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Search for Decays of $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$, $B^0 \to e^\pm\mu^\mp$

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We present a search for the decays $B^0 \to e^+ e^-$, $B^0 \to \mu^+ \mu^-$, and $B^0 \to e^\pm \mu^\mp$ in data collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the SLAC B Factory. Using a data set of 111 fb^{-1}, we find no evidence for a signal in any of the three channels investigated and set the following branching fraction

upper limits at the 90% confidence level: $\mathcal{B}(B^0 \to e^+ e^-) < 6.1 \times 10^{-8}$, $\mathcal{B}(B^0 \to \mu^+ \mu^-) < 8.3 \times 10^{-8}$, and $\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 18 \times 10^{-8}$.

In the standard model (SM), rare B decays such as $B^0 \to \ell^+ \ell^-$, where ℓ refers to e or μ, are expected to proceed through diagrams such as those shown in Fig. 1 (charge conjugate processes are included implicitly throughout). These decays are highly suppressed since they involve a $b \to d$ transition and require an internal quark annihilation within the B meson. In addition, the decays are helicity suppressed by factors of $(m_\ell/m_B)^2$, where m_ℓ is the mass of the lepton ℓ and m_B is the mass of the B meson. B^0 decays to leptons of two different flavors violate lepton flavor conservation and are therefore forbidden in the SM, although permitted in extensions to the SM with nonzero neutrino mass [1]. The SM expectations are given in Table I.

Since these processes are highly suppressed in the SM, they are potentially sensitive probes of physics beyond the SM. In the minimally supersymmetric standard model (MSSM) the branching fraction for these decays can be enhanced by orders of magnitude [2]. In particular, for MSSM models with modified minimal flavor violation ($\overline{\text{MFV}}$) and large $\tan\beta$ [3], the branching fraction can be increased by up to 4 orders of magnitude. Experimental bounds can restrict allowed regions of parameter space, specifically the mass of the charged Higgs boson. In models with two Higgs doublets and natural flavor conservation at large $\tan\beta$, an increase in the branching fraction of several orders of magnitude is expected [4]. $B^0 \to \ell^+ \ell^-$ decays are also allowed in specific models containing leptoquarks [5] and supersymmetric (SUSY) models without R parity [6]. The branching fractions for the flavor violating channels $B^0 \to \ell_i^+ \ell_j^-$ ($i \neq j$) are expected to be exceedingly small but can be enhanced by leptoquarks or R parity violating operators in SUSY models.

To date, $B^0 \to \ell^+ \ell^-$ decays have not been observed. As shown in Table I, experimental limits are approaching a level of sensitivity that will restrict the allowed parameter space of models that produce $B^0 \to \ell^+ \ell^-$ branching fraction enhancements of a few orders of magnitude with respect to the SM rates.

The data used in these analyses were collected with the *BABAR* detector at the PEP-II $e^+ e^-$ storage ring and correspond to an integrated luminosity of 111 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance ("on resonance") and 11.9 fb^{-1} accumulated at a center-of-mass (c.m.) energy about 40 MeV below the $\Upsilon(4S)$ resonance ("off resonance"). The latter sample is used for nonresonant $q\bar{q}$ ($q = u, d, s,$ and c) background studies. The collider is operated with asymmetric beam energies, producing a boost ($\beta\gamma = 0.55$) of the $\Upsilon(4S)$ along the collision axis.

The *BABAR* detector is optimized for the asymmetric beam configuration at PEP-II and is described in detail in

[7]. The 1.5-T superconducting solenoidal magnet, whose cylindrical volume is 1.4 m in radius and 3 m long, contains a charged-particle tracking system, a Cherenkov detector dedicated to charged-particle identification, and central and forward electromagnetic CsI calorimeters (EMC). The segmented flux return, including end caps, is instrumented with resistive plate chambers for muon and K_L^0 identification.

