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We report evidence for the decay $B^0 \to \pi^0\pi^0$. The analysis is based on a data sample of 152×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- storage ring. We detect a signal for $B^0 \to \pi^0\pi^0$ with a significance of 3.4 standard deviations, and measure the branching fraction to be $[1.7 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$.

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Recent measurements at B factories have improved significantly our knowledge of CP violation and heavy flavor physics. In particular, measurements of the mixing-induced CP violation parameter $\sin 2\phi_1$ [1,2] lend strong support to the Kobayashi-Maskawa mechanism [3]. It is of great importance to test precisely this theory with complementary measurements, such as those of the other unitarity triangle angles ϕ_2 and ϕ_3 [4].

The most promising technique for measuring ϕ_2 is by studying time dependent asymmetries in the $B^0 \to \pi^+\pi^-$ system [5,6]. The extraction of ϕ_2 from the observables is not trivial, however, because there are contributions from more than one weak phase. In order to disentangle ϕ_2, an isospin analysis of the $\pi\pi$ system can be performed [7]. One essential ingredient for these procedures, and hence for the measurement of ϕ_2, is knowledge of the branching fraction for the decay $B^0 \to \pi^0\pi^0$. Such knowledge would also play a pivotal role in the understanding of charmless hadronic B decays. Previously, upper limits for the branching fraction of $B^0 \to \pi^0\pi^0$ of $(3-6) \times 10^{-6}$ have been reported [8–10]. Theoretical predictions are typically around or below 1×10^{-6} [11], but phenomenological models incorporating large rescattering effects can accommodate larger values [12]. The BaBar group recently measured this branching fraction to be $(2.1 \pm 0.6 \pm 0.3)\times10^{-6}$ [13].

In this Letter we report evidence for the decay $B^0 \to \pi^0\pi^0$. The results are based on a 140 fb^{-1} (152×10^6 $B\overline{B}$ pairs) collected with the Belle detector at the KEKB e^+e^- storage ring [14]. KEKB operates at a center-of-mass (c.m.) energy of $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. Throughout this Letter neutral and charged B mesons are assumed to be produced in equal amounts at the $\Upsilon(4S)$, and the inclusion of charge conjugate modes is implied.

The Belle detector is a large-solid-angle spectrometer consisting of a three-layer silicon vertex detector, a 50-layer central drift chamber, an array of threshold Cherenkov counters with silica aerogel radiators, time-of-flight scintillation counters, and an electromagnetic calorimeter comprised 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. A detailed description of the Belle detector can be found elsewhere [15].

Pairs of photons with invariant masses in the range $115\ \text{MeV}/c^2 < m_{\gamma\gamma} < 152\ \text{MeV}/c^2$ are used to form π^0 mesons; this corresponds to a window of $\pm2.5\sigma$ 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 $32° < \theta_\gamma < 128°$, and greater than 100 MeV in the endcap regions, defined as $17° \leq \theta_\gamma \leq 32°$ and $128° \leq \theta_\gamma \leq 150°$, where θ_γ denotes the polar angle of the photon with respect to the beam line.

Signal B candidates are formed from pairs of π^0 mesons and are identified by their beam energy constrained mass $M_{\rm bc} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$ and energy difference $\Delta E = E^*_B - E^*_{\rm beam}$, where $E^*_{\rm beam}$ 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 $5.2\ {\rm GeV}/c^2 < M_{\rm bc} < 5.3\ {\rm GeV}/c^2$ and $-0.3\ {\rm GeV} < \Delta E < 0.5\ {\rm GeV}$. The signal efficiency of the kinematic reconstruction is estimated using GEANT-based [16] Monte Carlo (MC) simulations and found to be 26%. The resolution for signal is approximately 4 MeV$/c^2$ for $M_{\rm bc}$ and $^{+50}_{-100}$ MeV for ΔE.

We consider background from other B decays and from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum processes. A large generic MC sample shows that backgrounds from $b \to c$ decays are negligible. Among charmless B decays, the only significant background is $B^+ \to \rho^+\pi^0$. We take these events, which populate the negative ΔE region, into account in the signal extraction described below.

The dominant background is due to continuum processes. We discriminate signal events from the $q\bar{q}$ background using the event topology. In order to increase the expected sensitivity to the signal, we have improved the continuum rejection technique used in our previous publication [8]. Previously, we have defined modified Fox-Wolfram moments [17] that treat particles involved in the signal B candidate (s) separately from those in the rest of the event (o). We extend this idea, taking into account the missing momentum in the event, which we treat as a third category (m). We achieve some additional discrimination by considering charged and neutral particles in the o category independently, and by taking the correlations of charges into account. In our previously used continuum rejection technique, the moments are normalized relative to the zeroth moment; in this improved technique we do not normalize in this way. We combine 16 modified moments with the scalar sum of the transverse momentum into a Fisher discriminant [18], and tune coefficients separately for seven categories of missing mass squared to maximize the separation between signal and background. MC studies indicate that this redefinition of the Fisher discriminant leads to a 24% improvement in the maximum value of the figure of merit (FOM) defined as $N^{\rm exp}_s/\sqrt{N^{\rm exp}_{\rm BG}}$, where $N^{\rm exp}_s$ and $N^{\rm exp}_{\rm BG}$ denote the expected signal and observed background yields in a region $5.27\ {\rm GeV}/c^2 < M_{\rm bc} < 5.29\ {\rm GeV}/c^2$ and $-0.20\ {\rm GeV} < \Delta E < 0.05\ {\rm GeV}$.

