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Production of charmed mesons and charmonium states in B decays at Belle

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Belle recently performed extensive studies of charmed and charmonium states from B decays utilizing its 711 fb^{-1} data set collected at $\Upsilon(4S)$ resonance. We present here the results of three recent publications: arXiv:1504.02637, arXiv:1509.03363, arXiv:1505.03362. In the first publication improved measurements were reported of the product branching fractions $\mathscr{B}(B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)) \times \mathscr{B}(D_{s0}^{*+}(2317) \to D_s^+ \pi^0) = (7.8^{+1.3}_{-1.2} \pm 1.0 \pm 0.5) \times 10^{-4}$ and $\mathscr{B}(B^0 \to D^- D_{s0}^{*+}(2317)) \times \mathscr{B}(D_{s0}^{*+}(2317) \to D_s^+ \pi^0) = (10.0 \pm 1.2 \pm 1.0 \pm 0.5) \times 10^{-4}$, where the first errors are statistical, the second are systematic and the third are from D and D_s^* branching fractions. In addition, negative results were reported on a search for hypothetical neutral (Z^0) and doubly charged (Z^{++}) isospin partners of the $D_{s0}^{*+}(2317)$.
In the second article are reported results of a Dalitz analysis of the three-body $\bar{B}^0 \to D^{*+}\omega\pi^-$ decay. Measurements of decay fractions for the quasi-two-body $\bar{B} \to D_1(2430)^0\omega$, $\bar{B}^0 \to D_1(2420)^0\omega$, $\bar{B}^0 \to D_2(2460)^0\omega$ decays as well as $\bar{B}^0 \to D^{*+}\rho(1450)^-$ and combined fraction for ρ-like states are presented. An upper limit for the second-class current is also presented. The fractions of longitudinal polarizations are obtained and partial wave fractions of the D^{**} states are measured. The measurements also show evidence of nontrivial final-state interaction phases for the resonant amplitudes.
In the third article updated results are presented of the χ_{c1} and χ_{c2} inclusive production in B decays. Exclusive reconstruction was also performed of B decays including a $\chi_{cJ}(J=1,2)$ in the final state, as $\chi_{c1,c2}K$, $\chi_{c1,c2}K\pi$, $\chi_{c1,c2}\gamma K\pi$, $\chi_{c1,c2}K\pi\pi$ and $\chi_{c1,c2}K\pi\pi\pi$.

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1. "Measurements of $B \to DD_{s0}(2317)$ decay rates and a search for isospin partners of the $D_{s0}^{*+}(2317)$ "

The $D_{s0}^{*+}(2317)$ meson was first observed by BaBar as a narrow peak in the $D_s^+\pi^0$ invariant mass spectrum produced in inclusive $e^+e^- \to D_s^+\pi^0 X$ annihilation processes [1] and confirmed by CLEO [2]. Its production in the B meson decay processes $B \to \bar{D}D_{s0}(2317)$ was subsequently established by both Belle [3] and BaBar [4]. Although it is generally considered to be a conventional $I(J^P) = 0(0^+)$ P-wave $c\bar{s}$ meson, its mass $M_{D_{s0}^{*+}(2317)} = 2317.8 \pm 0.6$ MeV [5] is the same as the peak mass of its non-strange counterpart, the 0^+ P-wave $c\bar{q}$ ($q = u$ or d) D_0^* with mass $M_{D_0^*} = 2318 \pm 29$ MeV, in spite of the fact that the mass of the s-quark is ~ 100 MeV above that of either of the q-quarks. A $c\bar{s}$ meson with mass below the 2358.6 MeV threshold would decay via the isospin-violating process $D_{s0}^{*+}(2317) \to D_s^+\pi^0$ or the electromagnetic process $D_{s0}^{*+}(2317) \to D_s^+\gamma$ and, thus, have a narrow natural width. This is consistent with experimental measurements, which have established a 95% CL upper limit on the total width of $\Gamma_{D_{s0}^{*+}(2317)} \leq 3.8$ MeV [5].
We conclude that an $I = 1$; $I_z = 0$ assignment for the $D_{s0}^{*+}(2317)$ cannot be ruled out and claim, in fact, that an $I = 1$ diquark-diantiquark interpretation is favored by some existing data. If this were the case, doubly charged $I_z = 1(Z^{++})$ and neutral $I_z = -1(Z_0)$ partners of the $D_{s0}^{*+}(2317)$ with mass within $\sim \pm 10$ MeV of $M_{D_{s0}^{*+}(2317)}$ should exist. Since the Z^{++} and Z^0 would be charmed mesons with $I = 1$ and $S = 1$, they would necessarily have a minimal quark content of $c\bar{s}u\bar{d}$ and $c\bar{s}d\bar{u}$, respectively.

