Observation of $B^+ \to \psi(3770) K^+$

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We report the first observation of the decay $B^+ \to \psi(3770)K^+$ where the $\psi(3770)$ is reconstructed in the $D^0\bar{D}^0$ and D^+D^- decay channels. The obtained branching fraction is $\mathcal{B}(B^+ \to \psi(3770)K^+) = (0.48 \pm 0.11 \pm 0.07) \times 10^{-3}$. We have measured the branching fraction for the decay $B^+ \to D^0\bar{D}^0K^+$ to be $(1.17 \pm 0.21 \pm 0.15) \times 10^{-3}$ and set a 90% confidence level upper limit of 0.90×10^{-3} for the decay $B^+ \to D^+D^-K^+$. We also present the results of a search for possible decays to $D\bar{D}$ and $D^0\bar{D}^0\pi^0$ of the recently observed $X(3872)$ particle. The analysis is based on 88 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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B decay modes with charmonium in the final state are extensively used by the Belle and BaBar Collaborations for measurements of the CP violation parameter $\sin 2\phi_1$ [1,2]. Belle has recently reported the first observations of the decays $B^+ \to \chi_{c0}K^+$ [3] and $B \to \chi_{c2}X$ [4]. The decay rates for these modes were measured to be comparable to those for J/ψ and $\psi(2S)$.

In contrast to the charmonia seen so far in B decays, the $\psi(3770)$ state is just above open charm threshold and decays dominantly to pairs of D mesons [5]. The $\psi(3770)$ is generally considered to be predominantly the $1\,^3D_1$ charmonium state. However, it has a nonzero leptonic width, which indicates that there is some mixing with the nearby $\psi(2S)$ S-wave state [6]. A large S-D-wave mixing angle could result in comparable decay rates for B decays to the $\psi(3770)$ and the $\psi(2S)$. For a pure D-wave state, an estimate of $\mathcal{B}(B \to \psi(3770)X)$ based on the color-octet model gives a value of 0.28% [7], which is as large as the measured values for J/ψ and $\psi(2S)$. Experimental studies of $\psi(3770)$ production in B decays test theoretical models and provide additional information on the structure of the $\psi(3770)$ wave function.

In this Letter, we report the first observation of the decay $B^+ \to \psi(3770)K^+$ [8]. We also report measurements of the $B^+ \to D^0\bar{D}^0K^+$ and $B^+ \to D^+D^-K^+$ decay modes [9] and searches for the decays $B^+ \to X(3872)K^+$, $X(3872) \to D\bar{D}$, and $X(3872) \to D^0\bar{D}^0\pi^0$. The analysis is performed using data collected with the Belle detector [10] at the KEKB asymmetric-energy e^+e^- collider [11]. The data sample consists of 88 fb^{-1} taken at the $\Upsilon(4S)$ resonance, which corresponds to 96×10^6 $B\bar{B}$ pairs.

We select charged pions and kaons that originate from the region $dr < 1$ cm, $|dz| < 3$ cm, where dr and dz are the distances of closest approach to the interaction point in the plane perpendicular to the beam axis and along the beam direction, respectively. Charged kaons are required to satisfy $\mathcal{L}(K)/[\mathcal{L}(K) + \mathcal{L}(\pi)] > 0.6$, where $\mathcal{L}(K/\pi)$ is the particle identification likelihood for the K/π hypotheses calculated by combining information from the time-of-flight system and aerogel Cherenkov counters with dE/dx measurements in the central drift chamber. Candidate π^0 mesons are identified as pairs of non-charged-track-associated electromagnetic calorimeter (ECL) clusters that have an invariant mass within ± 15 MeV$/c^2$ of the π^0 mass. The energy of each photon is required to be greater than 50 MeV, and the momentum of the π^0 in the center of mass system (c.m.s.) is required to be greater than 0.15 GeV$/c$.

The D^0 meson is reconstructed in the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, and $K^-\pi^+\pi^0$ modes, and the D^+ in the $K^-\pi^+\pi^+$ and $K^+K^-\pi^+$ modes. We use a ± 10 MeV$/c^2$ D signal window for the charged modes ($\sim 2.5\sigma$) and ± 15 MeV$/c^2$ for the $K^-\pi^+\pi^0$ mode ($\sim 2\sigma$). Mass- and vertex-constrained fits are applied to all D candidates to improve their momentum resolution. The B^+ candidates (i.e., $D\bar{D}$ pairs combined with the positive kaons in the event) are identified by their c.m.s. energy difference, $\Delta E = \Sigma_i E_i - E_{\rm beam}$, and their beam-energy constrained

