

Evidence for $B^0 \rightarrow \rho^0 \pi^0$

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We present the first evidence of the decay $B^0 \rightarrow \rho^0 \pi^0$, using 140 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. We detect 15.1 ± 4.8 signal events with a significance of 3.5 standard deviations and measure the branching fraction to be $\mathcal{B}(B^0 \rightarrow \rho^0 \pi^0) = (5.1 \pm 1.6(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-6}$.

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Recent measurements of the CP violating parameter $\sin 2\phi_1$ [1,2] support the Kobayashi-Maskawa mechanism [3] as the origin of CP violation within the standard model. Measurements of other CP violating parameters are necessary to demonstrate that this is the only mechanism for CP violation in B decays. Of particular importance are the other two angles of the unitarity triangle, ϕ_2 and ϕ_3 . Measurements of ϕ_2 typically rely on time-dependent studies of decays of B mesons to light mesons, such as $B^0 \rightarrow \pi^+ \pi^-$ and $\rho^\pm \pi^\mp$. Although these analyses are complicated by the presence of penguin amplitudes, isospin analyses can be used to extract ϕ_2 [4]. Recent evidence for direct CP violation in $B^0 \rightarrow \pi^+ \pi^-$ [5] supports other empirical signatures of sizable penguin contributions; furthermore, measurements of the $B^0 \rightarrow \pi^0 \pi^0$ branching fraction at a level higher than most theoretical expectations [6] suggest that much larger data samples will be needed for a model-independent extraction of ϕ_2 from the $\pi\pi$ system using an isospin analysis.

Measurements of ϕ_2 from the $\rho\pi$ system rely on the knowledge of the branching fraction of $B^0 \rightarrow \rho^0 \pi^0$. The isospin analysis depends on this information and on the CP asymmetry, since all the other $\rho\pi$ final states have been observed [7,8]. An alternative technique to extract ϕ_2 uses an amplitude analysis of $B^0 \rightarrow \pi^+ \pi^- \pi^0$ [9]. Since $B^0 \rightarrow \rho^0 \pi^0$ results in this final state, it is essential to understand its contribution, as well as possible effects from scalar resonances, e.g., $\sigma \pi^0$, and nonresonant sources [10].

Recent theoretical predictions for the branching fraction of $B^0 \rightarrow \rho^0 \pi^0$ are around or below 10^{-6} [11], while the most restrictive experimental upper limit, recently set by the BABAR Collaboration, is $\mathcal{B}(B^0 \rightarrow \rho^0 \pi^0) < 2.9 \times$

10^{-6} [8] at the 90% confidence level. In this Letter, we present the first evidence for $B^0 \rightarrow \rho^0 \pi^0$.

The analysis is based on a 140 fb^{-1} data sample containing 152×10^6 B meson pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [12]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58 \text{ GeV}$) with a peak luminosity that exceeds $1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The production rates of $B^+ B^-$ and $B^0 \bar{B}^0$ pairs are assumed to be equal.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECL) 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 mesons and to identify muons. The detector is described in detail elsewhere [13].

Charged tracks are required to originate from the interaction point and have transverse momenta greater than $100 \text{ MeV}/c$. To identify tracks as charged pions, we combine specific ionization measurements from the CDC, pulse height information from the ACC, and timing information from the TOF into pion/kaon likelihood variables $\mathcal{L}_{\pi/K}$. We then require $\mathcal{L}_{\pi}/(\mathcal{L}_{\pi} + \mathcal{L}_K) > 0.6$, which provides a pion selection efficiency of 93% while keeping the kaon misidentification probability below 10%. Additionally, we reject tracks that are consistent with an electron hypothesis.

Neutral pion candidates are reconstructed from photon pairs with invariant masses in the range

$0.115 \text{ GeV}/c^2 < m_{\gamma\gamma} < 0.154 \text{ GeV}/c^2$, corresponding to a window of $\pm 3\sigma$ about the nominal π^0 mass, where σ is the experimental resolution for the most energetic π^0 candidates. Photon candidates are selected with a minimum energy requirement of 50 MeV in the barrel region of the ECL, defined as $32^\circ < \theta_\gamma < 129^\circ$ and 100 MeV in the end cap regions, defined as $17^\circ < \theta_\gamma < 32^\circ$ and $129^\circ < \theta_\gamma < 150^\circ$, where θ_γ denotes the polar angle of the photon with respect to the beam line. The π^0 candidates are required to have transverse momenta greater than 100 MeV/c in the laboratory frame. In addition, we make a loose requirement on the goodness of a π^0 mass-constrained fit of $\gamma\gamma$ ($\chi_{\pi^0}^2$).

