

Observation of $B^0 \rightarrow \pi^0 \pi^0$

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We report the observation of the decay $B^0 \rightarrow \pi^0 \pi^0$, using a 253 fb^{-1} data sample collected at the $Y(4S)$ resonance with the Belle detector at the KEKB e^+e^- collider. The measured branching fraction is $\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (2.3_{-0.5-0.3}^{+0.4+0.2}) \times 10^{-6}$, with a significance of 5.8 standard deviations including systematic uncertainties. We also make a measurement of the direct CP violating asymmetry in this mode.

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Measurements of the mixing-induced CP violation parameter $\sin 2\phi_1$ [1,2] at B factories are in good agreement with the Kobayashi-Maskawa (KM) mechanism [3]. To confirm this theory, one now has to measure the other two angles of the unitarity triangle, ϕ_2 and ϕ_3 . One technique for measuring ϕ_2 is to study [4,5] time dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$ decay, where we have recently reported [6] the observation of CP violation and evidence for direct CP violation. The extraction of ϕ_2 , however, is complicated by the presence of both tree and penguin amplitudes, each with different weak phases. An isospin analysis of the $\pi\pi$ system is necessary [7], and one essential ingredient is the branching fraction for the decay $B^0 \rightarrow \pi^0 \pi^0$.

QCD-based factorization predictions for $\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0)$ are typically around or below 1×10^{-6} [8], but phenomenological models incorporating large rescattering effects can accommodate larger values [9]. Evidence for $B^0 \rightarrow \pi^0 \pi^0$ emerged [10,11] at the B factories a year ago, with a combined value of $(1.9 \pm 0.5) \times 10^{-6}$ for the branching fraction [12]. If such a high value persists, an isospin analysis for ϕ_2 extraction would become feasible in the near future. To complete the program, one would need to measure both the B^0 and the \bar{B}^0 decay rates, i.e., direct CP violation.

In this Letter we report the observation of the decay $B^0 \rightarrow \pi^0 \pi^0$. We also make a measurement of the direct CP

violating asymmetry in this mode. The results are based on a 253 fb^{-1} ($275 \text{ M } B\bar{B}$ pairs) data set collected with the Belle detector at the KEKB e^+e^- asymmetric collider [13]. KEKB operates at a center-of-mass (c.m.) energy of $\sqrt{s} = 10.58 \text{ GeV}$, corresponding to the mass of the $Y(4S)$ resonance. Throughout this Letter, neutral and charged B mesons are assumed to be produced in equal amounts at the $Y(4S)$, and the inclusion of charge conjugate modes is implied, unless otherwise specified.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter (ECL) composed of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons. The detector is described in detail elsewhere [14]. Two different inner detector configurations were used. For the first sample of $152 \times 10^6 B\bar{B}$ pairs (set I), a 2.0 cm radius beam pipe and a 3-layer silicon vertex detector were used; for the latter $123 \times 10^6 B\bar{B}$ pairs (set II), a 1.5 cm radius beam pipe, a 4-layer silicon detector, and a small-cell inner drift chamber were used [15].

Pairs of photons with invariant masses in the range $115 < m_{\gamma\gamma} < 152 \text{ MeV}/c^2$ are used to form π^0 mesons;

this corresponds to a window of $\pm 2.5\sigma$ about the nominal π^0 mass, where σ denotes the experimental resolution, approximately 8 MeV/ c^2 . The measured energy of each photon in the laboratory frame is required to be greater than 50 MeV in the barrel region, defined as $32^\circ < \theta_\gamma < 129^\circ$, and greater than 100 MeV in the end-cap regions, defined as $17^\circ \leq \theta_\gamma \leq 32^\circ$ and $129^\circ \leq \theta_\gamma \leq 150^\circ$, where θ_γ denotes the polar angle of the photon with respect to the positron beam line. To further reduce the combinatorial background, π^0 candidates with small decay angles ($\cos\theta^* > 0.95$) are rejected, where θ^* is the angle between the π^0 boost direction from the laboratory frame and one of its γ daughters in the π^0 rest frame.

Signal B candidates are formed from pairs of π^0 mesons and are identified by their beam energy constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$ and energy difference $\Delta E = E_B^* - E_{\text{beam}}^*$, where E_{beam}^* denotes the beam energy and p_B^* and E_B^* are the momentum and energy, respectively, of the reconstructed B meson, all evaluated in the e^+e^- c.m. frame. We require $M_{bc} > 5.2$ GeV/ c^2 and $-0.3 < \Delta E < 0.5$ GeV. The signal efficiency is estimated using GEANT-based [16] Monte Carlo (MC) simulations. The resolution for the signal is approximately 3.6 MeV/ c^2 in M_{bc} . The distribution in ΔE is asymmetric due to energy leakage from the CsI(Tl) crystals. If it is parametrized by a bifurcated Gaussian, the upper and lower resolutions are 46 and 122 MeV, respectively.