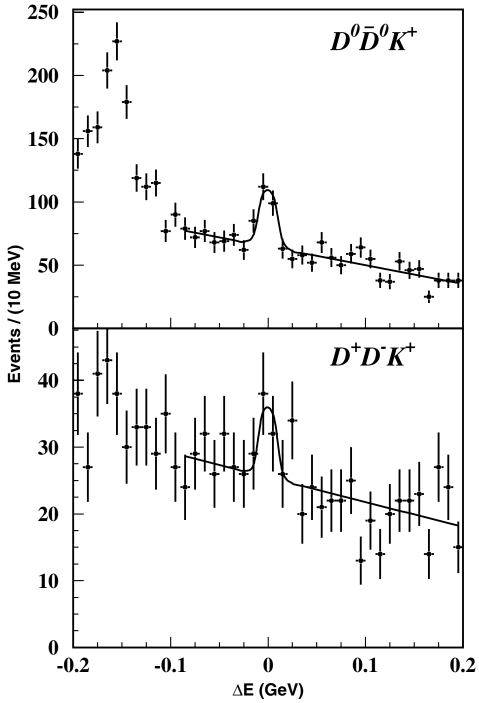

FIG. 1. The ΔE distributions for the $B^+ \to D^0\bar{D}^0K^+$ (upper) and $B^+ \to D^+D^-K^+$ (lower) candidates. Points with errors represent the data and curves show the results of the fits described in the text.

mass, $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - (\Sigma_i \vec{p}_i)^2}$, where $E_{\rm beam} = \sqrt{s}/2$ is the beam energy in the c.m.s. and $\vec{p}_i$ and E_i are the three-momenta and energies of the B^+ candidate's decay products. For the $B^+ \to D^0\bar{D}^0K^+$ final state, we require that one D^0 is reconstructed in the $D^0 \to K^-\pi^+$ mode, which has the smallest background. We accept B candidates with $5.272 < M_{\rm bc} < 5.288$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV. To suppress the continuum background we require the normalized Fox-Wolfram moment [12] R_2 to be less than 0.5 and $|\cos\theta_{\rm thr}| < 0.8$, where $\theta_{\rm thr}$ is the angle between the thrust axis of the B candidate and the thrust axis of the rest of the event. The last requirement is not applied for the cleanest subset of B candidates where both D^0's are reconstructed in the $K\pi$ mode. In the case of multiple B candidates, we choose the candidate with the smallest value of $\chi^2 = [(M_{\rm bc} - M_{B^+})/\sigma_{M_{\rm bc}}]^2$.

The ΔE distributions for the $B^+ \to D^0\bar{D}^0K^+$ and $B^+ \to D^+D^-K^+$ candidates are shown in Fig. 1, where the superimposed curves are the results of the fits. The fit to the ΔE distribution is a sum of a Gaussian with a fixed width taken from Monte Carlo (MC) simulation to describe the signal and a first order polynomial to parametrize the background [13]. In the fit to the ΔE distribution, the region $\Delta E < -0.08$ GeV is excluded to avoid contributions from other $B^+ \to D^{(*)}\bar{D}^{(*)}K$ decays. Table I summarizes the results of the fits, the reconstruction efficiencies [14], the statistical significance [15] of the signals, and the calculated branching fractions. For the latter, we assume $N(B^0\bar{B}^0) = N(B^+B^-)$. For the $D^+D^-K^+$ final state, a substantial signal is not seen and we set a 90% confidence upper limit. The systematic error in the branching fraction measurement is dominated by the uncertainty in the tracking efficiency (1% per track), kaon identification efficiency (2% for each kaon), π^0 reconstruction efficiency (6%), D^0 branching fraction uncertainty (in total 8%), MC statistics (3%), and the signal and background parametrization (5%).

We plot the $D^0\bar{D}^0$ and D^+D^- invariant mass distributions for events in the B signal region defined as $5.272 < M_{\rm bc} < 5.288$ GeV$/c^2$ and $|\Delta E| < 0.02$ GeV in Figs. 2(a) and 2(b), respectively. Here, for $B^+ \to D^0\bar{D}^0K^+$ candidates, when one of the D^0's is reconstructed in the $K^-\pi^+\pi^0$ mode, we use a looser ΔE requirement ($|\Delta E| < 0.025$ GeV) to take into account the poorer energy resolution due to shower leakage in the ECL. In the case of multiple B candidates, we choose the candidate with the smallest value of $\chi^2 = (\Delta E/\sigma_{\Delta E})^2 + [(M_{\rm bc} - M_{B^+})/\sigma_{M_{\rm bc}}]^2$. The $M(D^0\bar{D}^0)$ distribution has a peak at low masses, which we attribute to the $\psi(3770)$ signal.

