 - \vec{P}_{recon}^2}$, and energy difference $\Delta E = E_{recon} - E_{beam}$ in the $\Upsilon(4S)$ center of mass frame, are formed to isolate the signal. Here $E_{beam}$, $E_{recon}$ and $\vec{P}_{recon}$ are the beam energy, the reconstructed energy, and the reconstructed momentum of the signal candidate, respectively. Figure [3] shows the invariant masses of $\pi^+\pi^-$ and $K^+K^-$. The peaks near 3.4 GeV/$c^2$ are identified as the $\chi_{c0}$ meson. The peak position in the $K^+K^-$ spectrum
is shifted. This could be explained by the interference of $B^+ \to \chi_{c0}K^+$ with the non-resonant $B^+ \to K^+K^+K^-$. The peak at 3.69 GeV/$c^2$ in the $\pi^+\pi^-$ spectrum is due to $B^+ \to \psi(2S)K^+$, $\psi(2S) \to \mu^+\mu^-$ with the muons misidentified as pions.

Using the $\chi_{c0} \to \pi^+\pi^-$ decay channel, the ratio of branching fractions is found to be:

$$\frac{\mathcal{B}(B^+ \to \chi_{c0}K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.60^{+0.21}_{-0.18} \pm 0.05 \pm 0.08,$$

where the first error is statistical, the second is systematic, and the third is due to the uncertainty in the branching fraction for $\chi_{c0} \to \pi^+\pi^-$. The branching fraction is measured to be

$$\mathcal{B}(B^+ \to \chi_{c0}K^+) = (6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4},$$

which is comparable to those for $B^+ \to J/\psi K^+$ and $B^+ \to \chi_{c1}K^+$ decays. The $\chi_{c0} \to K^*0K^-\pi^+$ decay channel has been also studied and the results are in good agreement with those determined from $\chi_{c0} \to \pi^+\pi^-$. The statistical significance of the signal is $6\sigma$ when these two channels are combined. This measurement indicates a significant non-factorizable contribution in $B$ to charmonium decays.

### 2.2 Observation of $B \to \chi_{c2}X$

The Belle collaboration has also observed $\chi_{c2}$ production in $B$-meson decay \cite{7}. The analysis is based on a data sample containing 31.9 million $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider.

The $\chi_{c2}$ candidates are reconstructed via $J/\psi\gamma$, $J/\psi \to l^+l^-$. The photon energy resolution is studied using $D^{*0} \to D^0\gamma$ decay. The $\sigma_E/E_\gamma$ is $(2.61 \pm 0.04)\%$ around
400 MeV. The good photon energy resolution leads to a clear separation between the $\chi_{c2}$ peak and the larger $\chi_{c1}$ peak as shown in Fig. 4. To extract signal yields, the distribution is fit to two Crystal Ball line shapes and a third-order Chebyshev polynomial for the background. The continuum subtracted yield for $B \to \chi_{c2}$ is $607^{+76}_{-94}$ events and the branching fraction for $B \to \chi_{c2}X$ is $(1.80^{+0.23}_{-0.28} \pm 0.26) \times 10^{-3}$. The branching fraction for $B \to \chi_{c1}X$ is also measured. The momentum spectrum of $\chi_{c2}$ does not show a significant contribution from two body $B \to \chi_{c2}K$, in contrast to the momentum spectrum for $B \to \chi_{c1}$.

3 Other exclusive decay modes

3.1 $B^0 \to J/\psi \pi^+ \pi^-$

The BaBar collaboration has measured the branching fraction for the $B \to J/\psi \pi^+ \pi^-$ decay \[3\]. The data set contains approximately 56 million $B\bar{B}$ pairs produced at the $\Upsilon(4S)$ resonance with the BaBar detector at the PEP-II asymmetric $e^+e^-$ collider. The $B \to J/\psi \pi^+ \pi^-$ decay mode includes $J/\psi\rho^0$ and the non-resonant $J/\psi\pi^+\pi^-$ components. The invariant mass of the two pions, $M(\pi^+\pi^-)$, is plotted in Fig. 4. The signal yield is obtained by an unbinned maximum likelihood fit performed on the invariant mass distribution. The branching fraction for $B^0 \to J/\psi \pi^+ \pi^-$ is measured to be $(5.0 \pm 0.7 \pm 0.6) \times 10^{-5}$. It is about 20 times smaller than the branching fraction for $B^0 \to J/\psi K^0$ because of the Cabibbo suppression of $B \to J/\psi \pi^+ \pi^-$. 

