Observation of a Near-Threshold $D^0\bar{D}^0\pi^0$ Enhancement in $B \to D^0\bar{D}^0\pi^0 K$ Decay

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We report the first observation of a near-threshold enhancement in the $D^0\bar{D}^0\pi^0$ system from $B \to D^0\bar{D}^0\pi^0 K$ decays using a 414 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance. The enhancement peaks at a mass $M = 3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV$/c^2$ and the branching fraction for events in the peak is $\mathcal{B}(B \to D^0\bar{D}^0\pi^0 K) = (1.22 \pm 0.31\,^{+0.23}_{-0.30}) \times 10^{-4}$. The data were collected with the Belle detector at the KEKB energy-asymmetric e^+e^- collider.

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Belle recently discovered [1] a new state, the $X(3872)$, with a mass of $(3872.0 \pm 0.6 \pm 0.5)$ MeV$/c^2$ and width less than 2.3 MeV$/c^2$ in the $J/\psi\pi^+\pi^-$ system from $B^\pm \to J/\psi\pi^+\pi^-K^\pm$ decays. Other experiments confirmed the existence of the $X(3872)$ [2], but all published results are in the $J/\psi\pi^+\pi^-$ mode only. Although the initial expectations were that the $X(3872)$ was one of the unobserved charmonium states, subsequent experimental observations disfavor this hypothesis [3].

Since the properties of the $X(3872)$ are not consistent with a charmonium assignment, there have been speculations that it is some type of exotic state, for example, a $q\bar{q}g$ hybrid [4]. The $X(3872)$ mass is within errors of the $D^0\bar{D}^{*0}$ threshold $(3871.2 \pm 0.8$ MeV$/c^2)$, which triggered speculation that it might be a $D^0\bar{D}^{*0}$ bound state (deuson) [5]. If the $X(3872)$ is a loosely bound S-wave molecule composed of $D^0\bar{D}^{*0}$ charm mesons, it is expected that there will be an enhancement in the near-threshold $D^0\bar{D}^{*0}$ invariant mass distribution [5,6]. The Belle collaboration found no evidence for $D^0\bar{D}^0$, D^+D^- and $D^0\bar{D}^0\pi^0$ decays of $X(3872)$ with a smaller sample of $B\bar{B}$ events [7]. The distributions of daughter particle momenta for $D^0\bar{D}^0\pi^0$ decays of a $D^0\bar{D}^{*0}$ molecule are expected to be different from those of an incoherent sum of the decays of free D^{*0} and $\bar{D}^0$ [8].

In this Letter, the $D^0\bar{D}^0\pi^0$ system is studied in $B^+ \to D^0\bar{D}^0\pi^0K^+$ and $B^0 \to D^0\bar{D}^0\pi^0K^0_S$ decays. Inclusion of charge conjugate modes is implied throughout this Letter.

These results are based on a 414 fb^{-1} data sample corresponding to 447×10^6 $B\bar{B}$ pair events collected with the Belle detector [9] at the energy-asymmetric e^+e^- collider KEKB [10]. The fractions of neutral and charged B mesons produced in the $\Upsilon(4S)$ peak are assumed to be equal.

The Belle detector is a general purpose magnetic spectrometer with a 1.5 T magnetic field provided by a superconducting solenoid. Momenta of charged particles are measured using a silicon vertex detector and a 50-layer central drift chamber (CDC). Photons are detected in an electromagnetic calorimeter (ECL) consisting of 8736 CsI(Tl) crystals. Particle identification likelihoods, $\mathcal{L}_{\pi/K}$, are derived from the information provided by an array of 128 time-of-flight counters, an array of 1188 silica aerogel Čerenkov threshold counters and dE/dx measurements in the CDC.

Kaon candidates are selected from well-measured tracks by using a requirement on the likelihood ratio, $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, which has an average kaon identification efficiency ~97% with a pion misidentification rate of ~18%. Similarly, charged pions are selected with an efficiency of ~98% and kaon misidentification rate of ~12%. All tracks compatible with the electron hypothesis (~0.2% misidentification rates from pion/kaon) are eliminated.

