Evidence for the decay $B^0 \to K^+ K^- \pi^0$

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the latter diagram dominates in the decay $B^+ \rightarrow K^+ K^− π^0$, for

which only upper limits have been placed on the branching fraction $\frac{3}{5}$. This is in contrast to the related decays (having two kaons in the final state) that are already ob-

served such as $B^0 \rightarrow K^0 K^0$, $B^+ \rightarrow K^0 K^+ \frac{3}{5}$, and $B^+ \rightarrow K^+ K^− π^+ \frac{3}{5}$, where the $b \rightarrow d$ gluonic penguin amplitude can contribute as well $\frac{3}{5}$.

We report a search for charmless hadronic decays of neutral $B$ mesons to the final state $K^+ K^− π^0$. The results are based on a 711 fb$^{-1}$ data sample that contains $772 \times 10^6 B \overline{B}$ pairs, and was collected at the $T(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+ e^−$ collider. We find the first evidence for this decay with a significance of 3.5 standard deviations and measure its branching fraction as $B(B^0 \rightarrow K^+ K^− π^0) = [2.17 ± 0.60{\text{(stat)}} ± 0.24{\text{(syst)}}] \times 10^{−6}$.

PACS numbers: 13.25.Hw, 14.40.Nd

The $B$-meson decay $B^0 \rightarrow K^+ K^− π^0$ is suppressed in the standard model (SM) and thus offers a useful probe for new physics beyond the SM. Figure 1 shows typical Feynman diagrams that contribute to this decay. The dominant one is the color- and Cabibbo-suppressed $b \rightarrow u$ tree transition followed by the internal $W$ exchange dia-

The three-body decay $B^0 \rightarrow K^+ K^− π^0$ has not yet been observed, with only one measured upper limit of $B(B^0 \rightarrow K^+ K^− π^0) < 19 \times 10^{−6}$ at 90% confidence level from the CLEO Collaboration $\frac{3}{5}$. Intermediate resonant modes that decay preferentially to this final state have also not been seen. A search for a related channel by Belle has set an upper limit of $B(B^0 \rightarrow φπ^0) < 1.5 \times 10^{−7} \frac{3}{5}$. The latter mode is quite sensitive to possible beyond-the-SM contributions; a branching fraction of $O(10^{−7})$ would constitute evidence for new physics $\frac{3}{5}$. No exper-
imemental information is available for other potential resonance modes such as $K^*(892)^\pm K^\mp$, $K_0^*(1430)^\pm K^\mp$, and $f_0(980)^0$. For the decay $B^0 \rightarrow K^*(892)^\pm K^\mp$, dominated by internal $W$ exchange [Fig. 1(b)], the branching fraction is predicted to be in the range $10^{-8}$ to $10^{-7}$.

Another motivation for the study of $B^0 \rightarrow K^+K^-\pi^0$ comes from the observation of $B^+ \rightarrow K^+K^-\pi^+$ by the BaBar Collaboration [6]. In particular, an unexpected structure is seen near 1.5 GeV/$c^2$ in the $K^+K^-$ invariant-mass spectrum, which accounts for about half of the total events. Similar structures have also been observed in the Dalitz plots of $B^+ \rightarrow K^+K^-\pi^-$ and $B^0 \rightarrow K^+K^-\pi^0$ decays [15,17]. If these structures are due to a particular $K^+K^-$ resonant state, it should show up in $B^0 \rightarrow K^+K^-\pi^0$; on the other hand, if it is a reflection from the $b \rightarrow d$ penguin, it will not contribute to $K^+K^-\pi^0$. Since the $u$ and $d$ quarks are spectators in the $b \rightarrow u$ tree diagram [Fig. 1(a)] for $B^+ \rightarrow K^+K^-\pi^+$ and $B^0 \rightarrow K^+K^-\pi^0$, respectively, one can estimate the branching fraction for the latter using the BaBar results. Assuming isospin symmetry and the $b \rightarrow u$ transition to be the main contributor to $B^0 \rightarrow K^+K^-\pi^0$, we expect its branching fraction to be at the level of $3 \times 10^{-6}$, which is well within Belle’s reach.