Figure 2: The distribution of the mass difference between the $\chi_c$ and the $J/\psi$ candidates events \[4\].
3.2 \( B \rightarrow J/\psi K^* \)

The \( J/\psi K^* \) system has three helicity states and hence is a mixture of the CP-even and CP-odd eigenstates. The full angular analysis can determine the CP mix, which must be known to measure \( \sin^2 \phi_1 \) when the decay \( B^0 \rightarrow J/\psi K^{*0} \), \( K^{*0} \rightarrow K_S \pi^0 \) is used. The angular analysis also provides a test of the validity of the factorization hypothesis for B meson decays to charmonium.

The branching fractions for \( B^+ \rightarrow J/\psi K^{*+} \) and \( B^0 \rightarrow J/\psi K^{*0} \), where \( K^{*+} \rightarrow K^+ \pi^0 \), \( K_S \pi^+ \) and \( K^{*0} \rightarrow K^+ \pi^- \), \( K_S \pi^0 \), are listed in Table 1 for comparison [9] [10]. The results are all in good agreement. Figure 4 also shows evidence for the decay \( B^0 \rightarrow J/\psi K_2^{*0}(1430) \). Some excess is observed in the region between 1.1 GeV/\( c^2 \) to 1.3 GeV/\( c^2 \) in these measurements. Its source is not fully understood.

The decay amplitudes of \( B \rightarrow J/\psi K^* \) are measured in the transversity frame [11] by fitting the angular distributions in Fig. 5. The results from various experiments are compared in Table 2 [11] [12] [10]. They are consistent. The value of \( |A_\perp|^2 \), which corresponds to the CP-odd eigenstate, shows that CP-even component dominates in the \( B^0 \rightarrow J/\psi K^{*0} \), \( K^{*0} \rightarrow K_S \pi^0 \) decay. The parameter \( \arg(A_\parallel) \) should be 0 or \( \pi \) in the factorization limit. It is shifted from \( \pi \) in all four measurements. However, the shift is not yet statistically significant enough to draw a conclusion.

3.3 \( B \rightarrow \eta_c K^{(*)} \)

The decay \( B \rightarrow \eta_c K \) has the same quark level diagram as \( B \rightarrow J/\psi K \). However, unlike \( J/\psi \), \( \eta_c \) decays hadronically rather than leptonically with rates of a few percent or less for each channel. The decay modes \( B^0 \rightarrow \eta_c K^0 \), \( \eta_c \rightarrow K_S^0 K^- \pi^+ \) and \( K^+ K^- \pi^0 \) have been used to measure \( \sin^2 \phi_1 \). Other decay channels of the \( \eta_c \) may also be useful.
Figure 4: The $K^+\pi^-$ invariant mass distribution from Belle. The solid line is a fit to two Breit-Wigner functions corresponding to $K^*(892)$ and $K_2^*(1430)$ with a background function (dashed line).

Figure 5: The background-subtracted angular distributions for the channels without (top) and without (bottom) a $\pi^0$. The curves correspond to the fit [10].

for future CP measurements.

BaBar has measured the branching fractions of $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$ [13] using a data sample containing 22.7 million $B\overline{B}$ pairs. The $\eta_c$ is reconstructed in the decay modes: $K_S^0 K^- \pi^+$, $K^+ K^- \pi^0$, and $2(K^+ K^-)$. They observed statistically significant B meson signals in the $K_S^0 K^- \pi^+$ and $K^+ K^- \pi^0$ channels. They also observed exclusive $\eta_c$ signals.

Belle has measured the branching fraction of $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$ using a data sample containing 31.3 million $B\overline{B}$ pairs. The $\eta_c$ is reconstructed in the decay modes: $K_S^0 K^- \pi^+$, $K^+ K^- \pi^0$, $K^{*0} K^- \pi^+$ and $p\overline{p}$. We observed statistically significant B meson signals in $K_S^0 K^- \pi^+$, $K^+ K^- \pi^0$, $K^{*0} K^- \pi^+$ and in the $p\overline{p}$ channel. Figure 6 shows the invariant mass of $\eta_c$ for events in the $M_{bc}$ and $\Delta E$ signal region. Fitting to a Breit-Wigner convolved with the resolution determined from MC, we find a intrinsic
width $\Gamma(\eta_c) = 29 \pm 8$ MeV and a mass of $M(\eta_c) = 2979.6 \pm 2.3$ MeV. The errors are statistical only. The results are consistent with world averages [14] and the CLEO result [13].

