

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

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Using a sample of $31.3 \times 10^6 B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance, we make the first observation of the charged B meson decay to χ_{c0} and a charged kaon. The measured branching fraction is $\mathcal{B}(B^+ \rightarrow \chi_{c0}K^+) = (6.0_{-1.8}^{+2.1} \pm 1.1) \times 10^{-4}$, where the first error is statistical, and the second is systematic.

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Two-body decays of B mesons with a charmonium particle in the final state have recently received substantial attention due to their sensitivity to CP violation in the B system. The production rate of charmonium states in $b \rightarrow c\bar{c}s$ transitions also provides valuable insight into the dynamics of strong interactions in heavy meson systems. For instance, although the production of the $\chi_{c0}P$ -wave 0^{++} state in B decays vanishes in the factorization approximation as a consequence of spin-parity and vector current conservation, it is possible if there is an exchange of an additional soft gluon [1,2]. At present, only upper limits on the $B \rightarrow \chi_{c0}K$ branching fractions exist [3]. In this Letter, we report the first observation of the $B^+ \rightarrow \chi_{c0}K^+$ decay mode. The analysis is performed using data collected with the Belle detector at the KEKB asymmetric energy e^+e^- collider [4]. The data sample consists of 29.1 fb^{-1} taken at the $\Upsilon(4S)$ resonance containing $31.3 \times 10^6 B\bar{B}$ pairs, and 2.3 fb^{-1} taken 60 MeV below the $\Upsilon(4S)$ resonance to perform systematic studies of the $e^+e^- \rightarrow q\bar{q}$ background.

The Belle detector [5] is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC) for charged particle tracking and specific ionization measurement (dE/dx), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an array of 8736 CsI(Tl) crystals

for electromagnetic calorimetry (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L mesons and to identify muons. Electron identification is based on a combination of CDC dE/dx measurements, the response of the ACC, and the position, shape, and energy deposition of the associated ECL shower. We use a Monte Carlo simulation to model the response of the detector and determine acceptance [6].

The analysis of the $B^+ \rightarrow \chi_{c0}K^+$ decay is performed in the framework of a general study of the $B^+ \rightarrow K^+h^+h^-$ decay, where h stands for either pion or kaon [7] (charge conjugation is implied throughout this Letter). We reconstruct the χ_{c0} meson in the decay modes $\chi_{c0} \rightarrow \pi^+\pi^-$ and $\chi_{c0} \rightarrow K^+K^-$. Charged tracks are required to satisfy requirements based on the average hit residual and on their impact parameters relative to the interaction point. We require that the transverse momentum of the track be greater than 0.1 GeV/ c to reduce low momentum combinatorial background. For charged hadron identification, we use a combination of CDC dE/dx measurements, flight time measured in TOF, and the response of the ACC. We select kaon candidate tracks with a set of criteria that has about 90% efficiency, a charged pion misidentification probability of about 8%, and a negligible contamination from protons. We reject tracks that are positively identified as electrons.

We reconstruct B mesons by combining a χ_{c0} with a charged kaon. The candidate events are identified by their center-of-mass (c.m.) energy difference, $\Delta E = (\sum_i E_i) - E_b$, and the beam constrained mass, $M_{bc} = \sqrt{E_b^2 - (\sum_i \vec{p}_i)^2}$, where $E_b = \sqrt{s}/2$ is the beam energy in the c.m. frame, and \vec{p}_i and E_i are the c.m. three-momenta and energies of the candidate B meson decay products. We select events with $M_{bc} > 5.20 \text{ GeV}/c^2$ and $|\Delta E| < 0.2 \text{ GeV}$, and define a *signal* region of $|M_{bc} - M_B| < 9 \text{ MeV}/c^2$ and $|\Delta E| < 0.04 \text{ GeV}$ and two ΔE *sideband* regions $-0.08 \text{ GeV} < \Delta E < -0.05 \text{ GeV}$ and $0.05 \text{ GeV} < \Delta E < 0.15 \text{ GeV}$ [8].