The angle of the B-meson flight direction with respect to the beam axis (θ_B) provides additional 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 for the signal and from events in the $M_{\rm bc}$ sideband region ($5.20\ {\rm GeV}/c^2 < M_{\rm bc} < 5.26\ {\rm GeV}/c^2$) for the $q\bar{q}$ background. We find additional discrimination between signal and background using the Belle standard algorithm for b-flavor tagging [1,5]. The flavor tagging procedure yields two outputs: $q = \pm 1$ (which we ignore), indicating the flavor of the other purported 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. Moreover, we find that there is no strong correlation between r and any of the topological variables used above to separate signal from continuum.

We combine r and $\mathcal{R}_s$ into a single multidimensional likelihood ratio (MDLR) defined as $\mathcal{L}^{\rm MDLR}_s/(\mathcal{L}^{\rm MDLR}_s + \mathcal{L}^{\rm MDLR}_{q\bar{q}})$, where $\mathcal{L}^{\rm MDLR}_s$ denotes the likelihood determined by the r–$\mathcal{R}_s$ two-dimensional distribution for the signal and $\mathcal{L}^{\rm MDLR}_{q\bar{q}}$ is that for the $q\bar{q}$ background. We then make a requirement on the likelihood ratio that maximizes the FOM. Incorporating the flavor tagging information in this way gives a 4% improvement in the FOM as compared to making a selection requirement on $\mathcal{R}_s$ alone. This criterion eliminates 99% of the $q\bar{q}$ background while retaining 39% of the signal. The MDLR

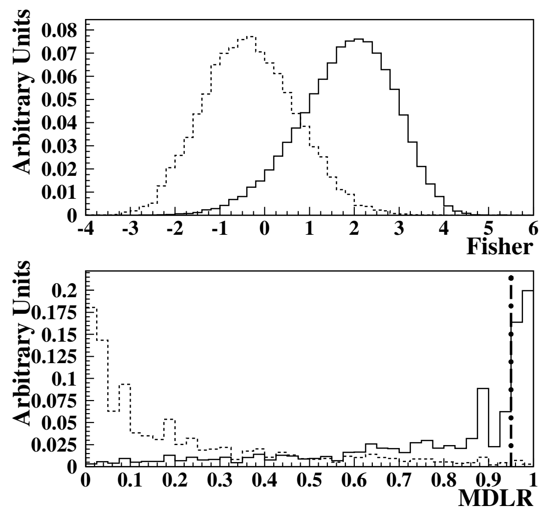

FIG. 1. Distributions of variables used for continuum suppression. (Top) Fisher discriminant using modified Fox-Wolfram moments for signal MC (solid line) and for events in the continuum dominated sideband region (dashed line); (bottom) MDLR for signal MC (solid line) and sideband data (dashed line). The dot-dashed line at MDLR=0.95 indicates the selection requirement made. Apparent structure in the MDLR distribution arises from the several B-tagging modes that contribute to the r distribution.

distributions for signal MC and for sideband data are shown in Fig. 1. We verified that there is no correlation between the MDLR cut and M_{bc} in the continuum MC events.

The signal yield is extracted using an unbinned maximum-likelihood fit to the $M_{bc} - \Delta E$ two-dimensional distribution of the 596 candidates obtained after all the event selection requirements discussed above. The fitting function contains components for the signal, $B^+ \to \rho^+ \pi^0$ and $q\overline{q}$ background. The probability density functions (PDFs) for the signal and for $B^+ \to \rho^+ \pi^0$ 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 due to imperfect simulation of the π^0 energy are calibrated using $D^0 \to \pi^0 \pi^0$ decay. The invariant mass distribution of D^0 is fitted with a bifurcated Gaussian for data and MC, and the observed discrepancies in peak position and width are converted to the differences of peak position and resolution of ΔE in our signal PDF, since observed differences are caused by imperfect simulation of π^0 energy. For the D^0 daughter particles, similar momentum ranges and the same reconstruction procedures are used as those for the signal daughters. We find a 3 ± 9 MeV difference between MC and data for the ΔE peak position and a $35 \pm 12\%$ discrepancy in the ΔE resolution. To obtain the two-dimensional PDF for the continuum background, we multiply the ΔE PDF, which is modeled with a first-order polynomial, with the M_{bc} PDF, for which we use the ARGUS function [19]. In the fit, the shapes of the signal and $B^+ \to \rho^+ \pi^0$ PDFs are fixed, the normalization of $B^+ \to \rho^+ \pi^0$ is fixed according to the recent result from the BaBar Collaboration [20], and all other fit parameters are allowed to float. The fit results are shown in Fig. 2.