The $B$ branching fractions are quoted for the $\eta_c \rightarrow K_S^0 K^- \pi^+$ and $\eta_c \rightarrow K^+ K^- \pi^0$ modes only. The $\eta_c \rightarrow K_S^0 K^- \pi^+$ mode is the most precisely and reliably measured mode, while the branching fraction for the $\eta_c \rightarrow K^+ K^- \pi^0$ mode is related by isospin. The results are consistent with the CLEO results [14] but more precise as shown in Table 3.

| Experiment | $B(B^0 \rightarrow \eta_c K^0) \ (\times 10^{-3})$ | $B(B^+ \rightarrow \eta_c K^+) \ (\times 10^{-3})$ |
|------------|---------------------------------|---------------------------------|
| CLEO       | 1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31 | 0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20 |
| BaBar      | 1.06 \pm 0.28 \pm 0.11 \pm 0.33   | 1.50 \pm 0.19 \pm 0.15 \pm 0.46 |
| Belle      | 1.23 \pm 0.23^{+0.12}_{-0.16} \pm 0.38 | 1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38 |

Table 3: The measured branching fractions for $B^+ \rightarrow \eta_c K^+$ and $B^0 \rightarrow \eta_c K^0$. The last errors come from the uncertainty in the $\eta_c$ branching fraction.

Belle has observed the decay mode $B^0 \rightarrow \eta_c K^{*0}$ for the first time. The $K^{*0}$ is reconstructed in the $K^- \pi^+$ channel and the $\eta_c$ in the $K_S^0 K^- \pi^+$ mode. To remove the $B\bar{B}$ background, we apply vetoes to events consistent with $J/\psi \rightarrow K_S^0 K \pi$, $\chi_{c1} \rightarrow K_S^0 K \pi$ and $D_s \rightarrow K^+ K^- \pi$. A fit to the $M_{\eta_c}$ spectrum yields a signal of $33.7 \pm 6.7$ events with a statistical significance of $7.7 \sigma$. The branching fraction for $B^0 \rightarrow \eta_c K^{*0}$ is found to be $(1.62 \pm 0.32^{+0.24}_{-0.34} \pm 0.50) \times 10^{-3}$. The ratio $R_{\eta_c} = B(B^0 \rightarrow \eta_c K^{*0})/B(B^0 \rightarrow J/\psi K^{*0})$ is...
Figure 6: Candidate $M(\eta_c)$ invariant mass distribution for events in the $M_{bc}$ and $\Delta E$ signal region. Signals at the $\eta_c$ and $J/\psi$ from $B \rightarrow \eta_c K$ and $B \rightarrow J/\psi K$ decays are visible.

Figure 7: The $M_{bc}$ distribution of $B^0 \rightarrow \eta_c K^{*0}$ candidates.

$\eta_c K^0$ is measured to be $1.33 \pm 0.36^{+0.29}_{-0.40}$. This result is somewhat higher than the theoretical prediction of Gourdin, Keum and Pham of 0.78 [17].

3.4 Exclusive $B \rightarrow J/\psi$, $\psi(2S)$ and $\chi_{c1}$

Table 4 lists branching fractions for two-body $B$ meson decays to $J/\psi$, $\psi(2S)$ and $\chi_{c1}$ with a kaon or pion [14, 18, 19, 20, 21, 22]. They are in good agreement with previous measurements but more precise. The decay modes $B^0 \rightarrow \chi_{c1} K^{*0}$, $B^+ \rightarrow J/\psi K_1^+(1270)$ and $B^0 \rightarrow J/\psi K_1^0(1270)$ have been observed for the first time.
distributions are plotted for twenty-five MeV \[23\]. The result has not been confirmed by the subsequent experiments.

Observation of \(\eta_c(2S)\) meson

The \(\eta_c(2S)\) meson has not been experimentally well established. The Crystal Ball group reported possible evidence for the \(\eta_c(2S)\) meson with a mass of 3594 ± 5 MeV \[23\]. The result has not been confirmed by the subsequent experiments.