To suppress the large combinatorial background, which is dominated by the two-jet-like $e^+e^- \rightarrow q\bar{q}$ continuum process, we use variables that characterize the event topology. We require $|\cos\theta_{\text{thr}}| < 0.80$, where θ_{thr} is the angle between the thrust axis of the B candidate and that of the rest of the event. This eliminates 83% of the continuum background and retains 79% of the signal events. We also define a Fisher discriminant, \mathcal{F} , that includes the production angle of the B candidate, the angle of the B candidate thrust axis with respect to the beam axis, and nine parameters that characterize the momentum flow in the event relative to the B candidate thrust axis in the c.m. frame [9]. We impose a requirement on \mathcal{F} that rejects 79% of the remaining continuum background and retains 74% of the signal. In the case where the χ_{c0} is reconstructed in the K^+K^- mode, the continuum background is much smaller, and a looser requirement that rejects 53% of the continuum background with about 89% efficiency for the signal is used.

As shown in Ref. [7], the background to the $K^+\pi^+\pi^-$ final state from $B\bar{B}$ decays is dominated by decays of the type $B^+ \rightarrow [K^+\pi^-]\pi^+$, where $[K^+\pi^-]$ denotes an intermediate state that can decay into the $K^+\pi^-$ such as $K^{*0}(892)$ or \bar{D}^0 . To suppress this type of background, we require that the invariant mass of the $K^+\pi^-$ system be greater than $2.0 \text{ GeV}/c^2$. For the $K^+K^+K^-$ final state, we require that the invariant mass for both K^+K^- combinations be greater than $2.0 \text{ GeV}/c^2$ to suppress the background from charmless B decays.

We select all $K^+\pi^+\pi^-$ ($K^+K^+K^-$) combinations from the B signal region that satisfy the selection criteria described above and have a $\pi^+\pi^-$ (K^+K^-) invariant mass in the range $3.2 \text{ GeV}/c^2 < M(h^+h^-) < 3.8 \text{ GeV}/c^2$. The resulting $\pi^+\pi^-$ and K^+K^- invariant mass spectra are shown in Fig. 1. Since in the case of the $K^+K^+K^-$ final state there are two kaons with the same charge, we distinguish the K^+K^- combinations with the smaller and larger invariant masses. Here, we plot only the larger of the two possible combinations and require the invariant mass of the smaller combination to be less than $3.35 \text{ GeV}/c^2$. The peaks near $3.4 \text{ GeV}/c^2$ in Figs. 1(a) and 1(b) are identified as the χ_{c0} meson. The peak at $3.69 \text{ GeV}/c^2$ in Fig. 1(a) corresponds to the $\psi(2S)$ meson from the decay mode $B^+ \rightarrow \psi(2S)K^+$, $\psi(2S) \rightarrow \mu^+\mu^-$ with muons misidentified as pions. The hatched histograms in Fig. 1

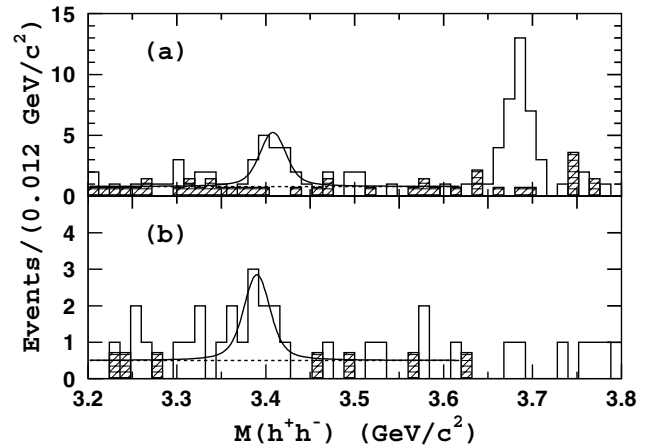


FIG. 1. The (a) $\pi^+\pi^-$ and (b) K^+K^- invariant mass spectra. Open histograms correspond to events from the B signal region and hatched histograms correspond to events from the ΔE sidebands. The curves are fits to the signal data.

correspond to the events from the ΔE sidebands plotted with a weight of 0.62.

