RAPID COMMUNICATIONS

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Search for $B^0 \to \ell^+ \ell^-$ at the Belle detector

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We report the results of a search for the decay $B^0 \rightarrow e^+e^-$, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ based on an analysis of 78 fb^{-1} of data collected by the Belle detector at KEKB. No candidate events have been found. Upper limits on the branching fractions are calculated at the 90% confidence level: $\mathcal{B}(B^0 \rightarrow e^+e^-) < 1.9 \times 10^{-7}$, $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.6 \times 10^{-7}$, and $\mathcal{B}(B^0 \rightarrow e^\pm\mu^\mp) < 1.7 \times 10^{-7}$. A limit on the Pati-Salam leptoquark mass M_{LQ}46 TeV/c^2 is obtained at the 90% confidence level.

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The B meson decays $B^0 \rightarrow e^+e^-$ and $B^0 \rightarrow \mu^+\mu^-$ can proceed at a low rate through the flavor-changing neutral current (FCNC) process. The standard model (SM) predictions for the branching fractions are $(2.34 \pm 0.33) \times 10^{-15}$ and $(1.00 \pm 0.14) \times 10^{-10}$ for $B^0 \rightarrow e^+e^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays, respectively [1]. These branching fractions could be two orders of magnitude larger in models with two Higgs doublets and Z-mediated FCNC [2]. The decays $B^0 \rightarrow e^\pm \mu^\mp$ are essentially forbidden in the SM by lepton number conservation, apart from a vanishingly small probability permitted by neutrino oscillation. They can occur, however, in the Pati-Salam model [3] or supersymmetric (SUSY) models [4]. The charge conjugate modes are implicitly included throughout this Rapid Communication.

In this Rapid Communication we report the results of a search for the decays $B^0 \rightarrow e^+e^-$, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ (collectively denoted as $B^0 \rightarrow \ell^+\ell^-$) using 78 fb^{-1} of data, corresponding to 85 million $B\bar{B}$ pairs, collected with the Belle detector at KEKB [5], an asymmetric e^+e^- collider operating at the $\Upsilon(4S)$ resonance. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an array of CsI(Tl) crystals (ECL) 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 (KLM). The detector is described in detail elsewhere [6].

For each primary charged track, the impact parameter relative to the run-by-run interaction point is required to be within 2 cm along the z axis (aligned with the positron beam) and within 0.08 cm in the plane transverse to this axis, and the transverse momentum must exceed 100 MeV/c. At least five charged tracks including nonprimary tracks are required. For each event the visible energy in the detector is required to be greater than 0.6 GeV. Monte Carlo (MC) studies show that the radiative Bhabha events (100%), as well as two-photon (94%) and $\tau^+\tau^-$ (85%) events, are rejected by these criteria. The two-photon MC studies use the generator AAFH [7], which includes all tree-level diagrams to fourth order in α_{QED}.

Electron tracks are distinguished from hadron tracks by examining the amount of energy and the transverse shower profile of the associated ECL cluster as well as light yield in the ACC. The dE/dx measurements in the CDC is also taken into account. Muon tracks are distinguished from hadron tracks by their range and transverse scattering in the KLM. We select electrons and muons by requiring that the normalized likelihood [8,9] that the track is a lepton rather than a hadron exceeds 0.9. The electron and the muon detection efficiencies are 88% and 89% which are studied via $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ in the same track momentum range, 1.5–4.5 GeV/c. The corresponding misidentification rates from kaon tracks and pion tracks are 1.7% $(K \rightarrow \mu)$, 1.0% $(\pi \rightarrow \mu)$, $< 0.005\%$ $(K \rightarrow e)$, and $< 0.1\%$ $(\pi \rightarrow e)$ which are studied using kaons and pions from the decay chain $D^* \rightarrow D^0\pi^- \rightarrow (K^-\pi^+)\pi^-$ in the same track momentum range, 1.5–4.5 GeV/c.

B meson candidates are formed from pairs of oppositely charged leptons, not necessarily of the same flavor, and selected using two kinematic variables defined in the $\Upsilon(4S)$ center-of-mass (c.m.) frame: the beam-energy constrained mass, $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$, and the energy difference, $\Delta E = E_B - E_{\mathrm{beam}}$, where p_B and E_B are the momentum and energy, respectively, of the B candidate and E_{beam} is the beam energy. The signal region is defined as $5.27\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.29\ \mathrm{GeV}/c^2$ and $|\Delta E| < 0.05$ GeV for all channels. The

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sideband region, used for the background determination, is defined as $5.20\ \text{GeV}/c^2 < M_{\text{bc}} < 5.26\ \text{GeV}/c^2$ and $|\Delta E| < 0.30$ GeV.