Our results are based on a data sample containing 772 $\times 10^6 BB$ pairs collected at the $Y(4S)$ resonance with the Belle detector [18] at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8.0 GeV) collider [19]. The principal detector components used in the study are a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and a CsI(Tl) crystal electromagnetic calorimeter (ECL). All these components are located inside a 1.5 T solenoidal magnetic field.

To reconstruct $B^0 \rightarrow K^+K^-\pi^0$ decay candidates, we combine two oppositely charged kaons with a $\pi^0$ meson. Each track candidate must have a minimum transverse momentum of 100 MeV/$c$, and a distance of closest approach with respect to the interaction point of less than 0.2 cm in the transverse $r$-$\phi$ plane and less than 5.0 cm along the $z$ axis, where the $z$ axis is defined by the direction opposite the $e^+$ beam. Identification of charged kaons is based on a likelihood ratio $R_{K/\pi} = L_K / L_\pi$, where $L_K$ and $L_\pi$ denote the individual likelihoods for kaons and pions, respectively, calculated using specific ionization in the CDC, time-of-flight information from the TOF, and the number of photoelectrons from the ACC. A requirement $R_{K/\pi} > 0.6$ is applied to select both kaon candidates. The kaon identification efficiency is approximately 86% and the probability of misidentifying a pion as a kaon is 11%. We reconstruct $\pi^0$ candidates from photon pairs that have an invariant mass between 112 and 156 MeV/$c^2$, corresponding to $\pm 3.5\sigma$ around the nominal $\pi^0$ mass [20]. These photons are reconstructed from neutral clusters in the ECL with energy above 60 (100) MeV in the barrel (endcap) region. In addition, requirements on the $\pi^0$ decay helicity angle, $|\cos\theta_{\text{hel}}| < 0.95$, and the $\pi^0$ mass-constrained fit statistic, $\chi^2_{\text{mass}} < 50$, are imposed. Here, $\theta_{\text{hel}}$ is the angle between one of the daughter photons and the $B$ momentum in the $\pi^0$ rest frame.

$B$-meson candidates are identified using two kinematic variables: beam-energy constrained mass, $M_{bc} = \sqrt{E_{\text{beam}}^2 - \sum_{i} p_i^2}$, and energy difference, $\Delta E = \sum_{i} E_i - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy, and $p_i$ and $E_i$ are the momentum and energy, respectively, of the $i$th daughter of the reconstructed $B$ in the center-of-mass (CM) frame. We retain events with $5.271$ GeV/$c^2 < M_{bc} < 5.289$ GeV/$c^2$ and $-0.30 \, \text{GeV} < \Delta E < 0.15 \, \text{GeV}$ for further analysis. The $M_{bc}$ requirement corresponds to approximately $\pm 3\sigma$ around the nominal $B^0$ mass [20]; we apply a looser window of $(-12\sigma, +6\sigma)$ around $\Delta E = 0$ because it is used in the fitter (as described below). The average number of $B$ candidates found per event is 1.3. In events with multiple $B$ candidates, we choose the one(s) whose $\pi^0$ has the lowest $\chi^2_{\text{mass}}$ value. If more than one $B$ candidate shares the same $\pi^0$ meson, the candidate yielding the best $B^0$ vertex fit is selected.

The dominant background is from the $e^+e^- \rightarrow q \bar{q}$ ($q = u, d, s, c$) continuum process. To suppress this background, observables based on the event topology are utilized. The event shape in the CM frame is more spherical for $BB$ events and jetlike for continuum events. We employ a neural network [21] to combine the following six input variables: the Fisher discriminant formed from 16 modified Fox-Wolfram moments [22], the cosine of the angle between the $B$ momentum and the $z$ axis, the cosine of the angle between the $B$ thrust and the $z$ axis, the cosine of the angle between the thrust axis of the $B$ candidate and that of the rest of the event, the ratio of the second- to the zeroth-order Fox-Wolfram moments (all of these quantities being calculated in the CM frame), and the separation along the $z$ axis between the vertex of the $B$ candidate and that of the remaining tracks. The training and optimization of the neural network are accomplished with signal and $q\bar{q}$ Monte Carlo (MC) simulated events. The signal MC sample is generated with the EvtGen program [23] by assuming a three-body phase diagram.
space. We require the neural network output ($C_{NB}$) to be above 0.2 to substantially reduce the continuum background. The relative signal efficiency due to this requirement is approximately 88%, whereas the continuum suppression achieved is close to 92%. The remainder of the $C_{NB}$ distribution peaks strongly near 1.0 for signal, and thus we have difficulty in modeling it with an analytic function. However, its transformed variable