We consider background from other B decays and from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) continuum processes. A large generic MC sample shows that backgrounds from $b \rightarrow c$ decays are negligible. Among charmless B decays, the only significant background is $B^\pm \rightarrow \rho^\pm \pi^0$ with a missing low momentum π^\pm . This background populates the negative ΔE region, and is taken into account in the signal extraction described below.

The dominant background is due to continuum processes. We use event topology to discriminate signal events from this $q\bar{q}$ background, and follow the continuum rejection technique from our previous publication [11]. We use modified Fox-Wolfram moments [17] where the particles in the signal B candidate (category s) and those in the rest of the event (category o) are treated separately; we also use the missing momentum of the event as a third category (category m). Some additional discrimination is achieved by considering charged and neutral particles in the o category independently, and by taking the correlations of charges into account. We combine 16 modified moments with the scalar sum of the transverse momentum into a Fisher discriminant [18] and tune the coefficients to optimize the separation between signal and background.

The angle of the B -meson flight direction with respect to the beam axis (θ_B) provides further discrimination. A likelihood ratio $\mathcal{R}_s = \mathcal{L}_s / (\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$ is used as the discrimination variable, where \mathcal{L}_s denotes the product of the individual Fisher and θ_B likelihoods for the signal and

$\mathcal{L}_{q\bar{q}}$ is that for the $q\bar{q}$ background. The likelihood functions are derived from MC simulations for the signal and from events in the M_{bc} sideband region ($5.20 < M_{bc} < 5.26$ GeV/ c^2) for the $q\bar{q}$ background.

Additional discrimination between signal and background can be achieved by using the Belle standard algorithm for b -flavor tagging [1,5], which is also needed for the direct CP violation measurement. The flavor tagging procedure yields two outputs: $q = \pm 1$, indicating the flavor of the other B in the event, and r , which takes values between 0 and 1 and is a measure of the confidence that the q determination is correct. Events with a high value of r are considered well tagged and are therefore unlikely to have originated from continuum processes. For example, an event that contains a high momentum lepton (r close to unity) is more likely to be a $B\bar{B}$ event so a looser \mathcal{R}_s requirement can be applied. We find that there is no strong correlation between r and any of the topological variables used above to separate the signal from the continuum.

We divide the data into $r \geq 0.5$ and $r < 0.5$ bins. The continuum background is reduced by applying a selection requirement on \mathcal{R}_s for events in each r region of sets I and II according to the figure of merit (FOM). The FOM is defined as $N_s^{\text{exp}} / \sqrt{N_s^{\text{exp}} + N_{BG}^{\text{exp}}}$, where N_s^{exp} and N_{BG}^{exp} denote the expected signal, assuming the branching fraction $\mathcal{B} = 2 \times 10^{-6}$, and background yields obtained from MC and sideband data, respectively. A typical requirement suppresses 97% of the continuum background while retaining 53% of the signal.

The signal yields are extracted by applying unbinned two-dimensional maximum likelihood fits to the $(M_{bc}, \Delta E)$ distributions of the B and \bar{B} samples. The likelihood is defined as

$$\mathcal{L} = \exp\left(-\sum_{s,k,j} N_{s,k,j}\right) \prod_i \left(\sum_{s,k,j} N_{s,k,j} \mathcal{P}_{s,k,j,i}\right), \quad (1)$$

where

$$\mathcal{P}_{s,k,j,i} = P_{s,k,j}(M_{bc,i}, \Delta E_i), \quad (2)$$

and s indicates set I or set II, k distinguishes events in the $r < 0.5$ or $r \geq 0.5$ bins, i is the identifier of the i th event, $P_{s,k,j}(M_{bc}, \Delta E)$ are the two-dimensional probability density functions (PDFs) in M_{bc} and ΔE for the signal and background components, N_j is the number of events for the category j , which corresponds to either signal, $q\bar{q}$ continuum, or background from $B^\pm \rightarrow \rho^\pm \pi^0$ decay.

The PDFs for the signal and for $B^+ \rightarrow \rho^+ \pi^0$ are taken from smoothed two-dimensional histograms obtained from large MC samples. For the signal PDF, discrepancies between the peak positions and resolutions in data and MC simulations are calibrated using $D^0 \rightarrow \pi^0 \pi^0$ and $B^+ \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^- \pi^0) \pi^+$ decays. The difference is caused by the imperfect simulation of the π^0 energy resolution while the effect of the opening angle distributions can be ne-

glected. The invariant mass distribution for D^0 is fitted with an empirical function for data and MC simulations, and the observed discrepancies in the peak position and width are converted to the differences in the peak position and resolution for ΔE in the signal PDF. We require the D^0 decay products to lie in the same momentum range as the π^0 s from $B \rightarrow \pi^0 \pi^0$. To obtain the two-dimensional PDF for the continuum background, we multiply the PDF for ΔE , which is modeled with a linear function based on studies of M_{bc} sidebands in data, with the PDF for M_{bc} , for which we use the ARGUS function [19]. In the fit, the shapes of the signal and $B^+ \rightarrow \rho^+ \pi^0$ PDFs are fixed, with the normalization for $B^+ \rightarrow \rho^+ \pi^0$ floated; all other fit parameters are allowed to float. The fit results are shown in Fig. 1.