These $\pi^+\pi^-$ and K^+K^- spectra are fitted in the range $3.20 \text{ GeV}/c^2 < M(h^+h^-) < 3.62 \text{ GeV}/c^2$ to the sum of a constant for the background and a Breit-Wigner function convolved with a Gaussian resolution function for the signal. The width of the resolution function is fixed at $11.0 \text{ MeV}/c^2$ as determined from a fit to the J/ψ peak in the $\mu^+\mu^-$ invariant mass spectrum. The full width of the Breit-Wigner function is fixed at the world average χ_{c0} width of 14.9 MeV [10]. The results of the fit are given in Table I. The statistical significance, Σ , of the signal, in terms of the number of standard deviations, is calculated as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$, where \mathcal{L}_{max} and \mathcal{L}_0 denote the maximum likelihood with the nominal signal yield and with the signal yield fixed at zero, respectively.

The peak position in the K^+K^- spectrum is found to be shifted below the PDG value [10] by $25 \pm 10 \text{ MeV}/c^2$: see Fig. 1(b) and Table I. Although this shift is consistent with a statistical fluctuation, we note that, as shown below, we observe evidence for a non-resonant-like signal in the $B^+ \rightarrow K^+K^+K^-$ final state. As a result, the K^+K^- invariant mass distribution in the χ_{c0} region could be distorted by the effects of interference with an amplitude not related to the $B^+ \rightarrow \chi_{c0}K^+$. Because of this uncertainty, we base our branching fraction measurement on the $\chi_{c0} \rightarrow \pi^+\pi^-$ decay mode only.

TABLE I. Results of the fit to the $\pi^+\pi^-$, K^+K^- , and $\mu^+\mu^-$ invariant mass spectra.

Channel	Eff. (%)	Peak (GeV/c^2)	Fit yield (events)	Σ (σ)
$\chi_{c0} \rightarrow \pi^+\pi^-$	21.0	3.408 ± 0.006	$16.5^{+5.6}_{-4.8}$	4.4
$\chi_{c0} \rightarrow K^+K^-$	12.9	3.390 ± 0.010	$8.7^{+4.3}_{-3.6}$	3.0
$J/\psi \rightarrow \mu^+\mu^-$	26.5	3.096 ± 0.001	406 ± 21	...

For the branching fraction calculation, we normalize our results to the observed $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+ \mu^-$ signal. This removes systematic effects in the particle identification efficiency, the charged track reconstruction efficiency, and the systematic uncertainty due to the cuts on event shape variables. To avoid additional systematic uncertainty in the muon identification efficiency, we do not use muon identification information for J/ψ reconstruction. Instead, we apply the same pion-kaon separation requirement for muons from the J/ψ as for pions from the χ_{c0} . The feed across from the $J/\psi \rightarrow e^+ e^-$ submode is found to be negligible (less than 0.5%) after the application of the electron veto requirement.

To determine the $B^+ \rightarrow \chi_{c0} K^+$ branching fraction, we use the signal yield obtained from the fit to the $\pi^+ \pi^-$ invariant mass spectrum. The number of $J/\psi K^+$ signal events is determined from the fit to the $\mu^+ \mu^-$ invariant mass spectrum (see Table I). Combining all the relevant numbers from Table I and using the intermediate branching fractions of $\mathcal{B}(\chi_{c0} \rightarrow \pi^+ \pi^-) = (5.0 \pm 0.7) \times 10^{-3}$ and $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (5.88 \pm 0.10) \times 10^{-2}$ [10], we find the ratio of branching fractions:

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

where the first error is statistical, the second is systematic, and the third is due to the uncertainty in the $\chi_{c0} \rightarrow \pi^+ \pi^-$ branching fraction. Here the statistical error includes the errors on the number of signal $\chi_{c0} K^+$ and $J/\psi K^+$ events. The systematic error consists of the uncertainty in the $J/\psi \rightarrow \mu^+ \mu^-$ branching fraction (1.7%) and the uncertainty in the background parametrization in the fit to the $\pi^+ \pi^-$ spectra (7.8%). Using the world average value of $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (10.0 \pm 1.0) \times 10^{-4}$ [10], we translate our measurement into the branching fraction:

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

where the first error is statistical, and the second is the total systematic error including uncertainties in the $\chi_{c0} \rightarrow \pi^+ \pi^-$ and $B^+ \rightarrow J/\psi K^+$ branching fractions.