$$C'_{NB} = \log \left[ \frac{C_{NB} - C_{NB,\text{min}}}{C_{NB,\text{max}} - C_{NB}} \right],$$  

(1)

where $C_{NB,\text{min}} = 0.2$ and $C_{NB,\text{max}} = 1.0$, has a distribution with a Gaussian-like tail.

The background due to $B$ decays via the dominant $b \to c$ transition is studied with an MC sample of a collection of such decays. The resulting $M_{bc}$ distribution is found to peak strongly in the signal region. We also observe two peaks in the $K^+K^-$ invariant-mass spectrum that corresponds to the contributions from (a) $D^0 \to K^+K^-$ peaking at the nominal $D^0$ mass, and (b) $D^0 \to K^-\pi^+$ with the peak shifted slightly from the $D^0$ mass owing to $K^-\pi$ misidentification. To suppress these peaking contributions, we exclude candidates for which the invariant mass of the $K^+K^-$ system lies in the range of $[1846, 1884] \text{ MeV}/c^2$ (about $\pm 5\sigma$ around the nominal $D^0$ mass). In the case of (b), we use the pion hypothesis for one of the tracks. The surviving events constitute the "generic $B\overline{B}$" background.

There are a few background modes that contribute in the $M_{bc}$ signal region having the $\Delta E$ peak shifted to positive values. The so-called "rare peaking" background modes arising mostly from $K^-\pi$ misidentification are identified with a $B\overline{B}$ MC sample in which one of the $B$ mesons decays via $b \to u, d, s$ transitions with known or estimated branching fractions. The rare peaking background includes the $B^0 \to K^+\pi^-\pi^0$ nonresonant decay as well as possible intermediate resonant modes that result in the $K^+\pi^-\pi^0$ final state, such as $B^0 \to K^*(892)^0\pi^0$ and $B^0 \to K^*(892)^+\pi^-$. The events that remain after removing the signal and rare peaking components comprise the "rare combinatorial" background.

The signal yield is obtained with an unbinned extended maximum likelihood fit to the two-dimensional distributions of $\Delta E$ and $C'_{NB}$. We define a probability density function (PDF) for each event category $j$ (signal, $q\overline{q}$, generic $B\overline{B}$, rare peaking, and rare combinatorial $B\overline{B}$ backgrounds):

$$P_j^{\Delta E} = P_j(\Delta E^i)P_j(C'_{NB,i}),$$  

(2)

where $i$ denotes the event index. Since the correlation between $\Delta E$ and $C'_{NB}$ is found to be negligible, the product of two individual PDFs is a good approximation for the combined PDF. We apply a tight requirement on $M_{bc}$ rather than including it in the fitter because it exhibits an irreducible correlation with $\Delta E$ owing to shower leakage in the ECL. The extended likelihood function is

$$L = \exp \left( -\sum_j n_j \right) \times \prod_i \left[ \sum_j n_j P_j^{\Delta E} \right]^{n_j},$$  

(3)

where $n_j$ is the yield of event category $j$. The correctly reconstructed (CR) and misreconstructed fragments of the $B$-meson decay referred to as self-crossfeed (SCF) components of the signal are considered distinct in the fitter: their combined PDF is $n_{\text{sig}} \times (1 - f) P_{\text{CR}} + f P_{\text{SCF}}$, where $n_{\text{sig}}$ is the total signal yield and $f$ is the SCF fraction fixed to the MC expected value of $3\%$.

| Event category | $\Delta E$ | $C'_{NB}$ |
|----------------|-----------|-----------|
| CR signal      | CB+AG     | 3 AG      |
| SCF signal     | histogram  | histogram |
| Continuum $q\overline{q}$ | Poly2 | AG |
| Generic $B\overline{B}$ | Poly2 | AG |
| Rare peaking $B\overline{B}$ | 2 G | AG |
| Rare combinatorial $B\overline{B}$ | histogram | 3 AG |

Table I lists the PDF shapes used to model the $\Delta E$ and $C'_{NB}$ distributions for various event categories. G, AG, CB, and Poly2 denote Gaussian, asymmetric Gaussian, Crystal Ball [24], and second-order Chebyshev polynomial function, respectively.