The obtained signal yield is $81.8_{-16.9}^{+15.5}$ with a statistical significance (S) of 6.1, where S is defined as $S = \sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{N_s})}$, and \mathcal{L}_0 and \mathcal{L}_{N_s} denote the maximum likelihoods of the fits without and with the signal component, respectively. The relative yields in sets I and II are consistent with the expectation based on their relative luminosities. The fitted yield of the $\rho^+ \pi^0$ background is 47.7 ± 16.0 , consistent with the known average branching fraction. We vary each calibration constant for the signal PDF by $\pm 1\sigma$ and obtain systematic errors from the change in the signal yield. Adding these errors in quadrature, the significance including systematic uncertainties is reduced to 5.8σ , which corresponds to the observation of $B^0 \rightarrow \pi^0 \pi^0$.

In order to obtain the branching fraction, we divide the signal yield by the reconstruction efficiency, measured from MC simulations to be 12.9%, and by the number of $B\bar{B}$ pairs. We consider systematic errors in the reconstruction efficiency due to possible differences between data and MC simulations. A 4.2% systematic error is assigned for the uncertainty in the efficiency for the track multiplicity requirement. This is determined by varying the multiplicity distribution of signal MC simula-

tions. We assign a total error of 6% due to π^0 reconstruction efficiency, measured by comparing the ratio of the yields of the $\eta \rightarrow \pi^0 \pi^0 \pi^0$ and $\eta \rightarrow \gamma \gamma$ decays. The experimental errors on the branching fractions for these decays [12] are included in this value. We check the effect of the continuum suppression using a control sample of $B^+ \rightarrow \bar{D}^0(\rightarrow K^+ \pi^- \pi^0) \pi^+$ decays; the \mathcal{R}_s requirement has a similar efficiency for the MC control sample and for signal MC simulations. Comparing the \mathcal{R}_s requirement on the control sample in data and MC simulations, a systematic error of 1.8% is assigned.

We check for a possible pileup background due to hadronic continuum events that contain energy deposits from earlier QED interactions. Such a background may peak in M_{bc} ; however, the showers from the QED interaction can be identified from timing information recorded in the ECL. For set II, it is possible to remove these events using this information and determine the change in event yield. We conservatively estimate a systematic uncertainty of 10.3% for this off-time QED background. Finally, we assign a systematic error of 1.1% due to the uncertainty in the number of $B\bar{B}$ pairs (274.8 ± 3.1) $\times 10^6$, and obtain a branching fraction of

$$\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (2.3_{-0.5}^{+0.4+0.2}) \times 10^{-6}.$$

The result is stable under variations of the \mathcal{R}_s cut.

Having observed a significant signal, we utilize the B^0/\bar{B}^0 separation provided by the flavor tagging to measure the CP asymmetry. Equation (2) is replaced by

$$\mathcal{P}_{s,k,j} = \frac{1}{2} [1 - q_i \mathcal{A}_{CP^l,j}] P_{s,k,j}(M_{bc^i}, \Delta E_i), \quad (3)$$

where q indicates the B meson flavor, $B(q = +1)$ or $\bar{B}(q = -1)$, and $\mathcal{A}_{CP^l,j}$ is the effective charge asymmetry, where $\mathcal{A}_{CP^l,j} = \mathcal{A}_{CPj}(1 - 2\chi_d)(1 - 2w_l)$. Here $\chi_d = 0.186 \pm 0.004$ [12] is the time-integrated mixing parameter and w_l is the wrong-tag fraction. For the $q\bar{q}$ continuum, χ_d and w_l are set to zero. The $\pi^0 \pi^0$ sample is divided into six r bins, and the r -dependent wrong-tag fractions, w_l ($l = 1, \dots, 6$), are determined using a high statistics sample of self-tagged $B^0 \rightarrow D^{(*)-} \pi^+$, $D^{*-} \rho^+$, and $D^{*-} \ell^+ \nu$ events and their charge conjugates [20]. The total number of signal events is fixed to the yield obtained from the branching fraction measurement. The relative fractions of signal events, $q\bar{q}$, and $\rho^\pm \pi^0$ background events in the different r bins are also fixed.