Possible contributions to the $\pi^+\pi^-\pi^0$ final state from charmed ($b \rightarrow c$) backgrounds are explicitly vetoed for the decays $B^0 \rightarrow D^-\pi^+$, $\bar{D}^0\pi^0$, and $J/\psi\pi^0$, based on the two-particle invariant masses. From Monte Carlo (MC) simulation, we find a small combinatorial background from $b \rightarrow c$ remains.

B candidates are selected using two kinematic variables: the beam-constrained mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$. Here, E_B and p_B are the reconstructed energy and momentum of the B candidate in the center of mass (c.m.) frame, and E_{beam} is the beam energy in the c.m. frame. We consider candidate events in the region $-0.20 \text{ GeV} < \Delta E < 0.40 \text{ GeV}$ and $5.23 \text{ GeV}/c^2 < M_{bc} < 5.30 \text{ GeV}/c^2$. We define signal regions in ΔE and M_{bc} as $-0.135 \text{ GeV} < \Delta E < 0.082 \text{ GeV}$ and $5.269 \text{ GeV}/c^2 < M_{bc} < 5.290 \text{ GeV}/c^2$, respectively.

To select $\rho^0\pi^0$ from the three-body $\pi^+\pi^-\pi^0$ candidates, we require the $\pi^+\pi^-$ invariant mass to be in the range $0.50 \text{ GeV}/c^2 < m_{\pi^+\pi^-} < 1.10 \text{ GeV}/c^2$ and the ρ^0 helicity angle to satisfy $|\cos\theta_{\text{hel}}^\rho| > 0.5$, where θ_{hel}^ρ is defined as the angle between the negative pion direction and the opposite of the B direction in the ρ rest frame [14]. Contributions from $B^0 \rightarrow \rho^\pm\pi^\mp$ are explicitly vetoed by rejecting candidates with $\pi^\pm\pi^0$ invariant masses that fall into the window $0.50 \text{ GeV}/c^2 < m_{\pi^\pm\pi^0} < 1.10 \text{ GeV}/c^2$. This requirement removes less than 2% of signal events and excludes the region of the Dalitz plot where the interference between ρ resonances is strongest. After all selection requirements, 11% of events have more than one candidate, and that with the smallest $\chi_{\text{vtx}}^2 + \chi_{\pi^0}^2$ is selected, where χ_{vtx}^2 is the goodness of fit of a vertex-constrained fit of $\pi^+\pi^-$.

The dominant background to $B^0 \rightarrow \pi^+\pi^-\pi^0$ comes from continuum events, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$). Since these tend to be jetlike, while $B\bar{B}$ events tend to be spherical, we use event shape variables to discriminate between the two. We combine five modified Fox-Wolfram moments [15] into a Fisher discriminant and tune the coefficients to maximize the separation between signal and continuum events. We define θ_B as the angle of the

reconstructed B candidate with respect to the beam direction in the c.m. frame. Signal events have a distribution proportional to $\sin^2\theta_B$, while continuum events are flatly distributed in $\cos\theta_B$. We combine the output of the Fisher discriminant with $\cos\theta_B$ into signal/background likelihood variables, $\mathcal{L}_{s/b}$, and define the likelihood ratio $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_b)$. In order to maximize the separation between signal and background, we make use of the additional discriminatory power provided by the flavor tagging algorithm developed for time-dependent analyses at Belle [16]. We utilize the parameter r , which takes values between 0 and 1 and can be used as a measure of the confidence that the remaining particles in the event (other than $\pi^+\pi^-\pi^0$) originate from a flavor specific B meson decay. Events with a high value of r are considered well tagged and hence are unlikely to have originated from continuum processes. Moreover, we find that there is no strong correlation with any of the topological variables used above to separate signal from continuum.