The presence of two charged high-momentum leptons provides a very clean signature for the three decay modes under consideration. We require two oppositely-charged high-momentum leptons (i.e., $|p_\ell^*| \sim m_B/2$ where p_ℓ^* is the c.m. momentum of lepton ℓ) from a common vertex consistent with the decay of a B^0 meson. Since the signal events contain two B^0 mesons and no additional particles, the total energy of each B^0 in the c.m. must be equal to half of the total beam energy. We define

$$m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - \left(\sum_i \mathbf{p}_i^*\right)^2} \qquad (1)$$

$$\Delta E = \sum_i \sqrt{m_i^2 + (\mathbf{p}_i^*)^2} - E_{\text{beam}}^*, \qquad (2)$$

where E_{beam}^* is the (e^+ or e^-) beam energy in the c.m. frame, $\mathbf{p}_i^*$ is the momentum of lepton i in the c.m. frame, and m_i is the mass of lepton i. In Eq. (1), E_{beam}^* is used as opposed to E_B^* because E_{beam}^* is known with much greater precision. For correctly reconstructed B^0 mesons, m_{ES} peaks at the mass of the B^0 meson with a resolution of about 2.8 MeV/c^2 and ΔE peaks near zero.

To reduce background from lepton misidentification, we require the leptons to satisfy stringent electron and muon identification criteria [8]. The electron identification efficiency is greater than 93% with a misidentification rate of less than 0.3%. The muon identification efficiency ranges from (55–70)% (depending on run period) with a misidentification rate of 3%. Electron energy lost through bremsstrahlung is partially recovered by adding the energy of photons that lie within a 3 degree cone about the electron direction.

Suppression of background from nonresonant $q\bar{q}$ production is provided by a series of topological requirements.
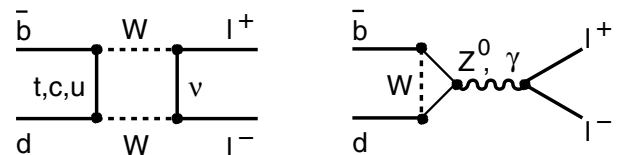

FIG. 1.   Representative Feynman diagrams for $B^0 \to \ell^+ \ell^-$ in the standard model.

TABLE I.   The expected branching fractions in the standard model [13] and the current best upper limits (U.L.) at the 90% C.L.

Decay Mode	SM Expectation	CLEO [14] 9.1 fb^{-1}	Belle [15] 78 fb^{-1}	CDF [16] 0.17 fb^{-1}
e^+e^-	2.4×10^{-15}	8.3×10^{-7}	1.9×10^{-7}	$\cdots$
$\mu^+\mu^-$	1.0×10^{-10}	6.1×10^{-7}	1.6×10^{-7}	1.5×10^{-7}
$e^\pm\mu^\mp$	$\cdots$	15×10^{-7}	1.7×10^{-7}	$\cdots$

In particular, we require $|\cos\theta_T| < 0.8$, where θ_T is the angle in the c.m. frame between the thrust axis of the particles that form the reconstructed B^0 candidate and the thrust axis of the remaining tracks and neutral clusters in the event. In addition, we employ cuts on the invariant mass of the "rest of the event" (ROE) (all tracks not associated with the B^0 candidate where all nonleptonic tracks are assumed to be pions) of $m_{ROE} > 0.5$ GeV and on the second normalized Fox-Wolfram moment of $R_2 < 0.8$ [9]. We also cut on the total multiplicity of both charged tracks and neutral particles by means of the variable N_{mult} defined as $N_{mult} = N_{trk} + N_\gamma/2$, where N_{trk} is the total number of tracks in the event and N_γ is the number of photons found with an energy $E_\gamma > 80$ MeV. We require $N_{mult} \geq 5.5$ for the ee and $e\mu$ channels and $N_{mult} \geq 5.0$ for the $\mu\mu$ channel. This variable is especially useful in the rejection of radiative Bhabha events. We also require that the total energy in the EMC (E_{EMC}) be less than 11 GeV. This cut is effective in reducing background from QED e^+e^- events, including radiative Bhabhas with many conversions.