Using a data set that contains 4.41 million \(B\bar{B}\) pairs, Belle has searched for the \(\eta_c(2S)\) meson produced via the exclusive decays \(B^+ \to \eta_c(2S)K^+\) and \(B^0 \to \eta_c(2S)K^0\) where \(\eta_c(2S) \to K_SK^-\pi^+\). To remove backgrounds from \(B \to D(D_s)X\) and \(B \to K^*(890)K\) decays, \(D, D_s\) and \(K^*\) vetoes are applied. The \(M_{bc}\) and \(\Delta E\) distributions are plotted for twenty-five \(M_{K_SK\pi}\) bins. Clear \(B\) meson signals are seen in the bins corresponding to the \(\eta_c\) and near the expected mass of the \(\eta_c(2S)\). The signal yields extracted from the simultaneous fits to the \(M_{bc}\) and \(\Delta E\) distributions are plotted in Fig. 8. A clear peak is seen around 3.65 GeV/c\(^2\) and identified as \(\eta_c(2S)\). The distribution is fit to two Breit-Wigner functions for the \(\eta_c\) and \(\eta_c(2S)\) respectively, a Gaussian for the \(J/\psi\), and a second-order polynomial for the non-resonant contribution. These functions are convolved with a Gaussian resolution function determined from MC. The fit value for the mass is 3654 ± 6 ± 8 MeV/c\(^2\). The 90% confidence level upper limit for the intrinsic width is 55 MeV/c\(^2\). The results are consistent with expectations of heavy-quark potential models. The ratio of product

| Decay mode                  | Previous (×10\(^{-4}\)) | BaBar (×10\(^{-4}\)) | Belle (×10\(^{-4}\)) |
|-----------------------------|--------------------------|-----------------------|------------------------|
| \(B^- \to J/\psi K^-\)     | 10.0 ± 1.0               | 10.1 ± 0.3 ± 0.5      | 10.1 ± 0.3 ± 0.8       |
| \(B^0 \to J/\psi K^0\)     | 9.6 ± 0.9                | 8.3 ± 0.4 ± 0.5       | 7.7 ± 0.4 ± 0.7       |
| \(B^- \to J/\psi K_1^-\) (1270) | 18.0 ± 3.4 ± 3.9   | 13.0 ± 3.4 ± 3.1     |
| \(B^0 \to J/\psi K_0^0\) (1270) |                      |                      |
| \(B^- \to \psi(2S)K^-\)    | 5.8 ± 1.0                | 6.4 ± 0.5 ± 0.8       | 6.7 ± 0.6 ± 0.7 (a)   |
| \(B^0 \to \psi(2S)K^0\)    | 5.0 ± 1.3                | 6.9 ± 1.1 ± 1.1       | 6.0 ± 1.1 ± 0.7 (a)   |
| \(B^- \to \chi_{c1}K^-\)   | 10.0 ± 4.0               | 7.5 ± 0.8 ± 0.8       | 6.1 ± 0.6 ± 0.6       |
| \(B^0 \to \chi_{c1}K^0\)   | 3.9\(^{+1.9}_{-1.4}\)  | 5.4 ± 1.4 ± 1.1       | 3.1 ± 0.9 ± 0.4       |
| \(B^0 \to \chi_{c1}K^{*0}\)| 4.8 ± 1.4 ± 0.9          | 5.4 ± 1.4 ± 1.1       | 3.1 ± 0.9 ± 0.4       |
| \(B^- \to J/\psi\pi^-\)    | 0.51 ± 0.15              | 0.39 ± 0.09           | 0.52 ± 0.07 ± 0.07    |
| \(B^0 \to J/\psi\pi^0\)    | 0.25\(^{+0.11}_{-0.09}\)| 0.20 ± 0.06 ± 0.02    | 0.24 ± 0.06 ± 0.02    |

Table 4: Measured branching fractions. (a) \(\psi(2S) \to l^+l^-\) (b) \(\psi(2S) \to J/\psi\pi^+\pi^-\).
branching fractions for the $\eta_c$ and $\eta_c(2S)$ is also measured to be

$$\frac{B(B \to \eta_c(2S) K)B(\eta_c(2S) \to K_S K^- \pi^+)}{B(B \to \eta_c K)B(\eta_c \to K_S K^- \pi^+)} = 0.38 \pm 0.12 \pm 0.05.$$

5 Summary

With the large $B\overline{B}$ data sets accumulated at the B-factories, we have improved the measurements of the branching fractions for the decays $B \to J/\psi K^{(*)}$, $B \to \psi(2S)K$, $B \to \chi_{c1}K$ and $B \to J/\psi\pi$. The decays modes $B^0 \to \chi_{c1}K^{*0}$, $B^+ \to \chi_{c0}K^+$, $B \to \chi_{c2}X$, $B^0 \to \eta_cK^{*0}$ and $B \to J/\psi K_1(1270)$ have been observed for the first time. The branching fractions for the non-factorizable decays $B^+ \to \chi_{c0}K^+$ and $B \to \chi_{c2}X$ are comparable to the factorizable decays $B^+ \to J/\psi K^+$ and $B \to \chi_{c1}X$. Belle has observed the $\eta_c(2S)$ meson. Its properties are consistent with expectations of the heavy-quark potential models.

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