We use a continuum suppression requirement on r and \mathcal{R} that maximizes the value of $N_s/\sqrt{N_s + N_b}$, where N_s and N_b are the numbers of signal and background events contained in the intersection of the ΔE and M_{bc} signal areas. To obtain N_s we use a large statistics sample of $\rho^0\pi^0$ MC and assume a branching fraction for $B^0 \rightarrow \rho^0\pi^0$ of 1×10^{-6} . We estimate N_b from a continuum dominated sideband in data, defined as the union of the two regions $-0.20 \text{ GeV} < \Delta E < 0.40 \text{ GeV}$ and $5.23 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$, and $0.20 \text{ GeV} < \Delta E < 0.40 \text{ GeV}$ and $5.26 \text{ GeV}/c^2 < M_{bc} < 5.30 \text{ GeV}/c^2$. We use an iterative procedure to find the optimal rectangular contiguous area in r - \mathcal{R} space. This method is found to be robust against statistical fluctuations in the samples used to obtain N_s and N_b . The result of the procedure is that we select events that satisfy either $\mathcal{R} > 0.92$ and $r > 0.70$ or $\mathcal{R} > 0.35$ and $r > 0.95$, as shown in Fig. 1. In addition to optimizing $N_s/\sqrt{N_s + N_b}$, this requirement is found to improve N_s/N_b by a factor of 76.

Following all the selection criteria described above, the signal efficiency measured in MC is found to be $(1.91 \pm 0.01)\%$, and we find 73 candidates remain in the data, as shown in Fig. 2(a). We obtain the signal yield using an unbinned maximum-likelihood fit to the ΔE - M_{bc} distribution of the selected candidate events. The fitting function contains components for the signal, continuum background, $b \rightarrow c$ background, and the charmless B decays $B^+ \rightarrow \rho^+\rho^0$, $B^+ \rightarrow \rho^+\pi^0$, and $B^+ \rightarrow \pi^+\pi^0$. The possible contribution from other charmless B decays is found to be small (0.7 events) using a large MC sample [17] and is taken into account in the systematic error. The probability density functions (PDFs) for the signal and charmless B backgrounds are taken from smoothed two-dimensional histograms obtained from large MC samples. For $B^+ \rightarrow \rho^+\rho^0$ our MC assumes 100% longi-

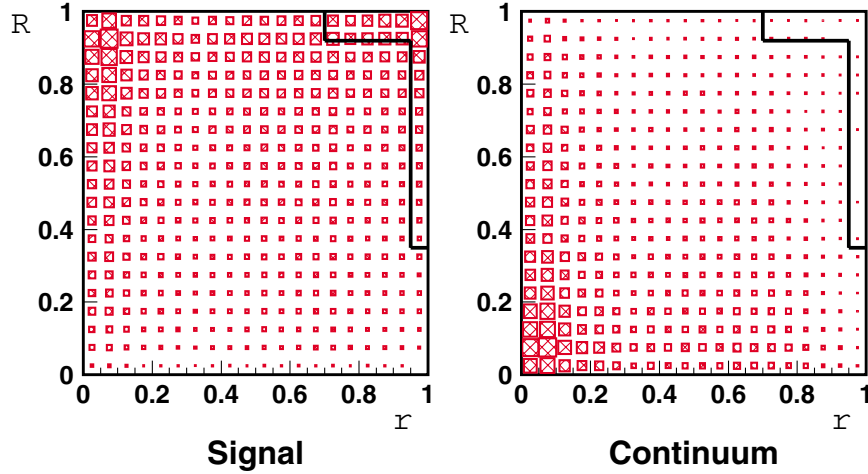


FIG. 1 (color online). Distributions of signal (MC) and continuum (sideband data) events in r - \mathcal{R} space. The marked region indicates the selection requirement obtained from the optimization procedure described in the text.

tudinal polarization [18]. For the signal PDF, small corrections to MC peak positions (< 0.5 MeV) and widths ($< 16\%$) are applied. These factors are derived from control samples ($B^0 \rightarrow D^{*-} \rho^+$ with $D^{*-} \rightarrow \bar{D}^0 \pi^-$, $\bar{D}^0 \rightarrow K^+ \pi^-$, $\rho^+ \rightarrow \pi^+ \pi^0$, and $B^+ \rightarrow \bar{D}^0 \rho^+$ with $\bar{D}^0 \rightarrow K^+ \pi^-$, $\rho^+ \rightarrow \pi^+ \pi^0$), in which we require that the π^0 momentum be greater than 1.8 GeV/ c in order to mimic the high momentum π^0 in our signal.