Figure 2 shows the projections of the ΔE signal bands for the selected $B^+ \rightarrow \chi_{c0} K^+$ candidates with $|M(h^+ \times h^-) - M_{\chi_{c0}}| < 0.05 \text{ GeV}/c^2$ and $5.270 \text{ GeV}/c^2 < M_{bc} < 5.288 \text{ GeV}/c^2$. The hatched histograms in Fig. 2 correspond to the events from the χ_{c0} mass sidebands defined as $0.07 \text{ GeV}/c^2 < |M(h^+ h^-) - M_{\chi_{c0}}| < 0.17 \text{ GeV}/c^2$ and plotted with a weight of 0.50. For the $K^+ \pi^+ \pi^-$ final state, the distribution for the sideband events is consistent with background. In contrast, in the three charged kaon final states we observe a substantial signal for events in the χ_{c0} mass sidebands. This is the evidence for nonresonantlike $B^+ \rightarrow K^+ K^+ K^-$ decays that may be responsible for the shift in the $\chi_{c0} \rightarrow K^+ K^-$ mass peak discussed above. A study of the full $K^+ K^+ K^-$ Dalitz plot [7] also supports this conclusion. We represent the background shape in ΔE with a linear function and

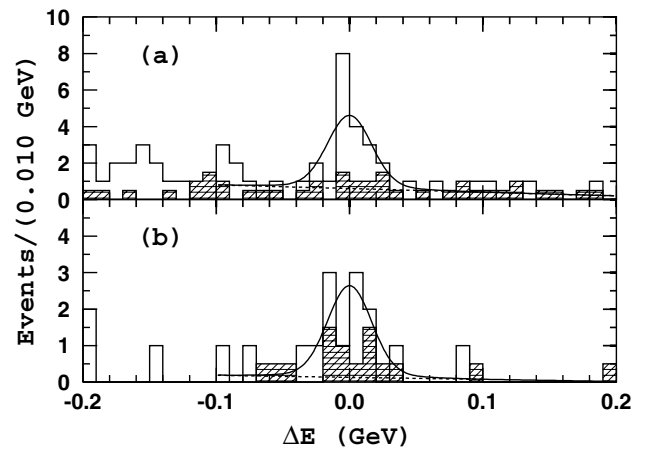


FIG. 2. The ΔE distributions for $B^+ \rightarrow \chi_{c0} K^+$ candidates; (a) $\chi_{c0} \rightarrow \pi^+ \pi^-$ and (b) $\chi_{c0} \rightarrow K^+ K^-$. The hatched histograms correspond to the χ_{c0} mass sidebands. The solid lines display the signal plus background combined shape. The dashed lines correspond to the background shape only.

restrict the fit to the range $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ [8]. The signal shape is parametrized by a sum of two Gaussians with the same mean. The ΔE shape for the signal is determined from the $B^+ \rightarrow \bar{D}^0 \pi^+$ events. The $B^+ \rightarrow \chi_{c0} K^+$ where the $\chi_{c0} \rightarrow \pi^+ \pi^- (K^+ K^-)$ signal yield of $16.4_{-4.6}^{+5.2} (9.7_{-3.8}^{+4.0})$ events obtained from the fit to the ΔE distributions agrees with that obtained from the fit to the $\pi^+ \pi^- (K^+ K^-)$ invariant mass spectrum.

To cross-check the result, we also reconstruct the χ_{c0} meson in the $K^+ K^- \pi^+ \pi^-$ final state. We reduce the large combinatorial background by using events where at least one $K\pi$ pair has an invariant mass within $75 \text{ MeV}/c^2$ of M_{K^*} . We also apply the tighter requirement $|\cos\theta_{\text{thr}}| < 0.6$ to suppress the continuum background. Figure 3 presents the $K^*(892)K\pi$ invariant mass spectrum for the selected events from the B signal region shown by open histogram and for events from the ΔE sidebands shown by hatched histogram plotted with a weight of 0.62. For the branching fraction calculation we normalize our result to the signal observed in the