Four of the selection criteria given above ($|\cos\theta_T|$, m_{ROE}, N_{mult}, and E_{EMC}) were simultaneously optimized for the best upper limit on $\mathcal{B}(B^0 \to \ell^+\ell^-)$ where the assumed number of observed events is determined from a Poisson distribution with the mean equal to the expected background. Sideband data are compared with signal Monte Carlo (MC) for the e^+e^- channel for four of these variables, $|\cos\theta_T|$, m_{ROE}, R_2, and N_{mult} in Fig. 2.

The $B^0 \to \ell^+\ell^-$ candidates are selected by simultaneous requirements on the energy difference ΔE and the energy-substituted mass m_{ES}. For the $B^0 \to \mu^+\mu^-$ decay mode, the size of this "signal box" is chosen to be $[+2, -2]\sigma$ of the m_{ES} distribution and $[+2, -2]\sigma$ for the ΔE. In the cases of the $B^0 \to e^+e^-$ and $B^0 \to e^\pm\mu^\mp$ decay modes, the signal box sizes in m_{ES} are also $[+2, -2]\sigma$ but in ΔE are relaxed to $[+2, -3]\sigma$ and $[+2, -2.5]\sigma$, respectively, to accommodate the tail in the distribution resulting from uncorrected bremsstrahlung and final state radiation. The resolution in m_{ES} is obtained from a fit to a Gaussian distribution, whereas the resolution in ΔE is obtained from a fit to an empirical function [10] that gives a good description of this tail.

Comparisons between data and MC indicate that two-photon processes result in substantial electron backgrounds
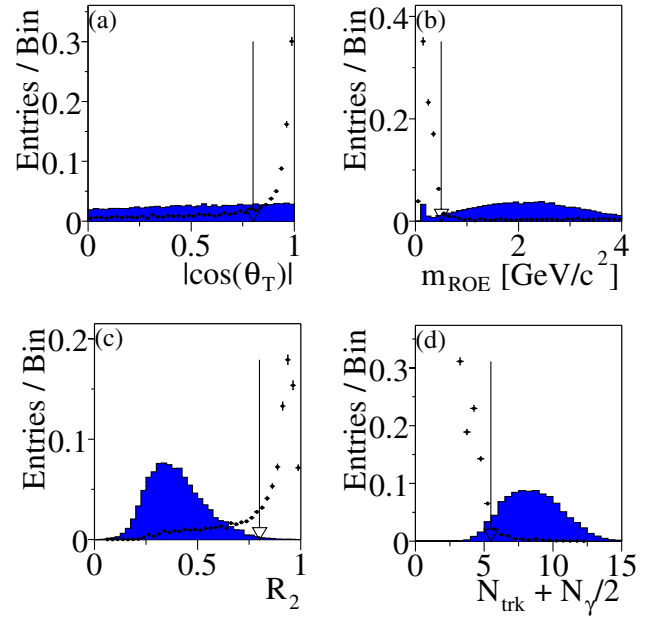

FIG. 2 (color online).   Distributions of signal MC (hatched) and sideband data (points) for the e^+e^- channel after the initial selection cuts for (a) $|\cos\theta_T|$, (b) m_{ROE}, (c) R_2, and (d) N_{mult}. Arrows indicate final cut values. All distributions are normalized to unit area.