The two-dimensional PDF for the continuum background is described as the product of a first-order poly-

nomial in ΔE with an ARGUS function [19] in M_{bc} . Contributions from $b \rightarrow c$ are also parametrized as a product of two one-dimensional PDFs. Using MC we find the ΔE distribution of this background in the fitting region is modeled accurately by an exponential function; the M_{bc} distribution is modeled by the ARGUS function. All of the shape parameters describing the continuum and $b \rightarrow c$ backgrounds are free parameters in the fit. The normalizations of $B^+ \rightarrow \rho^+ \pi^0$ (2.0 ± 0.5 events) and $B^+ \rightarrow \pi^+ \pi^0$ (2.3 ± 0.5 events) are fixed according to

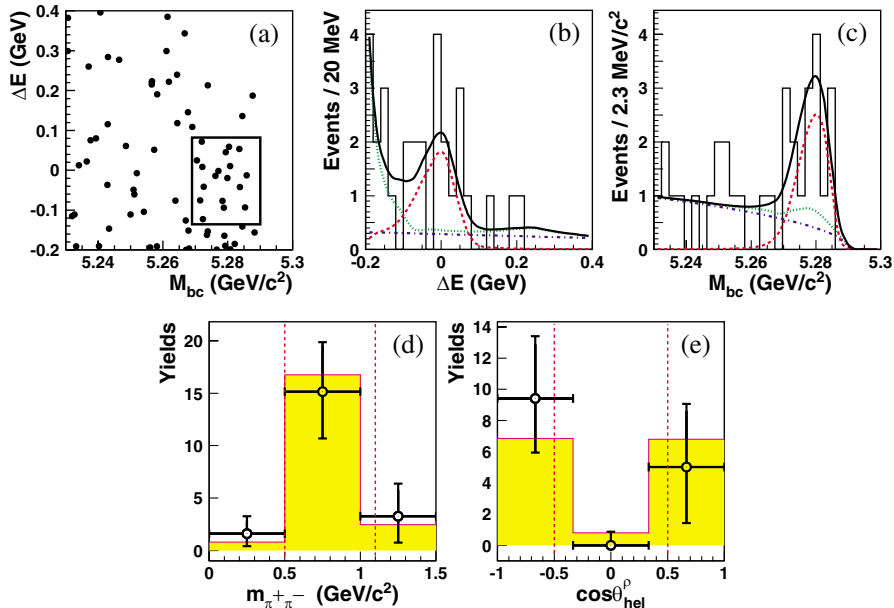


FIG. 2 (color online). (a) Scatter plot of ΔE versus M_{bc} for the selected candidate events; the box indicates the intersection of ΔE and M_{bc} signal regions. (b),(c) Distribution of $\Delta E(M_{bc})$ in the signal region of $M_{bc}(\Delta E)$. Projection of the fit result is shown as the solid curve; the dashed line represents the signal component; the dot-dashed curve represents the contribution from continuum events, and the dotted curve represents the composite of continuum and B -related backgrounds. (d),(e) Distributions of fit yields in $m_{\pi^+\pi^-}$ and $\cos\theta_{\text{hel}}^\rho$ variables for $\rho^0\pi^0$ candidate events. Points with error bars represent data fit results, and the histograms show signal MC expectation; the selection requirements described in the text are shown as dashed lines.

previous measurements [8,20], while the normalizations of all other components are allowed to float.

The fit result is shown in Figs. 2(b) and 2(c). The signal yield is found to be 15.1 ± 4.8 with 3.6σ significance. The significance is defined as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where \mathcal{L}_{\max} (\mathcal{L}_0) denotes the likelihood with the signal yield at its nominal value (fixed to zero). The backgrounds from $b \rightarrow c$ and from $B^+ \rightarrow \rho^+ \rho^0$ form a peak in the low ΔE region. The fit results for these background sources are consistent with the MC expectation, which for $B^+ \rightarrow \rho^+ \rho^0$ is based on our branching fraction measurement [18].

In order to check that the signal candidates originate from $B^0 \rightarrow \rho^0 \pi^0$ decays, we change the criteria on $m_{\pi^+ \pi^-}$ and $\cos\theta_{\text{hel}}^\rho$ in turn and repeat fits to the ΔE - M_{bc} distribution. The yields obtained in each $m_{\pi^+ \pi^-}$ and $\cos\theta_{\text{hel}}^\rho$ bin are shown in Figs. 2(d) and 2(e).