1.1 The $B \to \bar{D}D_{s0}^{*+}(2317); D_{s0}^{*+}(2317) \to D_s^+\pi^0$ results

The number of $B^0 \to DD_{s0}^{*+}(2317); D_{s0}^{*+}(2317) \to D_s^+\pi^0$ signal events was determined in the data by applying the three-dimensional fit described above to the selected $\bar{D} = D$ event sample. In this fit, the rms widths of the M_{bc}, $M(D_s^+\pi^0)$ and δE signal functions are kept fixed at their MC-determined values. Figure 1 shows the results of the fit to the M_{bc} (left), $M(D_s^+\pi^0)$ (center) and δE (right) projections of events that are in the signal regions of the other two quantities. The curves in each plot show the results of the fit, which returns a signal yield of $N_{evt} = 102.6^{+12.7}_{-12.0}$ events. The signal significance is 9.9σ.

1.2 Search for $Z^{++} \to D_s\pi^+$ and $Z^0 \to D_s\pi$

For the search for the doubly charged Z^{++} and neutral Z^0, we look for evidence for $Z^{++} \to D_s\pi^+$ and $Z \to D_s\pi$ signals in the $B \to DD_s\pi$ and $B^0 \to \bar{D}^0 D_s\pi^-$ decay channels, respectively, by applying the selection criteria discussed above with the replacement of the selected π^0 with a π^+ (for Z^{++}) or π (for Z^0). Here, for events with multiple D and/or D_s track combinations, those were selected which have a measured invariant mass closest to the corresponding PDG values. For Z^{++} signal MC, the number of remaining events with multiple entries is 11.2% over the full three-dimensional range of the likelihood fit; for Z^0 less than 0.1% of the remaining events have multiple entries. Figure 2 shows the fit results for the mass bin centered at $M(D_s^+\pi) = 2317.8$ MeV for the $Z^{++}(Z^0)$ search.

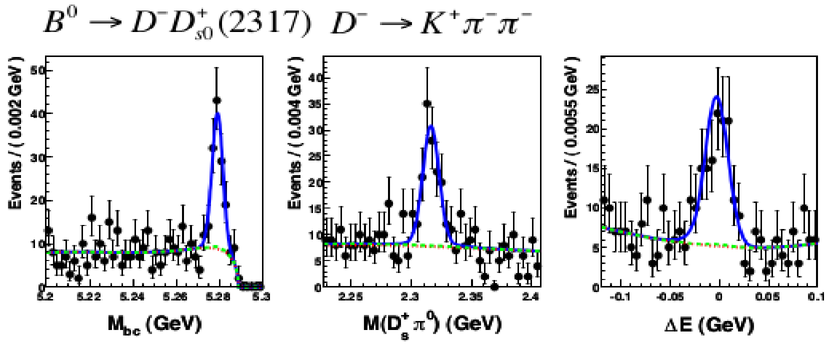

Figure 1: *The M_{bc} (left), $M(D_s\pi^0)$ (center) and δE (right) distributions for projections of the $B^0 \to D^- D^+_{s0}(2317)$ candidate events that are in the signal regions of the two quantities not plotted.*

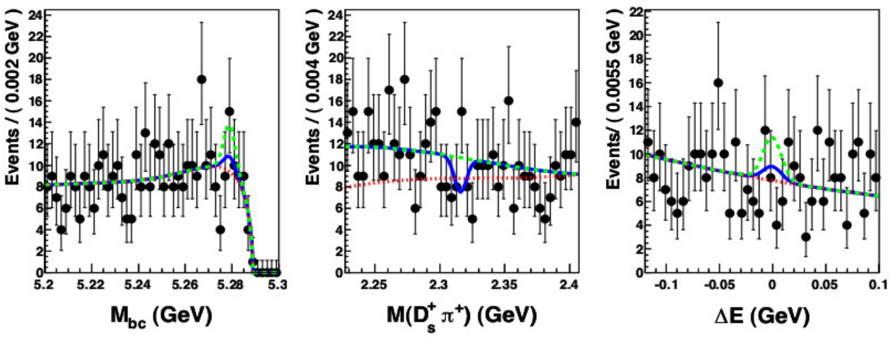

Figure 2: *The M_{bc} (left), $M(D_s\pi)$ (center) and δE (right) distributions for selected $B^+ \to D^- D^+_s \pi^+$ event candidates for the fit with the signal peak mass restricted to a 5 MeV region.*