which are not modeled in the generic MC. We thus parametrize the background level in the signal box from the data sidebands with the ARGUS function [11] in m_{ES} and an exponential function in ΔE. We use these parametrizations to extrapolate the background level found in the sidebands into the signal box. As indicated in Table II, three different sideband boxes are used. The grand sideband boxes are used to estimate the functional form of the ΔE distributions. The $\chi^2/$ d.o.f. for these fits are 24.5/38, 28.6/38, and 27.0/38 for the ee, $\mu\mu$, and $e\mu$ channels, respectively. The upper and lower m_{ES} sideband boxes are used to estimate the functional form of the m_{ES} distribution. The $\chi^2/$ d.o.f. for these fits are 27.1/34, 39.3/34, and 29.8/34 for the ee, $\mu\mu$, and $e\mu$ channels, respectively. The remaining background is dominated by pairs of real leptons (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) from $c\bar{c}$ decay, resulting in a proportionately larger background in the $e\mu$ channel (appearing almost entirely in the lower m_{ES} sideband box). Peaking backgrounds from misidentified two-body

TABLE II.   Definition of the three different sideband boxes used for all three decay modes and the observed number of events in each.

Sideband box	span in ΔE [GeV]	span in m_{ES} [GeV/c^2]	# events ee	$\mu\mu$	$e\mu$
Grand	$(-0.40, 0.40)$	$(5.20, 5.26)$	46	56	57
Upper m_{ES}	$(0.20, 0.50)$	$(5.20, 5.29)$	12	13	13
Lower m_{ES}	$(-0.50, -0.20)$	$(5.20, 5.29)$	33	40	52

TABLE III.   Summary of the analyses where N_{obs} and N_{exp}^{bg} are the observed and expected number of events in the signal box, ε is the efficiency, and $\mathcal{B}_{U.L.}(B^0 \to \ell^+ \ell^-)$ is the upper limit on the branching fraction at the 90% C.L. Uncertainties on N_{exp}^{bg} and ε are statistical and systematic added in quadrature.

Decay mode	N_{obs}	N_{exp}^{bg}	$\varepsilon[\%]$	$\mathcal{B}_{U.L.}(B^0 \to \ell^+ \ell^-)$
$e^+ e^-$	0	0.71 ± 0.31	21.8 ± 1.2	6.1×10^{-8}
$\mu^+ \mu^-$	0	0.72 ± 0.26	15.9 ± 1.1	8.3×10^{-8}
$e^\pm \mu^\mp$	2	1.29 ± 0.44	18.1 ± 1.2	18×10^{-8}

B decay modes were estimated using an MC sample equivalent to more than 20 times the data luminosity and found to be negligible. The total background expectations and signal efficiencies are given in Table III.

The systematic uncertainties on the signal efficiency ε, the number of B^0 mesons produced in the data, and the background estimate are incorporated into the determination of the upper limit on $\mathcal{B}(B^0 \to \ell^+ \ell^-)$. Since the signal efficiency is determined from MC simulation only, differences between data and the simulation would result in an error in our normalization. To estimate this uncertainty we perform comparisons of data and MC using high statistics control samples that have similar characteristics to our $B^0 \to \ell^+ \ell^-$ signal. The optimal control samples are $B^0 \to J/\psi K_S^0$, with $J/\psi \to e^+ e^-$ for $B^0 \to e^+ e^-$ and $J/\psi \to \mu^+ \mu^-$ for $B^0 \to \mu^+ \mu^-$, respectively. Since there exists no appropriate control sample for the $e^\pm \mu^\mp$ mode, we use the larger of the systematic errors derived from either the ee or $\mu\mu$ modes. In performing these comparisons we found a substantial uncertainty on the signal efficiency to be due to differences between data and the MC simulation in the mean and resolutions of various quantities, depend-
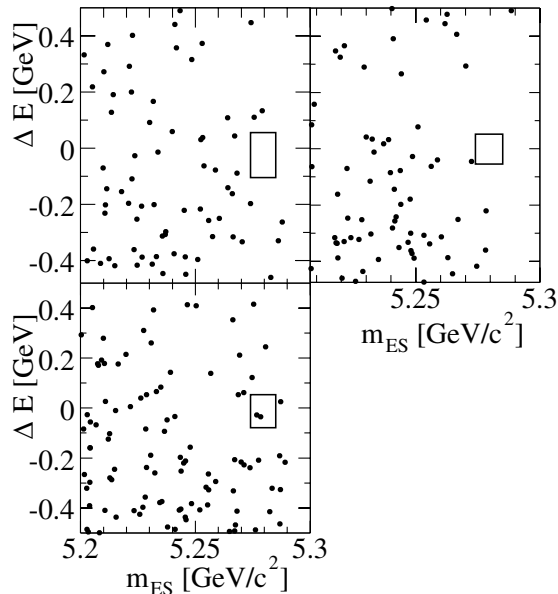