Neutral pions (π^0) are reconstructed from pairs of isolated ECL clusters (photons) with invariant mass in the range 119 MeV$/c^2 < M_{\gamma\gamma} < 150$ MeV$/c^2$($\sim\pm 3\sigma$). The energy of each photon is required to be greater than 30 MeV in the barrel region, defined as $32° < \theta_\gamma < 128°$, and greater than 50 MeV in the endcap regions, defined as $17° < \theta_\gamma \leq 32°$ or $128° < \theta_\gamma \leq 150°$, where θ_γ denotes the polar angle of the photon. A mass-constrained fit is applied to obtain the four-momentum of a π^0 candidate.

Neutral kaons (K^0_S) are reconstructed *via* the $K^0_S \to \pi^+\pi^-$ decay mode. There is no particle identification requirement for daughter pions and the requirement $|M_{\pi\pi} - M_{K^0_S}| < 11$ MeV$/c^2$ ($\sim 3.5\sigma$, where σ is the $\pi^+\pi^-$ invariant mass resolution) is applied. Selection criteria to reduce random combinations of two tracks are described in detail elsewhere [11]. A mass-vertex-constrained fit is performed to the K_S^0 candidate to improve the resolution on its momentum measurement.

Beam-gas events are rejected using the requirements $|P_z| < 2$ GeV$/c$ and $1.0 < E_{\rm vis}/E_{\rm beam} < 2.5$, where P_z, $E_{\rm beam}$ and $E_{\rm vis}$ are the longitudinal momentum sum, beam energy and total visible energy, respectively, in the center of mass (c.m.) frame. Continuum events ($e^+e^- \to q\bar{q}$, where $q = u$, d, s, c) are suppressed by requirements on the ratio of the second to the zeroth Fox-Wolfram moments [12], $R_2 < 0.50$.

Candidate D^0 mesons are reconstructed from well-measured charged tracks in the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and K^+K^- decay modes. A ± 3 sigma mass window is applied for selecting D^0's, where sigma is the decay-mode-dependent resolution of the reconstructed D^0 mass (typically ~ 4.5 MeV$/c^2$). Mass and vertex-constrained fits are applied to improve the D^0 meson momentum resolution.

A $D^0\bar{D}^0$ candidate pair is combined with a π^0 and a kaon to reconstruct a B candidate. Continuum events are further suppressed with the criterion, $|\cos\theta_{\rm Thrust}| < 0.9$, where $\theta_{\rm Thrust}$ is the angle between the thrust axis of the B candidates and the thrust axis of the remaining tracks and isolated ECL clusters. The beam-energy-constrained mass, $M_{\rm bc}$ $(= \sqrt{(E_{\rm beam})^2 - (\sum_i \vec{P}_i)^2})$, where $\vec{P}_i$ is the momentum of the ith daughter of the candidate B in the c.m. frame is restricted between 5.273 and 5.286 GeV$/c^2$. A peak in the difference between the measured energy of the B candidate and the beam energy, $\Delta E (= \sum_i E_i - E_{\rm beam})$ is a signature of B-meson signal events, where E_i is the c.m. energy of the ith daughter of the candidate B.

The $B \to D^0\bar{D}^0\pi^0K$ signal Monte Carlo (MC) sample is generated in two steps, $B \to X(3872)K$ followed by $X(3872) \to D^0\bar{D}^0\pi^0$ assuming a phase space distribution in both decay chains. The average number of $D^0\bar{D}^0\pi^0K$ entries per MC signal event is ~ 3.55, which are mainly due to multiple slow π^0's. The characteristics of incorrectly reconstructed π^0 candidates are identical to signal π^0's. To reduce this multiplicity we use the selection criterion, $M_{D^0\pi^0} < 2.013$ GeV$/c^2$ or $M_{\bar{D}^0\pi^0} < 2.013$ GeV$/c^2$. This requirement reduces background and the candidate multiplicity to 1.68 with almost no loss of signal efficiency. Possible bias due to this selection criterion is studied in the following event samples: (i) a large sample of generic $B\bar{B}$ and continuum MC events; (ii) $D^0D^-\pi^0K$ data; (iii) $D^0D^0\pi^0K$ (same-flavor charm) data; (iv) the D^0-mass side-band data (one D^0-meson is reconstructed when the invariant mass of daughters is outside the D^0-mass signal region); and (v) ΔE side-band data (60 MeV $< |\Delta E| <$ 110 MeV). No peaking behavior is observed in the $DD\pi^0$ mass distribution for any of the above-mentioned control samples, thereby confirming that there is no bias in the selection criteria on $M_{D^0\bar{D}^0\pi^0}$.