1.3 Summary

We report measurements of the product branching fractions $\mathscr{B}(B^+ \to \bar{D}^0 D^{*+}_{s0}(2317)) \times \mathscr{B}(D^{*+}_{s0}(2317) \to D^+_s \pi^0) = (7.8^{+1.3}_{-1.2} \pm 1.0 \pm 0.5) \times 10^{-4}$ and $\mathscr{B}(B^0 \to D^- D^{*+}_{s0}(2317)) \times \mathscr{B}(D^{*+}_{s0}(2317) \to D^+_s \pi^0) = (10.0 \pm 1.2 \pm 1.0 \pm 0.5) \times 10^{-4}$ These values agree with the existing PDG world=average values [5] and significantly improve upon their precision. In addition, negative results have been reported on a search for hypothetical doubly charged and neutral isospin partners of the D^{*+}_{s0} and upper limits were provided on the product branching fractions that are more than an order of magnitude smaller than the theoretical predictions [6].

2. "Study of D^{**} production and light hadronic current in $B^0 \to D^+ \omega \pi^-$ decay"

Orbitally excited states of the D meson (D states) provide a good opportunity to test the Heavy Quark Effective Theory (HQET) [13] and QCD sum rules predictions [8]. The simplest system consists of a charm quark and a light antiquark in an orbital angular momentum $L = 1$ (P-wave) state. Four such states are expected with spin-parities $J^P = 0^+(j = 1/2), 1^+(j = 1/2), 1^+(j = 3/2)$ and $2^+(j = 3/2)$, where j is the sum of the light quark spin and angular momentum L. All these states have been discovered [9]. They are $D_0^*(2400), D_1(2430), D_1(2420)$ and $D_2(2460)$.

In this paper an amplitude analysis of the $B^0 \to D^+\omega\pi^-$ decay is performed to measure the decay fractions for the D^{**} states produced via a color-suppressed channel and study their properties. The decay $\bar{B}^0 \to D^{*+}\omega\pi^-$ is expected to proceed predominantly via the ρ-like resonances, such as off-shell $\rho(770)^-$ and $\rho(1450)^-$. The structure of the ρ-like states is not yet completely clear. Another aim of this study is a test of the factorization hypothesis in the D^{**} production region.

2.1 Total branching fraction

Since the $\bar{B}^0 \to D^{*+}\pi^+\pi^-\pi^0\pi^-$ events observed in Fig. 3 produce a peak in ΔE, the fit is performed separately in the $M(\pi^+\pi^-\pi^0)$ signal and sideband regions. MC simulation shows that these events have the same shape as the correctly reconstructed component.

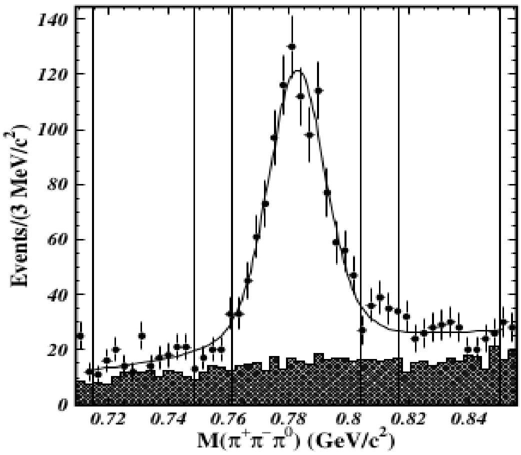

Figure 3: *$M(\pi^-\pi^+\pi^0)$ distribution of the $B^0 \to D^+\omega\pi^-$ candidates in the ΔE signal region (points with error bars) and sideband (hatched histogram).*

2.2 Amplitude analysis

To study the resonant structure of the $\bar{B}^0 \to D^{*+}\omega\pi^-$ decay, an amplitude analysis was performed. Using an unbinned likelihood method, the data were simultaneously fitted in the six-dimensional phase space according to [12]. Two sets of kinematic variables were defined:
$(M^2(\omega\pi), cos\theta_1, \phi_1, cos\beta_1, \psi_1$ and $cos\xi_1)$and $(M^2(\omega\pi), cos\theta_2, \phi_2, cos\beta_2, \psi_2$ and $cos\xi_2$, corresponding to the $\omega\pi$ and D^{**} production, respectively. The masses $M(\omega\pi)$ and $M(D\pi)$ are the invariant masses of the $\omega\pi$ and $D\pi$ combinations. The polar $\theta_1(\theta_2)$ angle describes the orientation of the normal to the ω decay plane relative to the $\omega\pi(D\pi)$ direction in the ω rest frame and the azimuthal $\phi_1(\phi_2)$ angle defines the orientation of the B-decay plane relative to the plane including the $\omega\pi(D^*\pi)$ direction and orthogonal to the ω decay plane in the ω rest frame. The polar $\beta_1(\beta_2)$ angle defines the direction of the D^0 relative to the $\omega\pi(D^*\pi)$ direction in the D^+ rest frame and