Defining the direct CP asymmetry as

$$\mathcal{A}_{CP} \equiv \frac{N(\bar{B} \rightarrow \bar{f}) - N(B \rightarrow f)}{N(\bar{B} \rightarrow \bar{f}) + N(B \rightarrow f)}, \quad (4)$$

the result is $\mathcal{A}_{CP} = 0.44_{-0.52}^{+0.53} \pm 0.17$. Systematic errors are estimated by varying the fitting parameters by $\pm 1\sigma$. Including the result of a null asymmetry check with the same analysis procedure for the $B \rightarrow D(K\pi\pi^0)\pi$ control sample, the total systematic error is ± 0.17 . The fitted

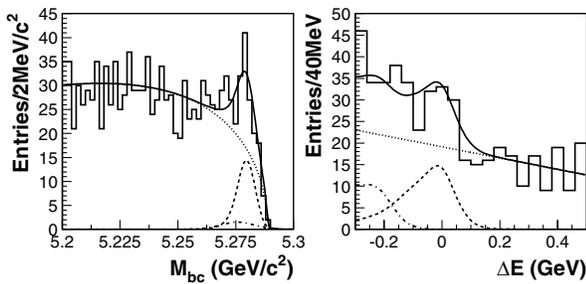


FIG. 1. Result of the fit described in the text. Left: M_{bc} projection for events that satisfy $-0.2 < \Delta E < 0.05$ GeV. Right: ΔE projection for events that satisfy $5.27 < M_{bc} < 5.29$ GeV/c^2 . The solid lines indicate the sum of all components, and the dashed, dotted, and dot-dashed lines represent the contributions from signal, continuum, and $B^+ \rightarrow \rho^+ \pi^0$, respectively.

asymmetry in the $\rho^\pm\pi^0$ is found to be $0.09^{+0.45}_{-0.46}$, which is consistent with zero. To illustrate this asymmetry, we show the results separately for B^0 and \bar{B}^0 tags in Fig. 2. While not significant, the method already gives constraints on ϕ_2 [21].

Our results confirm the previous evidence [10,11] and establish the decay $B^0 \rightarrow \pi^0\pi^0$. Since the observed branching fraction is much larger than predictions based on QCD factorization [8], recent theoretical discussions have focused on the possibility of an enhanced color-suppressed amplitude, together with a sizable strong phase [22]. Other color-suppressed modes such as $B^0 \rightarrow \bar{D}^0\pi^0$ and $B^0 \rightarrow \rho^0\pi^0$ have also been measured [23,24] at rates considerably higher than factorization predictions [9,25]. In addition, the recent evidence for large direct CP violation in $B^0 \rightarrow \pi^+\pi^-$ [6] and $B^0 \rightarrow K^+\pi^-$ modes [26] disagrees with QCD-based factorization predictions. Some effect beyond factorization appears to be present in charmless two-body B decays.

In conclusion, we have observed the $B^0 \rightarrow \pi^0\pi^0$ decay mode in a data sample of $275 \times 10^6 B\bar{B}$ pairs with a branching fraction significantly higher than factorization predictions. We obtain $81.8^{+15.5}_{-16.9}$ signal events with a significance of 5.8 standard deviations (σ) including systematic uncertainties. The branching fraction is measured to be $(2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$. This result is consistent with, and supersedes, our previous result. It is consistent within 2σ with the latest result from *BABAR* [27]. We have also made a measurement of the direct CP violating asymmetry. The large branching fraction for $B^0 \rightarrow \pi^0\pi^0$, together with the measurements of its direct CP violating asymmetry \mathcal{A}_{CP} , will allow a model-independent extraction of the Cabibbo-KM angle ϕ_2 from measurements of the $B \rightarrow \pi\pi$ system in the near future [21].

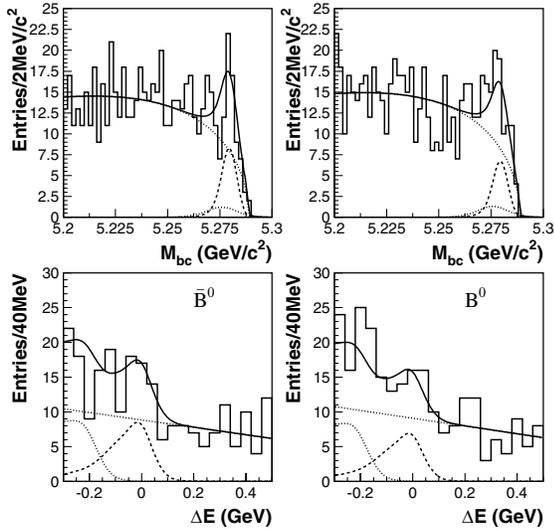


FIG. 2. M_{bc} and ΔE distributions with projections of the fit superimposed. The distributions are shown separately for events tagged as \bar{B}^0 (left) and B^0 (right).

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