A unique $D^0\bar{D}^0\pi^0K$ candidate is chosen out of possible multiple candidates in a given event by taking the combination with the minimum value of $(\frac{\Delta M_{\pi^0}}{\sigma_{M_{\pi^0}}})^2 + (\frac{\Delta M_{D^0}}{\sigma_{M_{D^0}}})^2 + (\frac{\Delta M_{\bar{D}^0}}{\sigma_{M_{\bar{D}^0}}})^2$, where Δx and σ_x are the deviation of the measured quantity x from its nominal value and the uncertainty in its measurement, respectively. Multiple kaon entries are resolved by choosing the candidate with the highest kaon identification probability for charged kaon and minimum $|M_{\pi\pi} - M_{K_S^0}|$ for neutral kaon. There is a negligibly small number of events with charged and neutral kaon multiple entries.

An unbinned extended maximum likelihood fit to the $D^0\bar{D}^0\pi^0$ invariant mass, $M_{D^0\bar{D}^0\pi^0}$, and ΔE distributions is used to obtain the signal yield. The fit includes three components: (i) a signal function, which is modeled by the sum of two Gaussian functions with the same mean value for ΔE and single Gaussian function for $M_{D^0\bar{D}^0\pi^0}$; (ii) a nonresonant $B \to D^0\bar{D}^{*0}K$ signal, where ΔE is also modeled by a double Gaussian function and $M_{D^0\bar{D}^0\pi^0}$ with a threshold function; and (iii) the remaining backgrounds, which are modeled with a first-order polynomial for ΔE and another threshold function for $M_{D^0\bar{D}^0\pi^0}$, this threshold function is obtained from the ΔE side-band data of $B \to D^0\bar{D}^0\pi^0K$ events. Shapes of the ΔE distributions for signal and nonresonant $B \to D^0\bar{D}^{*0}K$ background are fixed from the $B \to D^0\bar{D}^{*0}K$ data sample. The signal has a narrow Gaussian component with width $\sigma \sim 4.5$ MeV and a wide Gaussian component with width 4.6 times larger that accounts for 40% of the signal.

Parameters of the $M_{D^0\bar{D}^0\pi^0}$ threshold functions are fixed from a large MC sample of $B \to D^0\bar{D}^{*0}K$ events for the nonresonant components and $B \to D^0\bar{D}^0\pi^0K$ ΔE side-band data for remaining backgrounds. The normalization factor for the nonresonant component is fixed according to the branching fraction from [13]. The slope of the background polynomial, the parameters of $M_{D^0\bar{D}^0\pi^0}$ threshold peak, and the normalization factors of signal and combinatorial background component are free parameters of the fit.

Figure 1(a) shows the scatter plot of ΔE and $M_{D^0\bar{D}^0\pi^0}$ in data. There is a cluster of events in the $D^0\bar{D}^0\pi^0$ threshold region. The ΔE distributions for different $M_{D^0\bar{D}^0\pi^0}$ intervals are shown in plots (b)–(m), where a one-dimensional fit gives a signal of (23.4 ± 5.6) events in the $M_{D^0\bar{D}^0\pi^0}$ range from 3.870 GeV$/c^2$ to 3.878 GeV$/c^2$. The statistical significance of this signal, defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{0({\rm max})}$ is the likelihood without (with) the signal contribution, is 6.4σ. A similar analysis that uses the $M_{\rm bc}$ distribution rather than the ΔE distribution to measure the signal also shows a clear peak for the same $M_{D^0\bar{D}^0\pi^0}$ interval, with a consistent signal yield and similar statistical significance.

To obtain the exact position of the near-threshold peak as well as its branching fraction, the two-dimensional dis-