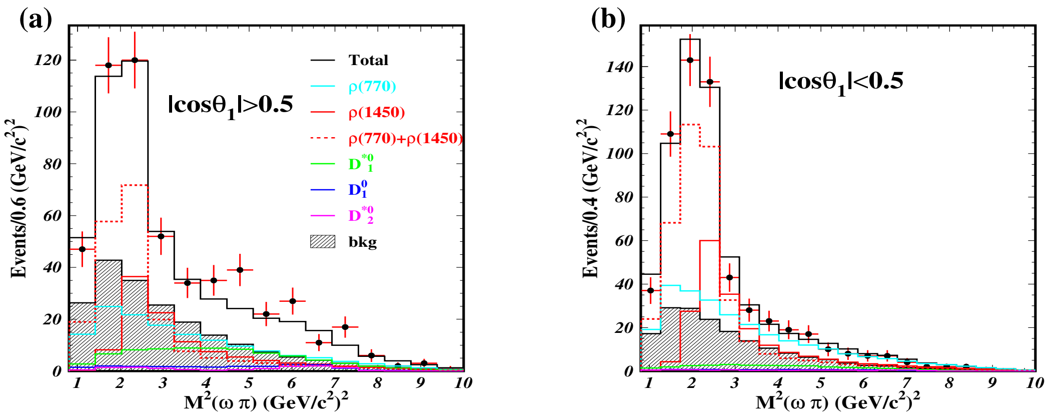

Figure 4: *Distribution of $M^2(\omega\pi)$ variables for $D^+\omega\pi$ candidates in two different subregions of the signal region (points with error bars), defined by $|cos\theta_1| > 0.5$(D enriched) and $|cos\theta_1| < 0.5$(D depleted).*

azimuthal $\psi_1(\psi_2)$ angle defines the orientation of the B-decay plane relative to the plane including the D^0 and $\omega\pi(D^*\pi)$ flight directions in the D rest frame. The polar angle $\xi_1(\xi_2)$ is the angle between the D^+ and ω flight directions in the $\omega\pi(D^*\pi)$ rest frame. The quantity cos ξ_1 is related to the $M^2(D\pi)$, whereas the $cos\xi_2$ is related to $M^2(\omega\pi)$.

2.3 Conclusion

This analysis is devoted to the study of the three-body $B^0 \to D^+\omega\pi^-$ decay. The total branching fraction $B = (2.31\pm0.11(stat.)\pm0.14(syst.))\times 10^3$ has been obtained, consistent within errors with the CLEO [10] and BaBar [11] measurements but with a slightly smaller central value. A full amplitude analysis of the final state has been performed.

3. "Study of inclusive and multi-body B decays into χ_{c1} and χ_{c1}"

In two-body B meson decays, the daughter mesons can be directly generated by a quark current carrying the appropriate parity and the flavor quantum numbers. The corresponding contribution to a decay amplitude factorizes into the product of two current matrix elements and this picture is called factorization. On the basis of factorization, χ_{c1} (vector 1^+) couples to the $V-A$ operator which results in a proper matrix element. On the other hand, since χ_{c2} is a tensor (2^+), it does not couple to vector or axial-vector operator, $<\chi_{c2}|(\bar{c}c)_{V-A}|0>= 0$ in the factorization limit. From this it can be said that decay of $B\to\chi_{c1}K$ should be favored while $\chi_{c2}K$ should be disfavored [13]. After taking into account the next-to-leading order (NLO) corrections [14], resscattering effects [15], $B\to\chi_{c2}K$ decays are allowed but highly suppressed. A recent study performed at Belle [16] has seen the $B^\pm\to\chi_{c2}K^\pm$ decay mode with a 3.6σ significance and measured the ratio of its yield with respect to $B^\pm\to\chi_{c1}K^\pm$ as:

$$\frac{N(B^\pm\to\chi_{c2}K^\pm)}{N(B^\pm\to\chi_{c1}K^\pm)} = \frac{33\pm11}{2308\pm52} = 1.4\pm0.4\%. \tag{3.1}$$

