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Study of Υ(5S) decays to B^0 and B^+ mesons

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Decays of the Υ(5S) resonance to channels with B^+ and B^0 mesons are studied using a 23.6 fb^{-1} data sample collected on the Υ(5S) resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider. The fully reconstructed $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^+ \to \bar{D}^0\pi^+$ and $B^0 \to D^-\pi^+$ decays are used to obtain the B^+ and B^0 production rates per $b\bar{b}$ event, $f(B^+) = (67.5 \pm 3.6 \pm 4.8)\%$ and $f(B^0) = (70.4^{+5.2}_{-5.1} \pm 6.2)\%$. Assuming equal rates to B^+ and B^0 mesons in all channels produced at the Υ(5S) energy, we measure the fractions for $b\bar{b}$ event transitions to the two-body and multi-body channels with $B^{+/0}$ meson pairs, $f(B\bar{B}) = (5.1 \pm 0.9 \pm 0.4)\%$, $f(B\bar{B}^* + B^*\bar{B}) = (12.6^{+1.2}_{-1.1} \pm 1.0)\%$, $f(B^*\bar{B}^*) = (34.5^{+1.9}_{-1.8} \pm 2.7)\%$, $f(B^{(*)}\bar{B}^{(*)}\pi(\pi)) = (16.4^{+1.6}_{-1.5} \pm 1.2)\%$, $f(B\bar{B}\pi) = (0.0 \pm 1.1 \pm 0.2)\%$, $f(B\bar{B}^*\pi + B^*\bar{B}\pi) = (6.8^{+2.1}_{-2.0} \pm 0.7)\%$, and $f(B^*\bar{B}^*\pi) = (1.0^{+1.3}_{-1.2} \pm 0.3)\%$.

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New aspects of beauty dynamics can be explored using the large data sample recently collected by the Belle collaboration at the energy of the Υ(5S) resonance (also called Υ(10860)). At this energy a $b\bar{b}$ quark pair can be produced and hadronized in various final states, which can be classified as two-body B_s^0 channels $B_s^0\bar{B}_s^0$, $B_s^0\bar{B}_s^*$, $B_s^*\bar{B}_s^0$, $B_s^*\bar{B}_s^*$, two-body B channels $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}$, $B^*\bar{B}^*$, three-body channels $B\bar{B}\pi$, $B\bar{B}^*\pi$, $B^*\bar{B}\pi$, $B^*\bar{B}^*\pi$, and four-body channel $B\bar{B}\pi\pi$. Here B denotes a B^+ or a B^0 meson and $\bar{B}$ denotes a B^- or a $\bar{B}^0$ meson, and the excited states decay to their ground states via $B^* \to B\gamma$ and $B_s^* \to B_s^0\gamma$. Fractions and decay parameters for all of these channels provide important information about b-quark dynamics.

The first study of B^+ and B^0 mesons at the Υ(5S) was performed by the CLEO collaboration [1] using a $0.42\,\text{fb}^{-1}$ data sample, where the fraction of events with $B^{+/0}$ meson pairs was found to be $(58.9 \pm 10.0 \pm 9.2)\%$. Only two-body B meson channels were observed by CLEO. Several theoretical papers are devoted to Υ(5S) decays to final states with the two-body B_s^0 and $B^{+/0}$ meson pairs [2, 3, 4, 5] and with the three-body channels [6, 7]. The three-body fractions were predicted to be about 2-3 orders of magnitude smaller than two-body fractions. Interesting information about Υ(5S) behaviors can be obtained using multi-body decays [8].