Figure 2 shows the $\Delta E$ and $C'_{NB}$ projections of the fit applied to 39066 candidate events. We obtain $299 \pm 83$ signal events ($n_{\text{sig}}$), $32167 \pm 428$ continuum $q\overline{q}$, $3814 \pm 517$ generic $B\overline{B}$, and $2691 \pm 321$ rare combinatorial $B\overline{B}$ background events. The statistical significance of the signal is 3.8 standard deviations. It is calculated as $\sqrt{2 \log(L_0/L_{\text{max}})}$, where $L_0$ and $L_{\text{max}}$ are the fit likelihood values with the signal yield set to zero and the best-fit case, respectively. The obtained background yields are
consistent with the respective MC predictions. The signal decay branching fraction is calculated as

$$\mathcal{B}(B^0 \rightarrow K^+K^-\pi^0) = \frac{n_{\text{sig}}}{N_{BB} \times \varepsilon_{\text{rec}} \times r_{K/\pi}}$$

where $N_{BB}$ is the total number of $BB$ pairs ($772 \times 10^6$), $\varepsilon_{\text{rec}}$ is the signal reconstruction efficiency (19.6%) obtained in the study described below, and $r_{K/\pi}$ denotes the kaon-identification efficiency correction factor that accounts for a small data-MC difference. It is given by

$$r_{K/\pi} \equiv \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}},$$

where $\varepsilon_{\text{data}} (\varepsilon_{\text{MC}})$ is the efficiency of the $R_{K/\pi}$ requirement in data (MC simulations). The $r_{K/\pi}$ value per kaon track is 0.95, resulting in a total $r_{K/\pi} = 0.95^2 = 0.90$ for two kaons. We have verified that the $R_{K/\pi}$ correction factor is almost constant over the Dalitz plot. For the branching fraction calculation presented in Eq. (4), we assume equal production of $B^0\overline{B}^0$ and $B^+\overline{B}^-$ pairs at the $Y(4S)$ resonance. The resulting value is

$$\mathcal{B}(B^0 \rightarrow K^+K^-\pi^0) = [2.17 \pm 0.60 \pm 0.24] \times 10^{-6},$$

where the uncertainties are statistical and systematic, respectively. The contributions to the systematic uncertainty are discussed below and listed in Table III.