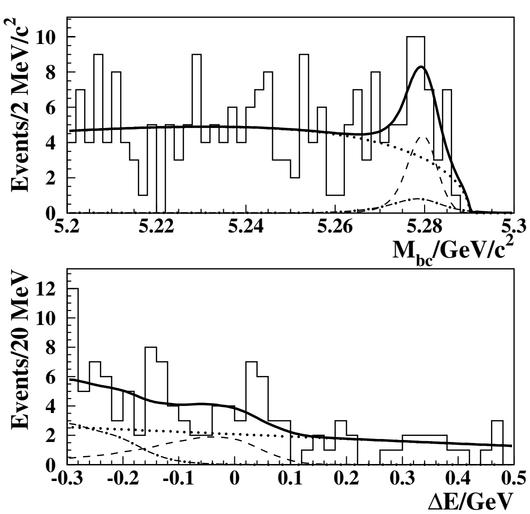

FIG. 2. Result of the fit described in the text. (Top) M_{bc} projection for events which satisfy $-0.2\ \text{GeV} < \Delta E < 0.05\ \text{GeV}$; (bottom) ΔE projection for events which satisfy $5.27\ \text{GeV}/c^2 < M_{bc} < 5.29\ \text{GeV}/c^2$. The solid lines indicate the sum of all components,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

The obtained signal yield is $25.6^{+9.3}_{-8.4}$ with a statistical significance (S) of 3.5, 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. In order to take the uncertainty in the contribution from $B^+ \to \rho^+ \pi^0$ into account in the significance calculation, we repeat the fit after increasing this contribution according to the error in the measurement of its branching fraction. In this case we find $S = 3.4$; we interpret this value as the significance of our signal. We also obtain consistent results when the normalization of the $B^+ \to \rho^+ \pi^0$ component is allowed to float in the fit.

We vary each calibration constant for the signal PDF by $\pm 1\sigma$ and obtain systematic errors from the change in the signal yield. We also vary the $B^+ \to \rho^+ \pi^0$ normalization, as described earlier, and assign systematic errors accordingly. Adding these errors in quadrature, we find the yield is $25.6^{+9.3}_{-8.4}(\text{stat})^{+1.6}_{-1.4}(\text{syst})$.

In order to obtain the branching fraction, we divide the signal yield by the reconstruction efficiency, measured from MC to be 9.9%, and by the number of $B\overline{B}$ pairs. The trigger efficiency is not corrected since it is estimated to be 99% using our trigger simulator. We consider systematic errors on the reconstruction efficiency due to possible differences between data and MC. We assign a total error of 7% due to π^0 reconstruction efficiency, measured by comparing the ratio of the yields of the $\eta \to \pi^0 \pi^0 \pi^0$ and $\eta \to \gamma\gamma$ decays. The experimental errors on the branching fractions of these decays [4] are included in this number. We compare the performance of the continuum suppression requirement on a control sample of $B^+ \to \overline{D}^0 (\to K^+ \pi^- \pi^0) \pi^+$ in data and MC; a systematic error of 2% is assigned. The efficiency of the MDLR cut for the MC control sample is close to that for the signal MC. Finally, we assign a systematic error of 0.5% due to the uncertainty in the number of $B\overline{B}$ pairs $(152.0 \pm 0.7) \times 10^6$, and obtain a branching fraction of

$$\mathcal{B}(B^0 \to \pi^0 \pi^0) = [1.7 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}.$$

The result is stable for variations of the MDLR cut; for example, if we use 0.925 and 0.9 cut, we obtain 1.5×10^{-6} and 1.8×10^{-6}, respectively, which are within the systematic error.

In conclusion, we have measured the branching fraction of $B^0 \to \pi^0 \pi^0$ from a data sample of 152×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle experiment. We obtain $25.6^{+9.3}_{-8.4}(\text{stat})^{+1.6}_{-1.4}(\text{syst})$ signal events with a significance of 3.4 standard deviations (σ). We measure the branching fraction to be $[1.7 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$. This result supersedes our previous result. We find evidence for $B^0 \to \pi^0\pi^0$ at a level above most theoretical predictions [11] and consistent with the BaBar measurement [13]. While larger values of the branching fraction for $B^0 \to \pi^0\pi^0$ enhance the feasibility of the isospin analyses [7], more precise measurements of the branching fraction, in addition to studies of the *CP* asymmetries in all $B \to \pi\pi$ decays, will be required in order to determine ϕ_2 from the $\pi\pi$ system.

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