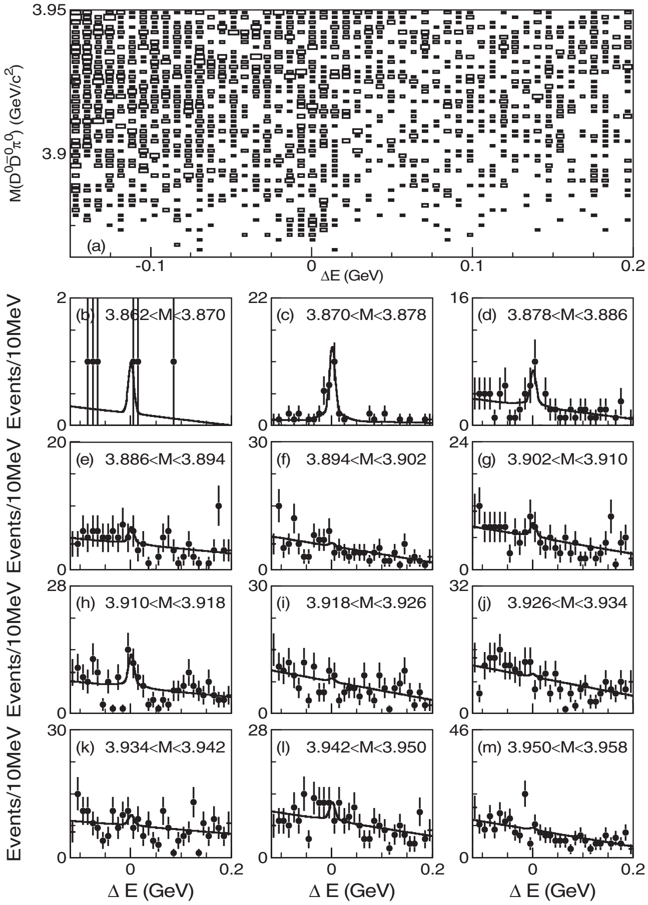

FIG. 1. (a) Scatter plot of ΔE and $M_{D^0\bar{D}^0\pi^0}$ distribution in the data sample. (b)–(m) ΔE distributions in 8 MeV/c^2 $D^0\bar{D}^0\pi^0$ mass bins for a possible $B \to D^0\bar{D}^0\pi^0 K$ signal in data.

tribution of ΔE and Q value ($= M_{D^0\bar{D}^0\pi^0} - 2M_{D^0} - M_{\pi^0}$) is fitted. Projections onto Q value (for $|\Delta E| < 25$ MeV) and ΔE (for 6 MeV/c^2 $<Q$ value <14 MeV/c^2) are shown in Fig. 2 along with the results of the fit. The fitted mean and width of the near-threshold peak are 11.21 ± 0.68 and 2.42 ± 0.55 MeV/c^2, respectively, in the Q value. The signal yield is 24.1 ± 6.1 and the significance, including the effects of systematic errors, is 6.4σ. Individual results for the charged and neutral B meson samples are given in Table I together with the combined result.

In terms of the invariant mass of $D^0\bar{D}^0\pi^0$ system, the peak position is $M_{D^0\bar{D}^0\pi^0} = 3875.4 \pm 0.7$ MeV, where the error is statistical only.

The MC-determined signal efficiency for the near-threshold peak is $(1.87 \pm 0.05)\%$. The contribution from nonresonant $B \to D^0\bar{D}^{*0}K$ events in the near-threshold $M_{D^0\bar{D}^0\pi^0}$ region, calculated from a large sample ($\sim$60 times real data) is found to be 1.6 ± 0.2 events.

Because of the limited available phase space, the $M_{D^0\pi^0}/M_{\bar{D}^0\pi^0}$ distributions near the threshold show some clustering around D^{*0} mass. Thus, it is not possible to

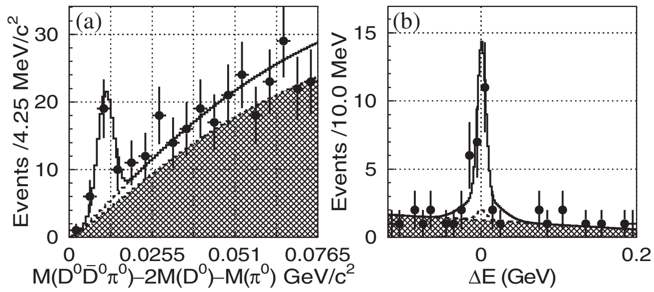

FIG. 2. Projection of the unbinned fit (a) Q value ($= M_{D^0\bar{D}^0\pi^0} - 2M_{D^0} - M_{\pi^0}$) in ΔE signal region ($|\Delta E| <$ 25 MeV) and (b) ΔE in the signal region of Q value (6 MeV/c^2 $<Q$ value <14 MeV/c^2). The dots are data points, the hatched histogram corresponds to combinatorial background; the dashed line indicates the total background and the solid line is from the combined fitting function.

separate the contributions of $D^0\bar{D}^{*0}$ and $D^0\bar{D}^0\pi^0$ to the peak.