The decays $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$ do not contribute measurably to the background because of their small branching fractions, the small lepton fake rates and, for the $K^+\pi^-$ mode, the shift of the B candidate out of the ΔE signal region due to the use of lepton masses for the tracks. Background from other B decays is also found to be negligible. Backgrounds from continuum $e^+e^- \to q\bar{q}$ $(q = u,d,s,c)$ production are suppressed using seven variables that characterize the event topology: five modified Fox-Wolfram moments [10], $S_\perp$ [11], and the cosine of the polar angle θ_{thr} of the B candidate's thrust axis [12]. Events $e^+e^- \to c\bar{c}$ with two semileptonic charm decays produce $B^0 \to \ell^+\ell^-$ candidates which are not suppressed by lepton identification cuts; without special treatment, these events would be the dominant source of background. We use four additional variables to suppress these events: the missing energy E_{miss} and momentum p_{miss}, the cosine of the angle θ_{pl} between the missing momentum and the B candidate's thrust axis, the cosine of the angle θ_{pb} between the missing momentum and the thrust axis of the remaining particles in the event. All eleven variables are combined into a Fisher discriminant [12]. We obtain probability density functions (PDFs) for the signal and for continuum background as functions of this Fisher discriminant (F) and of the cosine of the polar angle $(\cos\theta_B)$ of the B candidate's flight direction. We then obtain signal and background likelihoods, $\mathcal{L}_S$ and $\mathcal{L}_B$, from the product of the PDFs for F and $\cos\theta_B$, and demand that $\mathcal{L}R = \mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_B)$ exceeds 0.9. This criterion was chosen to optimize the performance of the signal significance $(N_S/\sqrt{N_S+N_B})$ using both MC and data samples, where N_S and N_B are predicted signal yields and predicted background yields, respectively. Assuming the branching fractions of $B^0 \to \ell^+\ell^-$ are $10^{-7} \sim 10^{-15}$, we then obtain the signal yields from the product of the total number of $B\bar{B}$ events, the signal efficiency from MC and the assumed branching fractions. The predicted background yields are obtained by fitting the distribution of ΔE from the sideband data projection in the signal region. The backgrounds in the on-resonance sideband region are compared to MC and to data taken 50–60 MeV below the $\Upsilon(4S)$ resonance. The results are summarized in Table I. Distributions of E_{miss}, $\cos\theta_B$, F and $\mathcal{L}R$ are shown in Fig. 1.

TABLE I. The number of expected events are normalized to the integrated luminosity of the data sample. The results show that the backgrounds in MC, off-resonance data and on-resonance data are in good agreement after the $N \geq 5$ cut.

Mode	$N^{\text{trk}=3,4}$	$N^{\text{trk}\geq 5}$	$N^{\text{trk}\geq 5}_{\mathcal{L}R>0.9}$
$\tau^+\tau^-$	14 ± 4	2.4 ± 1.7	0
two photon	250 ± 109	16 ± 5	0
$q\bar{q}$ $(q=u,d,s)$	6 ± 1	82 ± 7	1.3 ± 0.9
$q\bar{q}$ $(q=c)$	54 ± 6	396 ± 16	3.8 ± 1.5
off-resonance data	396 ± 46	431 ± 46	10 ± 7
data	441	473	12

The signal efficiency for each mode, after application of all selection criteria, is determined by MC simulation and itemized in Table II. The systematic error of this efficiency arises from tracking efficiency (1% per track), electron and muon identification efficiencies (4% and 2% per lepton, respectively, determined from a study of J/ψ decays), the charged-track-count criterion (10%, measured from the uncertainty in the efficiency using a $B^0 \to K^+\pi^-$ control sample), and the likelihood ratio cut [4%, based on a study of $B^- \to D^0\pi^- \to (K^-\pi^+)\pi^-$]. The total systematic uncertainty is obtained by first summing the correlated errors linearly and then adding the noncorrelated errors in quadrature.