We use the $\cos\theta_{\text{hel}}^\rho$ distribution to limit contributions from $\sigma\pi^0$, $f_0(980)\pi^0$, and $\pi^+ \pi^- \pi^0$ (nonresonant), which are expected to have similar shapes in this variable. We perform a χ^2 fit including components for pseudoscalar \rightarrow pseudoscalar vector (PV $\sim \cos^2\theta_{\text{hel}}^\rho$), and pseudoscalar \rightarrow pseudoscalar scalar (PS \sim flat) decays, for which the shapes are obtained from our $\rho^0 \pi^0$ signal MC, and a sample of $\sigma\pi^0$ MC [21], respectively. We find the PS level is consistent with zero and assign a systematic error due to the possible contribution in our signal region of $^{+0.0}_{-5.0}\%$. The $m_{\pi^+ \pi^-}$ distribution supports the conclusion that our signal is due to $B^0 \rightarrow \rho^0 \pi^0$.

To extract the branching fraction, we measure the reconstruction efficiency from MC and correct for discrepancies between data and MC in the pion identification and continuum suppression requirements. The correction factor due to pion identification (0.89) is obtained in bins of track momentum and polar angle from an inclusive D^* control sample ($D^{*-} \rightarrow \bar{D}^0 \pi^-$, $\bar{D}^0 \rightarrow K^+ \pi^-$). The resulting systematic error is $\pm 3.3\%$. For the continuum suppression requirement on r and \mathcal{R} , we use a control sample $B^0 \rightarrow D^- \rho^+$ with $D^- \rightarrow K^+ \pi^- \pi^-$, $\rho^+ \rightarrow \pi^+ \pi^0$, which has the necessary feature of being a neutral B decay to ensure the r behavior is the same as that of our signal. A correction factor of 1.15 is obtained; the statistical error of this control sample accounts for the largest contribution to the systematic error, $\pm 11\%$.

We further calculate systematic errors from the following sources: PDF shapes $^{+1.6}_{-1.5}\%$ (by varying parameters by $\pm 1\sigma$); π^0 reconstruction efficiency $\pm 3.5\%$ (by comparing the yields of $\eta \rightarrow \pi^0 \pi^0 \pi^0$ and $\eta \rightarrow \gamma\gamma$ between data and MC); track finding efficiency $\pm 2.4\%$ (from a study of partially reconstructed D^* decays). We use our calibration control samples to study possible effects on the efficiency due to the $\Delta E > -0.2$ GeV requirement and assign a 2% systematic error. The total systematic error due to possible charmless B decays not otherwise included is $\pm 5.3\%$. We repeat the fit after changing the normalization of the fixed

B decay components according to the error in their branching fractions and obtain systematic errors from the change in the result of $\pm 1\%$. In the case that the normalizations of B backgrounds fixed in the fit are simultaneously increased by 1σ , the statistical significance decreases from 3.6σ to 3.5σ ; we interpret the latter value as the significance of our result. Finally, we estimate the systematic uncertainty due to possible interference with $B^0 \rightarrow \rho^\pm \pi^\mp$ by varying the $m_{\pi^\pm \pi^0}$ veto requirement. We find the largest change in the result (by 9.3%) when this requirement is removed and assign this as the error. The total systematic error is $\pm 17\%$, and we measure the branching fraction of $B^0 \rightarrow \rho^0 \pi^0$ to be

$$\mathcal{B}(B^0 \rightarrow \rho^0 \pi^0) = (5.1 \pm 1.6(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-6}.$$

In order to test the robustness of this result, a number of cross-checks are performed. We vary the selection on r and \mathcal{R} . We try numerous combinations of requirements, with efficiencies that vary between 1.60% and 2.70%. In all cases consistent central values of the branching fraction are obtained. We also repeat the analysis using a looser requirement on the lower bound of ΔE and obtain consistent results. Finally, we select $\rho^\pm \pi^\mp$ candidates from the $\pi^+ \pi^- \pi^0$ phase space using the same continuum suppression requirement and measure a branching fraction for $B^0 \rightarrow \rho^\pm \pi^\mp$ that is consistent with previous measurements [7].

In summary, we observe the first evidence, with 3.5σ significance, for $B^0 \rightarrow \rho^0 \pi^0$ with a branching fraction higher than most predictions [11], and a central value above the upper limit set by the BABAR Collaboration [8].

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