Extrapolating this in a naive manner, one may expect the same order of suppression in the total yield of χ_{c2} in comparison to χ_{c1} in inclusive production in B decays. However, a relatively large inclusive production of χ_{c2} has been seen in the B decays. An early study performed by Belle [17] with 30 fb^{1} found that

$$\frac{N(B^{\pm} \to \chi_{c2} K^{\pm})}{N(B^{\pm} \to \chi_{c1} K^{\pm})} = \frac{611 \pm 76}{2529 \pm 127} = 24.2 \pm 3.2\%. \tag{3.2}$$

This means that inclusive production of χ_{c2} in B decays is relatively large in spite of the fact that two-body B decays into χ_{c2} are highly suppressed.

3.1 Branching fraction measurement

To identify the signal, the $J/\psi\gamma$ invariant mass $M_{J/\psi\gamma}$ distribution has been used and the signal yield has been extracted from a binned extended maximum likelihood fit. The signal of χ_{cJ} is described by a double-sided Crystal Ball function [18].

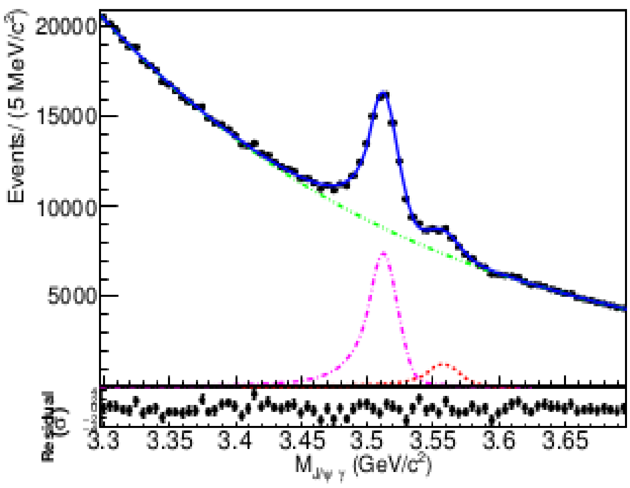

Figure 5: *$M_{J/\psi\gamma}$ distribution of the $B \to \chi_{cJ}(\to J/\psi(\to l^{+}l)\gamma)X$ decays in data. The curves show the signal (magenta dash-dotted for χ_{c1} and red dashed for χ_{c2}) and the background component (violet dash double-dotted for combinatorial) as well as the overall fit (blue solid). The lower plot shows the pull of the residuals with respect to the fit.*

Figure 5 shows the fit of the $M_{J/\psi\gamma}$ distribution for $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ decays in the range of $[3.297, 3.697] GeV/c^2$. A yield of 51353 ± 614 was obtained for events for the χ_{c1} peak and 9651 ± 446 events for the χ_{c2} peak, where the errors are statistical only.

3.2 Summary

The branching fractions $\mathscr{B}(B \to \chi_{c1}X)$ and $\mathscr{B}(B \to \chi_{c2}X)$ were measured to be $(3.29 \pm 0.04 \pm 0.26) \times 10^3$ and $(0.97 \pm 0.05 \pm 0.11) \times 10^3$, respectively, where the first (second) error is statistical (systematic). After subtracting the ψ' feed-down contribution, we get the direct branching fractions $\mathscr{B}(B \to \chi_{c1}X)$ and $\mathscr{B}(B \to \chi_{c2}X)$ to be $(3.03 \pm 0.04 \pm 0.21) \times 10^3$ and $(0.70 \pm 0.05 \pm 0.07) \times 10^3$, respectively, where the first (second) error is statistical (systematic). Here, a systematic uncertainty dominates the measured branching fraction. This is the first observation of the $B^0 \to \chi_{c2}\pi^- K^+$ decay mode with 206.34 ± 24.7 signal events with a 8.7σ significance. We report the first observation of $B^+ \to \chi_{c2}\pi^- K^0_S$ decay mode having 76.38 ± 14.7 signal events with a significance of 4.6σ. First observation of $B^+ \to \chi_{c1}\pi^+\pi^- K^+[B^+ \to \chi_{c1}\pi^+\pi^- K^+]$ with a measured branching fraction of $(3.72 \pm 0.17 \pm 0.24) \times 10^4[(1.33 \pm 0.17 \pm 0.08) \times 10^4]$. In other four body decay $B^0 \to \chi_{c1}\pi^+\pi^- K_S[B^0 \to \chi_{c1}\pi^0\pi^- K^+]$ was also observed for the first time with a significance of $7.1\sigma(6.5\sigma)$.

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