Since no signal events are found for any mode, we deter-

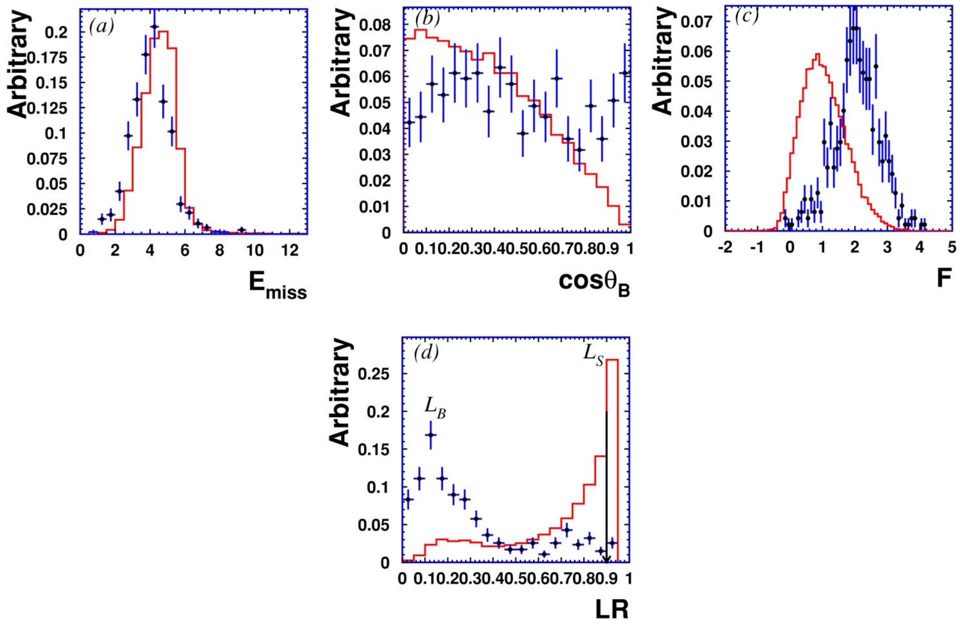

FIG. 1. Open histograms are from signal MC and the points with error bars are from sideband data. The arrow in the (d) $\mathcal{L}R$ plot indicates the optimized selection.

TABLE II. Summary of the $B^0\to\ell^+\ell^-$ search, where ϵ is the reconstruction efficiency, $N_{\rm obs}$ is the measured number of events in the signal region, $N_{\rm exp}^{\rm bg}$ is the expected background in the signal region and BF is the 90% confidence level upper limit for the branching fractions.

Mode	ϵ[%]	$N_{\rm obs}$	$N_{\rm exp}^{\rm bg}$	BF(10^{-7})
$B^0\to e^+e^-$	14.3 ± 2.0	0	0.30 ± 0.12	<1.9
$B^0\to\mu^+\mu^-$	16.9 ± 2.0	0	0.19 ± 0.10	<1.6
$B^0\to e^\pm\mu^\mp$	15.8 ± 1.9	0	0.22 ± 0.10	<1.7

mine 90% confidence level upper limits on the branching fractions by an extension of the Feldman-Cousins method, which takes systematic uncertainties into account [13]. The $q\bar{q}$ events are the main background after all the event selections. In order to estimate the number of expected background events in the signal box, a $q\bar{q}$ MC sample (corresponding to an integrated luminosity 1.6 times greater than that of the data) is used to fit the shape of the background distribution in ΔE and $M_{\rm bc}$ in the sideband region. These distributions are scaled to the number of observed data events in the sideband region; the number of expected background events is then obtained from the signal-to-sideband ratio. The dominant systematic uncertainty on the background estimation comes from the statistical error of the number of sideband data events. The results are listed in Table II.

These upper limits can be used to constrain certain extensions of the standard model. For example, the Pati-Salam model [14] predicts the existence of leptoquarks—heavy spin-1 gauge bosons that carry both color and lepton quantum number—that mediate the decays $B^0\to e^\pm\mu^\mp$ [14,15]. The branching ratio is related to the leptoquark mass $M_{\rm LQ}$ by [14]

$$\Gamma(B^0\to e^\pm\mu^\mp)=\pi\alpha_s^2(M_{LQ})\frac{1}{M_{LQ}^4}F_{B^0}^2 m_{B^0}^3 R^2,$$

where

$$R=\frac{m_{B^0}}{m_b}\left(\frac{\alpha_s(M_{LQ})}{\alpha_s(m_t)}\right)^{-4/7}\left(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right)^{-12/23}.$$

We follow the method in Refs. [16,17] and use $F_B=175\pm30$ MeV for the B^0 decay constant, $m_{B^0}=5279.3\pm0.7$ MeV/c^2 [18] for the B^0 meson mass, $m_b=4.3\pm0.2$ GeV/c^2 [16] for the b-quark mass and $m_t=176.0\pm6.5$ GeV/c^2 [18] for the t-quark mass. We use α_s $(M_Z)=0.117$ [18] which is evolved to $M_{\rm LQ}$ using the Marciano approximation [19], assuming no other colored particles exist between m_t and $M_{\rm LQ}$. We obtain a limit of $M_{\rm LQ}>46$ TeV/c^2 on the mass of the Pati-Salam leptoquark at the 90% confidence level. This bound holds in the case where the τ lepton is associated with the strange and charm quarks within the Pati-Salam theory. Previous lower limits for this case from $B^+\to\ell^+\nu$ [15,20] and $B^0\to\mu e$ [16,17] are weaker than the bound presented here; the limit from lepton universality in $\pi^+\to\ell^+\nu$ is stronger [14,15].

In conclusion, we find no evidence for $B^0\to e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ decays in 85 million $B\bar{B}$ events, and set upper limits on the branching fractions of 1.9×10^{-7}, 1.6×10^{-7}, and 1.7×10^{-7}, respectively, at the 90% confidence level. We use the latter upper limit to set a lower bound on the mass of the Pati-Salam leptoquark of 46 TeV/c^2.

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