The superimposed hatched histogram in Fig. 2(a) shows the $M(D^0\bar{D}^0)$ mass distribution for events in the ΔE sidebands [16]. The curve (shown as a solid line) is the result of a fit where the low-mass peak is described by a p-wave Breit-Wigner function [17] with a floating mass and its natural width fixed to its nominal value of $\Gamma(\psi(3770)) = 23.6$ MeV$/c^2$ [5]. The combinatorial background along with the contribution from nonresonant $B^+ \to D^0\bar{D}^0K^+$ decays is described by the product of square root threshold factor and $(M_{\rm max} - M(D^0\bar{D}^0))^\alpha$ function and is represented as a dashed line in Fig. 2(a).

The fit yields a $\psi(3770)$ signal of $N = 33.6 \pm 8.3$ events with a statistical significance of 5.9σ. The mass of the $\psi(3770)$ is found to be $M(\psi(3770)) = 3778.4 \pm 3.0 \pm 1.3$ MeV$/c^2$, which corresponds to a mass differ-

TABLE I. Summary of the fit results, efficiencies, statistical significance, and branching fractions for $B^+ \to D^0\bar{D}^0K^+$ and $B^+ \to D^+D^-K^+$ decays.

Mode	ΔE yield	Efficiency (10^{-4})	$\mathcal{B}(10^{-3})$	Significance
$B^+ \to D^0\bar{D}^0K^+$	97.5 ± 17.6	8.7	$1.17 \pm 0.21 \pm 0.15$	5.5σ
$B^+ \to D^+D^-K^+$	20.7 ± 9.9	5.0	$0.43 \pm 0.21 \pm 0.06 < 0.90$ (90%C.L.)	2.7σ

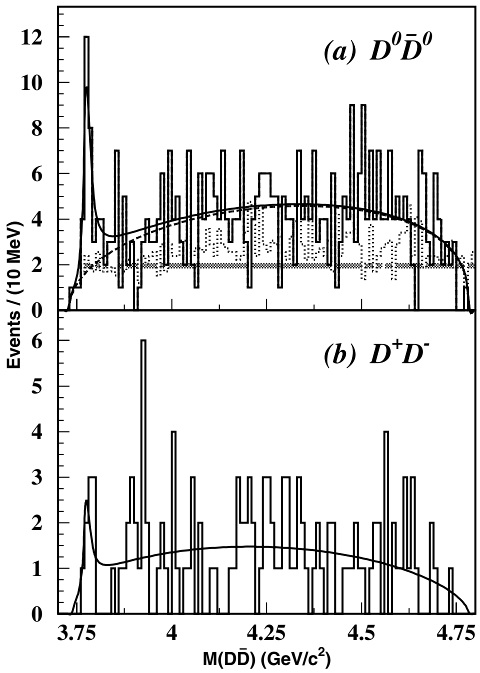

FIG. 2. (a) The $M(D^0\bar{D}^0)$ distribution for the events from the B-signal region. The dashed line represents the background parametrization (see the text). The hatched histogram is constructed from the ΔE sidebands. (b) Fitted $M(D^+D^-)$ distribution.

ence $\Delta m = M(\psi(3770)) - M(\psi(2S)) = 92.4 \pm 3.0 \pm 1.3\ \mathrm{MeV}/c^2$, where we used $M(\psi(2S)) = 3685.96 \pm 0.09\ \mathrm{MeV}/c^2$ [5]. Table II compares our measurement of Δm with the available results from the MARK I, DELCO, and MARK II Collaborations [5,18]; our measurements agree with the MARK I and DELCO results and are $\sim 3\sigma$ above the MARK II result. The systematic error on the mass measurement is evaluated by varying the background function, the width of the $\psi(3770)$ within its errors [5], changing the fit range and changing the bin width. It also includes the uncertainty in the D^0 mass.

A fit to the $M(D^+D^-)$ distribution of Fig. 2(b) yields 7.7 ± 4.2 events with a statistical significance of 2.5σ. Here the $\psi(3770)$ mass was fixed at $3778.4\ \mathrm{MeV}/c^2$, the value found from the $M(D^0\bar{D}^0)$ fit.