In this analysis we use the data sample of $23.6\,\text{fb}^{-1}$, which was taken at the Υ(5S) center-of-mass (CM) energy of ∼10867 MeV with the Belle detector [9] at KEKB [10]. The number of $b\bar{b}$ events in the data sample is $N_{b\bar{b}}^{\Upsilon(5S)} = (7.13 \pm 0.34) \times 10^6$. We fully reconstruct the decay modes $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^+ \to \bar{D}^0\pi^+$ ($\bar{D}^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^+\pi^-\pi^-$) and $B^0 \to D^-\pi^+$ ($D^- \to K^+\pi^-\pi^-$). The B decays are reconstructed and identified using two variables: the energy difference $\Delta E = E_B^{CM} - E_{\text{beam}}^{\text{CM}}$ and the beam-energy-constrained mass $M_{\text{bc}} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - (p_B^{\text{CM}})^2}$, where E_B^{CM} and p_B^{CM} are the energy and momentum of the B candidate in the e^+e^- CM system, and $E_{\text{beam}}^{\text{CM}}$ is the CM beam energy. Two-body and multi-body channels with $B^{+/0}$ pairs are located in kinematically different regions of the M_{bc} and ΔE plane, however the central positions for all channels are distributed in this plane along a straight line described approximately by the function $\Delta E = m_B - M_{\text{bc}}$, where m_B is the nominal B meson mass.

The two-dimensional M_{bc} and ΔE scatter plots for the $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^+ \to \bar{D}^0\pi^+$, and $B^0 \to D^-\pi^+$ modes (with the following $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^+\pi^-\pi^-$, and $D^- \to K^+\pi^-\pi^-$ decays) are shown in Fig. 1. Events are clearly concentrated along the $B^{+/0}$ meson production line.

We used the inclined $\Delta E + M_{\text{bc}} - 5.28$ projections of the two-dimensional scatter plots for all events within the range $5.268 < M_{\text{bc}} < 5.43\,\text{GeV}/c^2$ to obtain integrated B event yields. To obtain the event yields we fit these distributions with a function that includes two terms: a Gaussian to describe the signal and a linear function to describe background. Using the fit results, the average production rates over studied B modes, $f(B^+) = (67.5 \pm 3.6 \pm 4.8)\%$ and $f(B^0) = (70.4^{+5.2}_{-5.1} \pm 6.2)\%$, are obtained. The mean value over B^+ and B^0 modes is $f(B^{+/0}) = (68.5^{+3.0}_{-2.9} \pm 5.0)\%$. Within errors this rate is in agreement with the CLEO value of $f(B^{+/0}) = (58.9 \pm 10.0 \pm 9.2)\%$.

Taking into account the obtained similarity of $f(B^+)$ and $f(B^0)$ rates, it is natural to assume that the B^+ and B^0 mesons are symmetrically included in all possible channels with $B^{+/0}$ meson pairs. Therefore the five studied B decays are treated simultaneously everywhere below. First the M_{bc} projections of the two-dimensional M_{bc} and ΔE distributions are studied. Only events from the signal bands restricted to the $\pm 30\,\text{MeV}$ interval in ΔE (which corresponds to a range of

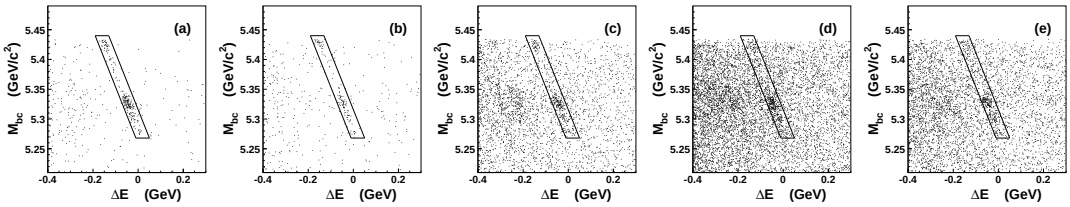

Figure 1: The $M_{\rm bc}$ and ΔE scatter plots for the (a) $B^+ \to J/\psi K^+$, (b) $B^0 \to J/\psi K^{*0}$, (c) $B^+ \to \bar{D}^0(K^+\pi^-)\pi^+$, (d) $B^+ \to \bar{D}^0(K^+\pi^+\pi^-\pi^-)\pi^+$, and (e) $B^0 \to D^-\pi^+$ modes. The bands indicate the signal regions corresponding to the $5.268 < M_{\rm bc} < 5.44\,{\rm GeV}/c^2$ and $|\Delta E + M_{\rm bc} - 5.28| < 30\,{\rm MeV}$ intervals.