FIG. 3.   Distribution of events in m_{ES} and ΔE for $B^0 \to e^+ e^-$ (top left), $B^0 \to \mu^+ \mu^-$ (top right), and $B^0 \to e^\pm \mu^\mp$ (bottom).

ing on the channel. For the electron channels, the dominant quantities are ΔE and m_{ROE}, whereas for the muon channels, they are $|\cos \theta_T|$, N_{mult}, and m_{ROE}. When combined with the uncertainties on tracking efficiency of 2.6% and that for particle identification (1.0% per electron, 3.0% per muon), the total systematic uncertainty on the efficiency is estimated to be 5.7%, 7.1%, and 6.8% for the ee, $\mu\mu$, and $e\mu$ modes, respectively.

The background estimate is obtained from a fit to side-band data, so the primary uncertainty is due to fluctuations in the fit procedure as events fall in or out of the sideband box. We have studied the stability of the fit and the background estimate when adding or removing events from the m_{ES} and ΔE histograms. We find that the fit is unbiased and stable to a level significantly less than the statistical uncertainty on the background estimate.

As shown in Fig. 3 and Table III, when the contents of the signal box were revealed, 0, 0, and 2 events were found in the ee, $\mu\mu$, and $e\mu$ channels, respectively. As can be seen in Table III, the numbers of events found in the signal boxes are compatible with the expected background for each mode.

An upper limit (U.L.) on the branching fraction is computed using

$$\mathcal{B}(B^0 \to \ell^+ \ell^-) = \frac{N_{UL}(N_{obs})}{(N_{B^0} + N_{\overline{B}^0}) \cdot \varepsilon}, \qquad (3)$$

where $N_{UL}(N_{obs})$ is the Poisson 90% U.L. on the number of events for N_{obs} events having been observed, $N_{B^0}(N_{\overline{B}^0})$ is the number of $B^0(\overline{B}^0)$ mesons produced in the data, and ε is the signal efficiency. We have $N_{B^0} + N_{\overline{B}^0} = N_{B\overline{B}}$ under the assumption of equal production of $B^0 \overline{B}^0$ and $B^+ B^-$ in $\Upsilon(4S)$ decays. For our data set, $N_{B\overline{B}} = (122.5 \pm 1.2) \times 10^6$.

We follow the technique of [12] in order to account for the presence of background and to include our systematic uncertainties in the determination of the upper limit. As summarized in Table III, the resulting upper limits at the 90% confidence level (C.L.) for $\mathcal{B}(B^0 \to e^+ e^-)$, $\mathcal{B}(B^0 \to \mu^+ \mu^-)$, and $\mathcal{B}(B^0 \to e^\pm \mu^\mp)$ are 6.1×10^{-8}, 8.3×10^{-8}, and 18×10^{-8}, respectively. The corresponding non-background-subtracted upper limits are 8.6×10^{-8}, 1.2×10^{-7}, and 2.4×10^{-7} respectively.

These bounds are stringent enough to place interesting constraints on popular models. For example, for the MSSM ($\overline{\text{MFV}}$) models, the relation between $\mathcal{B}(B^0 \to \mu^+ \mu^-)$ and the mass of the charged Higgs boson m_H is given as a function of $\tan \beta$ in [7]. We find that for $\tan \beta = 60$, $m_H > 138$ GeV/c^2 (90% C.L.).

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