From a MC sample of generic $B\bar{B}$ events that has the same size as the data sample, we find that the $D\bar{D}$ invariant mass exhibits a smooth behavior without peaks. We also analyzed off-resonance data taken 60 MeV below the $\Upsilon(4S)$ with a $10\ \mathrm{fb}^{-1}$ data sample. The same selection applied to $D^0\bar{D}^0K^+$ combinations results in one event over the whole $M(D^0\bar{D}^0)$ region, which corresponds to a negligible contribution from the continuum.

TABLE II. Result of the measurement of $\Delta m = M(\psi(3770)) - M(\psi(2S))$ (MeV/c^2) obtained in this Letter and previous measurements.

Belle	$92.4 \pm 3.0 \pm 1.3$
MARK I	88 ± 3
DELCO	86 ± 2
MARK II	80 ± 2

The $\psi(3770) \to D^0\bar{D}^0$ helicity distribution, determined by fitting the $M(D^0\bar{D}^0)$ distribution for the $\psi(3770)$ yield in each of eight $\cos\theta_{\psi(3770)}$ bins [19], is shown in Fig. 3. The points are data, and the histogram gives the result of a fit using MC-based expectations for a $J^{PC} = 1^{--}\ \psi(3770)$ with a floating normalization. The confidence level of the fit is 10.5%.

The MC-determined efficiencies for $B^+ \to \psi(3770)K^+$ followed by $\psi(3770) \to D^0\bar{D}^0$ and $\psi(3770) \to D^+D^-$ are 10.3×10^{-4} and 5.7×10^{-4}, respectively. This gives $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^0\bar{D}^0) = (0.34 \pm 0.08 \pm 0.05) \times 10^{-3}$ and $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^+D^-) = (0.14 \pm 0.08 \pm 0.02) \times 10^{-3}$, where the first error is statistical and the second is systematic. The latter measurement corresponds to a 90% C.L. upper limit of $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^+D^-) < 0.27 \times 10^{-3}$. In addition to the sources already mentioned, the systematic error includes the uncertainties from varying the signal and background shapes in $M(D\bar{D})$ fitting (5%) and from varying the π^0 reconstruction efficiency (6%). From these two measurements we obtain the ratio $\mathcal{B}(\psi(3770) \to D^0\bar{D}^0)/\mathcal{B}(\psi(3770) \to D^+D^-) = 2.43 \pm 1.50 \pm 0.43$. Given the large errors, our measurement is consistent with the previous measurement of this ratio by the MARK III Collaboration of $1.36 \pm 0.23 \pm 0.14$ [20].

To extract $\mathcal{B}(B^+ \to \psi(3770)K^+)$ from the measurements of $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^0\bar{D}^0)$ and $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^+D^-)$, we assume that the $D^0\bar{D}^0$ and D^+D^- modes com-

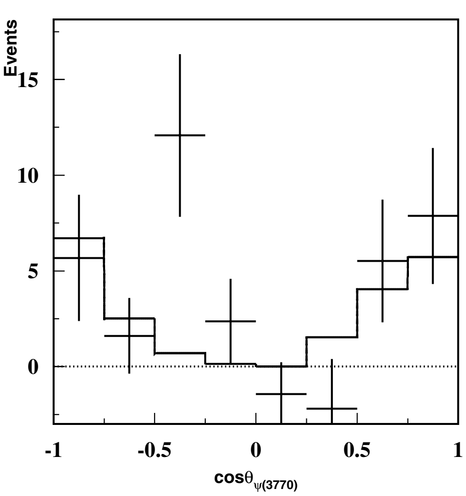

FIG. 3. Helicity distribution for $B^+ \to \psi(3770)K^+$ decay followed by $\psi(3770) \to D^0\bar{D}^0$. The points with errors are obtained from fits to the $M(D^0\bar{D}^0)$ data in each $\cos\theta_{\psi(3770)}$ bin. The histogram shows the expected distribution for $B^+ \to \psi(3770)K^+$ (see text).

pletely saturate the $\psi(3770)$ decay width. Summing both measurements gives $\mathcal{B}(B^+ \to \psi(3770)K^+) = (0.48 \pm 0.11 \pm 0.07) \times 10^{-3}$.