(2.5-4.0)σ) around the signal linear function (Fig. 1) are used to obtain the signal $M_{\rm bc}$ distributions. To describe combinatorial backgrounds under the signals, we used left and right sideband regions corresponding to a shift of 70 MeV in ΔE relative to the signal bands.

Fig. 2a shows the $M_{\rm bc}$ distributions for the specific two-, three- and four-body channels obtained from MC simulation for the $B^0 \to D^-\pi^+$ decay. Evidently the two-body channels are well separated from each other. The decay matrix elements responsible for the three- and four-body decays are not known and the specific three- and four-body channel contributions cannot be obtained in a model independent way from the fit of these $M_{\rm bc}$ distributions. Therefore we restricted the fit procedure only to the region $5.268 < M_{\rm bc} < 5.348$ MeV/c^2 to extract the two-body channel fractions. To obtain the sum of all three- and four-body channel fractions we used the $5.348 < M_{\rm bc} < 5.44$ MeV/c^2 interval for the fit procedure, similar to that used to obtain the full $f(B^{+/0})$ production rate for the entire interval $5.268 < M_{\rm bc} < 5.44$ MeV/c^2, described above. We measured the fractions of $b\bar{b}$ event transitions to the two-body channels with $B^{+/0}$ meson pairs, $f(B\bar{B}) = (5.1 \pm 0.9 \pm 0.4)\,\%$, $f(B\bar{B}^* + B^*\bar{B}) = (12.6^{+1.2}_{-1.1} \pm 1.0)\,\%$, $f(B^*\bar{B}^*) = (34.5^{+1.9}_{-1.8} \pm 2.7)\,\%$, and to the sum of three-body and four-body channels with $B^{+/0}$ meson pairs, $f(B^{(*)}\bar{B}^{(*)}\pi(\pi)) = (16.4^{+1.6}_{-1.5} \pm 1.2)\,\%$. The sum of background subtracted $M_{\rm bc}$ distributions for the five studied B decays is shown in Fig. 2b, where the fit results are also superimposed.

To obtain the three-body channel production rates we additionally used the charged pions directly produced in $B^{(*)}\bar{B}^{(*)}\pi^+$ channels. For all charged pions not contained in the reconstructed B candidate, we formed $B^{-/0}\pi^+$ combinations and calculated the values $M_{\rm bc}^{\rm mis}$ and $\Delta E^{\rm mis}$ for the missing B meson. To obtain these values we used the energy and momentum of reconstructed $B\pi$ combination (all values in CM system): $E(B^{\rm mis}) = 2E_{\rm beam} - E(B\pi)$ and $p(B^{\rm mis}) = p(B\pi)$.

Figure 2c shows the corrected $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$ projections ($m_B = 5.28\,{\rm MeV}/c^2$) for MC simulated events where $B\bar{B}\pi^+$, $B\bar{B}^*\pi^+ + B^*\bar{B}\pi^+$, and $B^*\bar{B}^*\pi^+$ channels are generated. The reconstructed B meson candidates are selected from the signal region within the intervals $5.37 < M_{\rm bc} < 5.44\,{\rm GeV}/c^2$ and $|\Delta E + M_{\rm bc} - m_B| < 30\,{\rm MeV}$. To improve the resolution we applied additional correction requiring the exact equality $\Delta E = M_{\rm bc} - 5.28$ for the reconstructed B meson. As we can see in Fig. 2c, the $B\bar{B}\pi^+$, $B\bar{B}^*\pi^+ + B^*\bar{B}\pi^+$ and $B^*\bar{B}^*\pi^+$ channel contributions are well separated in $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$.