The uncertainties due to the PDF shape parameters are estimated by varying all fixed parameters by ±1σ. To assign a systematic error for the histogram PDF used to model $\Delta E$ for the rare combinatorial component, we carry out a series of fits by fluctuating each of the histogram bin contents according to the Poisson distribution. The spread of the fitted signal yields is taken as the systematic error. We also vary the yield of final states that dominantly contribute to that component according to their errors. As we use a fairly complex function (a sum of three asymmetric Gaussians) to model the signal $C'_{NB}$ PDF shape, we evaluate possible systematics due to the uncertainty in the functional dependence by checking other alternatives. This systematic contribution is denoted as "signal $C'_{NB}$ functional dependence" in Table III. The uncertainty due to the fixed (small) SCF fraction is estimated without knowing a priori how these SCF events vary across the Dalitz plot. We adopt a conservative approach to vary the SCF fraction by ±50% when calculating the associated systematic error. The potential fit bias is evaluated by performing an ensemble test comprising 200 pseudoexperiments, where the signal and rare peaking background components are embedded from the corresponding MC samples, and the PDF shapes are used to generate the data for the other event categories. We obtain an almost Gaussian pull distribution of unit width, and add the mean and error on the pull in quadrature for assigning the systematics. Uncertainty due to continuum suppression is derived with the control sample by comparing the nominal fit result with that obtained without any $C_{NB}$ requirement. We estimate the error due to the $M_{bc}$ requirement by varying its nominal selection threshold by the resolution. The $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ control sample is used to determine the systematic uncertainty due to the $R_{K/\pi}$ requirement. The systematic uncertainty due to $\pi^0$ reconstruction is evaluated by comparing data-MC differences of the yield ratio between $\eta \rightarrow \pi^0\pi^0\pi^0$ and $\eta \rightarrow \pi^+\pi^-\pi^0$. We use partially reconstructed $D^{*+} \rightarrow D^0(K^-\pi^+\pi^-)\pi^+$ decays to assign the systematic uncertainty due to charged-track reconstruction (0.35% per track). To account for the possible variation of efficiency across the Dalitz-plot distribution, we calculate a weighted signal reconstruction efficiency by fitting different regions of that distribution. The mean value is used to obtain the branching fraction and the error is taken as the systematic contribution due to the efficiency variation. The total systematic uncertainty is calculated by summing all these uncertainties in quadrature. To determine the significance of our measurement, we use a convolution of the statistical likelihood with a Gaussian function of width equal to the additive systematic errors that only affect the signal yield. The total significance, including these uncertainties, is 3.5 standard deviations.

To elucidate the nature of the observed signal, especially whether there are contributions from the decays with intermediate resonant states, we study the $K^+K^-$ and $K^+\pi^0$ invariant mass distributions. We perform the $|\Delta E|, C'_{NB}$ two-dimensional fit in bins of the $m(K^+K^-)$ and $m(K^+\pi^0)$ distributions after applying the orthogonal requirements $m(K^+\pi^0) > 1.5\text{ GeV}/c^2$ and $m(K^+K^-) > 2.0\text{ GeV}/c^2$, respectively. These requirements suppress kinematic reflections. Figure 3 shows the resulting signal yields along with their statistical errors. With these data, we cannot make any definitive state-
ment about possible intermediate $K^+K^-$ resonances, including the structure seen by BABAR near 1.5 GeV/c^2. It is worth noting here that the recent LHCb study of $B^\pm \to K^+K^-\pi^\pm$ decays has revealed an unidentified structure in the same mass range; however, it is only present in $B^+$ events, giving rise to a large local $CP$ asymmetry. Furthermore, we observe some excess of events around 1.4 GeV/c^2 in the $K^+\pi^0$ invariant-mass spectrum. A detailed interpretation will require an amplitude analysis with higher statistics that would be available at a next-generation flavor factory.

In summary, we report measurement of the suppressed decay $B^0 \to K^+K^-\pi^0$ using the full $\Upsilon(4S)$ data sample collected with the Belle detector. We employ a two-dimensional fit for extracting the signal yield. Our measured branching fraction $B(B^0 \to K^+K^-\pi^0) = [2.17 \pm 0.60\text{(stat)} \pm 0.24\text{(syst)}] \times 10^{-6}$ constitutes the first evidence for the decay.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group, the National Institute of Informatics, and the PNRL/EMSL computing group for valuable computing and SINET4 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council and the Australian Department of Industry, Innovation, Science and Research; Austrian Science Fund under Grant No. P 22742-N16; the National Natural Science Foundation of China under Contracts No. 10575109, No. 10775142, No. 10875115, and No. 10825524; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. MSM0021620859; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft and the VolkswagenStiftung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; the BK21 and WCU program of the Ministry Education Science and Technology, National Research Foundation of Korea Grants Nos. 2010-0021174, No. 2011-0029457, No. 2012-008143, No. 2012R1A1A2008330, BRL program under NRF Grant No. KRF-2011-0020333, and GSDC of the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Basque Foundation for Science (IKERBASQUE) and the UPV/EHU under program UFI 11/55; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy and the National Science Foundation. This work is supported by a Grant-in-Aid from MEXT for Science Research in a Priority Area (“New Development of Flavor Physics”), and from JSPS for Creative Scientific Research (“Evolution of Tau-lepton Physics”).

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