With a large sample of MC-simulated $D^0\bar{D}^0\pi^0$ events generated in a narrow, near-threshold mass peak, it is found that the reconstructed peak in the $M_{D^0\bar{D}^0\pi^0}$ distribution has a high-mass tail that is caused by poorly reconstructed π^0's. We are unable to distinguish this high-mass tail component in the data or in samples of MC signal plus background with sizes similar to the data. This tail, if it exists, would produce a positive bias on the peak mass measurement. We account for this possibility with asymmetric systematic errors on the peak mass and efficiency of $^{+0.0}_{-1.7}$ MeV/c^2 and $^{+25.9}_{-4.8}\%$, respectively. Including all systematics, the observed $M_{D^0\bar{D}^0\pi^0}$ peak position is $3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV/c^2, where the second error is mainly due to the calibration uncertainty of the π^0 energy and the effects of a possible high-mass tail as discussed above. The third error is due to the uncertainty in the world-average D^0 mass [14].

The systematic uncertainty on the $B \to D^0\bar{D}^0\pi^0 K$ branching fraction for the near-threshold peak is obtained from the quadratic sum of the uncertainties due to (a) limited MC statistics (1.3%), (b) subtraction of the $B \to D^0\bar{D}^{*0}K$ contribution (5.1%), (c) number of $B\bar{B}$ events ($N_{B\bar{B}}$) (1.3%), (d) PDG branching fraction of D^0 and K_S^0 (5.0%), (e) track finding efficiencies (9.5%), (f) K/π identification uncertainties (7.0%), estimated using $D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^-$ events, (g) π^0 detection efficiency (7.0%), estimated from a comparison of $D^0 \to K^-\pi^+\pi^0$ yields in data and MC events, (h) K_S^0 selection efficiency, estimated from a comparison of $D^0 \to K_S^0\pi^+\pi^-$ yields in data and MC events (2.1%), (i) the ratio of D^0-mass window in data and MC events (2.0%), (j) signal efficiency, calculated from the difference in ΔE and $M_{D^0\bar{D}^0\pi^0}$ fits (5.8%), (k) efficiency due to poorly reconstructed π^0 ($^{+4.8}_{-25.9}\%$), and (l) mass and spin (1.0%). Asymmetric errors are combined according to model-1 of Ref. [15]. The total uncertainty is estimated to be $^{+18.9}_{-28.2}\%$.

TABLE I. Signal yield and branching fraction for $B \to D^0 \bar{D}^0 \pi^0 K$ with near-threshold peak near 3.875 GeV/c^2.

Signal	$\epsilon_i \mathcal{B}_i \times 10^4$	$N_{\rm obs}$	sig, σ	$\mathcal{B} \times 10^4$
$B \to D^0 \bar{D}^0 \pi^0 K$	2.12 ± 0.10	24.1 ± 6.1	6.4	$1.22 \pm 0.31^{+0.23}_{-0.30}$
$B^+ \to D^0 \bar{D}^0 \pi^0 K^+$	3.62 ± 0.14	17.4 ± 5.2	5.0	$1.02 \pm 0.31^{+0.21}_{-0.29}$
$B^0 \to D^0 \bar{D}^0 \pi^0 K^0$	0.84 ± 0.04	6.5 ± 2.6	4.6	$1.66 \pm 0.70^{+0.32}_{-0.37}$

In summary, a near-threshold $D^0 \bar{D}^0 \pi^0$ invariant mass enhancement is observed at $3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV/c^2 in $B \to D^0 \bar{D}^0 \pi^0 K$ decays. The significance of this enhancement is 6.4σ.

The observed $D^0 \bar{D}^0 \pi^0$ mass is 2.0σ higher than the world-average value of the $X(3872)$ mass of 3871.2 ± 0.5 MeV/c^2 while the branching fraction of this threshold peak is $8.8^{+3.1}_{-3.6}$ times larger than $\mathcal{B}(B^+ \to X(3872) K^+) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)$ [14]. Reference [16] ruled out all possible quantum states of $X(3872)$ except $J^{PC} = 1^{++}$ and 2^{++} while CDF finds that possible quantum number assignments are 1^{++} and 2^{-+} [17]. If this near-threshold enhancement is due to the $X(3872)$, the $J^{PC} = 1^{++}$ quantum number assignment for the $X(3872)$ is favored, because the near-threshold decay $X(3872) \to D^0 \bar{D}^{*0} / D^0 \bar{D}^0 \pi^0$ is expected to be strongly suppressed for $J = 2$.

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