Belle recently reported the observation of a narrow charmoniumlike state $X(3872)$ that decays to $\pi^+\pi^- J/\psi$ [21]. This state, which is seen in the exclusive decay $B \to KX(3872)$, is above $D\bar{D}$ threshold. Information about the $X(3872) \to D\bar{D}$ decay rate would be useful for determining its quantum numbers. We refitted the $D^0\bar{D}^0$ and D^+D^- invariant mass distributions including possible contributions from $B^+ \to X(3872)K^+$, $X(3872) \to D\bar{D}$ decays. The fits yield 2.1 ± 1.8 and 0.4 ± 0.8 events for the $D^0\bar{D}^0$ and D^+D^- channels, respectively. From this we determine 90% C.L. upper limits $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^0\bar{D}^0) < 6 \times 10^{-5}$ and $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^+D^-) < 4 \times 10^{-5}$. We have also searched for a possible reflection from $B^+ \to X(3872)K^+$, $X(3872) \to D^0\bar{D}^0\pi^0$ decays. This decay mode of the $X(3872)$ is interesting because it is predicted to be large if the $X(3872)$ is a $D\bar{D}^*$ multiquark "molecular state" [22]. A MC study shows that these decays produce a narrow, nearly Gaussian reflection peak ($\sigma = 9$ MeV) centered at $\Delta E = -145$ MeV. Using the $D^0\bar{D}^0K^+$ signal described above, we require $M(D^0\bar{D}^0)$ to be less than $M(X(3872)) - M(\pi^0) = 3737\ \mathrm{MeV}/c^2$ and fit the resulting ΔE distribution to a Gaussian with mean and width fixed at the values expected for the reflection peak and a linear background contribution. The fit yields 2.2 ± 1.7 events. From this we determine a 90% C.L. upper limit $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^0\bar{D}^0\pi^0) < 6 \times 10^{-5}$.

In summary, we have measured the branching fraction for $B^+ \to D^0\bar{D}^0K^+$ decay to be $\mathcal{B}(B^+ \to D^0\bar{D}^0K^+) = (1.17 \pm 0.21 \pm 0.15) \times 10^{-3}$. A search for$B^+ \to D^+D^-K^+$ decay results in an upper limit of $\mathcal{B}(B^+ \to D^+D^-K^+) < 0.90 \times 10^{-3}$ (90% C.L.). We observe a peak in the $D^0\bar{D}^0$ invariant mass spectrum from $B^+ \to D^0\bar{D}^0K^+$ decays with a mass near 3770 MeV/c^2 that we attribute to exclusive $B^+ \to \psi(3770)K^+$ decay. This signal, which has a statistical significance of 5.9σ, is the first observation of this decay mode. The mass of the $\psi(3770)$ is measured to be $3778.4 \pm 3.0 \pm 0.8\ \mathrm{MeV}/c^2$. The value of $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^0\bar{D}^0)$ is measured to be $(0.34 \pm 0.08 \pm 0.05) \times 10^{-3}$. For $B^+ \to \psi(3770)K^+$ followed by $\psi(3770) \to D^+D^-$ we extract $\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to D^+D^-) = (0.14 \pm 0.08 \pm 0.02) \times 10^{-3}$. The ratio $\frac{\mathcal{B}(\psi(3770) \to D^0\bar{D}^0)}{\mathcal{B}(\psi(3770) \to D^+D^-)}$ is $2.43 \pm 1.50 \pm 0.43$. By assuming that the $D^0\bar{D}^0$ and D^+D^- modes totally saturate the $\psi(3770)$ decay width we obtain $\mathcal{B}(B^+ \to \psi(3770)K^+) = (0.48 \pm 0.11 \pm 0.07) \times 10^{-3}$, which is comparable to $\mathcal{B}(B^+ \to \psi(2S)K^+) = (6.6 \pm 0.6) \times 10^{-4}$ [5]. This result suggests a large amount of S-D mixing in the $\psi(3770)$.

For the decays $B^+ \to X(3872)K^+$ followed by $X(3872) \to D^0\bar{D}^0$ and D^+D^- we have set 90% C.L. upper limits on $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D\bar{D})$ of 6×10^{-5} and 4×10^{-5}, respectively. For the decay $B^+ \to X(3872)K^+$ followed by $X(3872) \to D^0\bar{D}^0\pi^0$ we have set a 90% C.L. upper limit of 6×10^{-5}.

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[14] Throughout this Letter the reconstruction efficiencies include intermediate branching fractions.

[15] The statistical significance is defined as $\sqrt{-2\ln(L_0/L_{\max})}$, where L_0 and $L_{\max}$ are the likelihood with the signal fixed at zero and at the fitted value, respectively.

[16] The definition of the ΔE sidebands is $-0.080 < \Delta E < -0.040$ GeV or $0.040 < \Delta E < 0.200$ GeV. If there is more than one B candidate, we choose the one with the smallest value of $[(M_{bc} - M_{B^+})/\sigma_{M_{bc}}]^2$.

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