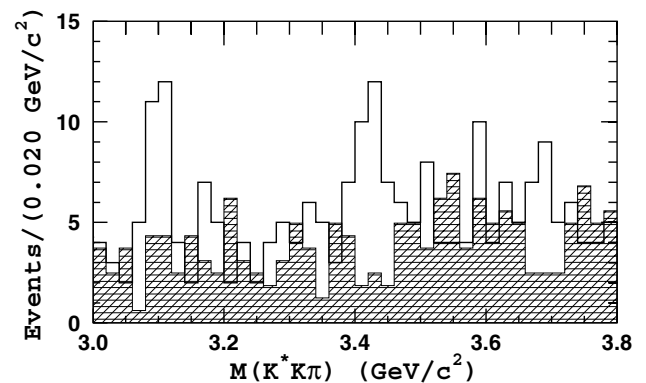


FIG. 3. The $K^*(892)K\pi$ invariant mass spectrum for events from the B signal region (open histogram) and for events from the ΔE sidebands (hatched histogram).

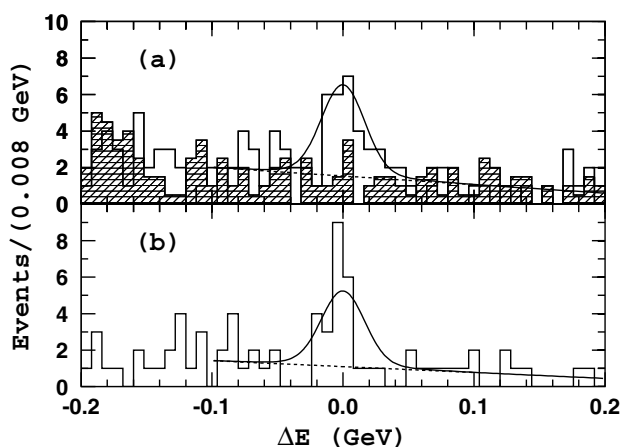


FIG. 4. The ΔE distributions for (a) $B^+ \rightarrow \chi_{c0} K^+$, $\chi_{c0} \rightarrow K^{*0}(892)K^- \pi^+$ candidates and (b) $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow K^{*0}(892)K^- \pi^+$ candidates. The hatched histogram in (a) corresponds to events from the χ_{c0} mass sidebands. The solid lines display the signal plus background combined shape. The dashed lines correspond to the background shape only.

$B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow K^*(892)K^- \pi^+$ decay mode. Figure 4 shows the ΔE distributions for $B^+ \rightarrow \chi_{c0} K^+$ and $B^+ \rightarrow J/\psi K^+$ candidates. From the fit to the ΔE distributions we find 21.9 ± 6.3 and 18.0 ± 5.2 signal events, respectively. The statistical significance of the $B^+ \rightarrow \chi_{c0} K^+$ signal in this mode is 4.3σ . Using the intermediate branching fractions of $\mathcal{B}[\chi_{c0} \rightarrow K^{*0}(892)K^- \pi^+ + \text{c.c.}] = (1.2 \pm 0.4) \times 10^{-2}$ [10,11] and $\mathcal{B}[J/\psi \rightarrow K^{*0}(892)K^- \pi^+ + \text{c.c.}] = (6.3 \pm 2.1) \times 10^{-3}$ [12], we determine the ratio of branching fractions: $\mathcal{B}(B^+ \rightarrow \chi_{c0} K^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+) = 0.64 \pm 0.26 \pm 0.30$, where the first error is statistical, and the second consists of the uncertainty in the secondary branching fractions. The obtained number is in agreement with that determined from the $\chi_{c0} \rightarrow \pi^+ \pi^-$ decay mode. We do not include this result in the final value for the $B^+ \rightarrow \chi_{c0} K^+$ branching fraction because of the large systematic uncertainty.

In summary, we report the first observation of the $B^+ \rightarrow \chi_{c0} K^+$. The statistical significance of the signal is 6σ when the $\chi_{c0} \rightarrow \pi^+ \pi^-$ and $\chi_{c0} \rightarrow K^* K \pi$ modes are combined. The measured branching fraction is $\mathcal{B}(B^+ \rightarrow \chi_{c0} K^+) = (6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4}$ which is comparable to those for the $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \chi_{c1} K^+$ decays. This provides evidence for a significant nonfactorizable contribution in B to charmonium decay processes. The result reported here supersedes the previous value based on 21.3 fb^{-1} as reported in Ref. [13].

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