Finally the $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$ distribution is obtained in data for the sum of five reconstructed B modes (Fig. 2d). We fit the $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$ distribution with a function including four terms: three Gaussians with fixed shapes and free normalizations used to describe the $B\bar{B}\pi^+$, $B\bar{B}^*\pi^+ + B^*\bar{B}\pi^+$, and $B^*\bar{B}^*\pi^+$ channel contributions, and a second order polynomial to

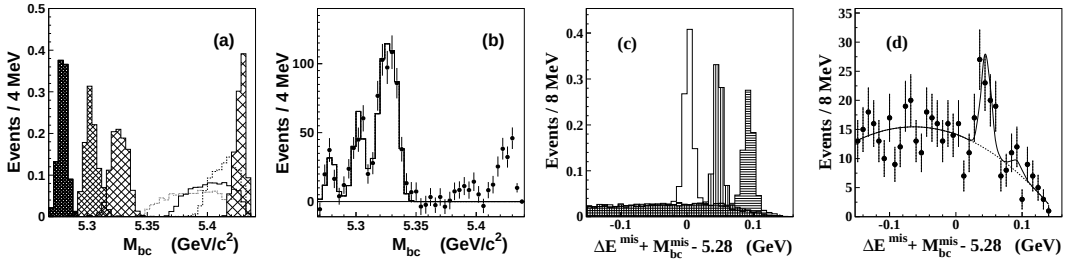

Figure 2: (a) MC simulated $M_{\rm bc}$ distributions for the $B^0 \to D^- \pi^+$ decay for (hatched histograms from the left to the right) (1) $B\bar{B}$, (2) $B\bar{B}^* + B^*\bar{B}$, (3) $B^*\bar{B}^*$ and (4) $B\bar{B}\pi\pi$ channels, and also for three-body channels $B\bar{B}^*\pi + B^*\bar{B}\pi$ (histogram), $B\bar{B}\pi$ (dotted histogram) and $B^*\bar{B}^*\pi$ (dashed histogram). The distributions are normalized to unity. (b) $M_{\rm bc}$ data distribution after background subtraction for the sum of five studied B decays (points with error bars) and results of fit (histogram) used to extract two-body channel fractions. (c) The $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$ distribution normalized per reconstructed B meson for the MC simulated $B^- \to J/\psi K^-$ decays in the (peaks from the left to the right) $B\bar{B}\pi^+$, $B\bar{B}^*\pi^+ + B^*\bar{B}\pi^+$, and $B^*\bar{B}^*\pi^+$ channels. (d) The $\Delta E^{\rm mis} + M_{\rm bc}^{\rm mis} - 5.28$ data distribution for $B^{-/0}\pi^+$ combinations for the sum of five studied B modes. The curve shows the fit results described in the text.

describe background. The central positions and widths of the Gaussians are obtained from fits of the MC simulated distributions and are fixed in the fit to data. Using the fit results we measured the fractions for $b\bar{b}$ event transitions to the three-body channels with $B^{+/0}$ meson pairs, $f(B\bar{B}\pi) = (0.0 \pm 1.1 \pm 0.2)\,\%$, $f(B\bar{B}^*\pi + B^*\bar{B}\pi) = (6.8^{+2.1}_{-2.0} \pm 0.7)\,\%$, and $f(B^*\bar{B}^*\pi) = (1.0^{+1.3}_{-1.2} \pm 0.3)\,\%$. The three-body rates are calculated assuming the ratio of charged and neutral directly produced pions to be 2:1 (Clebsch-Gordan coefficient). It is interesting to note that using the method with the reconstructed direct pions, we observe about one half of the rate obtained above for the sum of the three-body and four-body channels. This implies a sizable rate for the four-body $B\bar{B}\pi\pi$ channel, however no definitive conclusion about this deficit can be reached with the current statistics.

In conclusion, the production of B^+ and B^0 mesons is studied at the Υ(5S) energy. We measured the average fractions per $b\bar{b}$ event for integrated B production, two-body, and multi-body channels. The multi-body channels with unexpectedly large fractions are observed for the first time.

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