Presented at 31st International Conference On High Energy Physics (ICHEP 2002)
24-31 Jul 2002, Amsterdam, The Netherlands

SLAC-PUB-9705
April 2003

Leptonic B Decays at BABAR

Thomas B. Moore[a]

[a]University of Massachusetts, Amherst MA 01003-4525 USA

We present results on searches for the rare B decays $B^0 \to \ell^+\ell^-$ ($\ell = e$ or μ) and $B^+ \to K^+\nu\bar{\nu}$ in $\Upsilon(4S)$ decays. The data used in these analyses were collected with the BABAR detector at the PEP-II e^+e^- storage ring during the years 2000 and 2001. The $B^0 \to \ell^+\ell^-$ search was performed using an integrated luminosity of 54.4 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance (about 60 million $B\bar{B}$ pairs) while the $B^+ \to K^+\nu\bar{\nu}$ search was performed with 50.7 fb^{-1} (about 56 million $B\bar{B}$ pairs). Both analyses use an additional 6.4 fb^{-1} of data accumulated about 40 MeV below resonance. We see no evidence for a signal in either the $B \to \ell^+\ell^-$ or $B \to K^+\nu\bar{\nu}$ decay modes and set the following upper limits at the 90% CL: $\mathcal{B}(B^0 \to e^+e^-) < 3.3 \times 10^{-7}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.0 \times 10^{-7}$, $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 2.1 \times 10^{-7}$, and $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 9.4 \times 10^{-5}$.

1. $B^0 \to \ell^+\ell^-$

In the Standard Model (SM), the rare leptonic B decays $B^0 \to \ell^+\ell^-$, where ℓ refers to e or μ, are expected to proceed through box and penguin diagrams. These decays are highly suppressed since they involve a $b \to d$ transition and require an internal quark annihilation within the B meson which further suppresses the decay by a factor of $(f_B/M_B)^2 \approx 2 \times 10^{-3}$ relative to the electroweak "penguin" $b \to d\gamma$ decays. In addition, the decays are helicity suppressed by a factor of $(m_\ell/m_B)^2$. The expected branching ratios are 1.9×10^{-15} and 8.0×10^{-11} for $B^0 \to e^+e^-$ and $B^0 \to \mu^+\mu^-$ respectively. B^0 decays to leptons of different flavors violate lepton flavor conservation and are forbidden in the SM. They are allowed, however, in extensions to the SM with non-zero neutrino mass. To date, $B^0 \to \ell^+\ell^-$ decays have not been observed. The previous best upper limits are from the CLEO [1] and BELLE [2] collaborations.

Since these processes are highly suppressed in the SM, they are potentially sensitive probes of new physics. Significant enhancements are possible through interaction with a charged Higgs in multi-Higgs doublet models [3], in models with an extra vector-like down-type quark [4], in models containing leptoquarks [5], and in supersymmetric models with R-parity violation.

The presence of two charged high-momentum leptons provides a very clean signature for the three decay modes under consideration. In the center-of-momentum (CM) frame we require two oppositely charged high momentum leptons from a common vertex consistent with the decay of a B^0 meson. Since the signal events contain two B mesons and no additional particles, the energy of each B in the CM frame must be equal to the e^+ or e^- beam energy. We therefore define

$$m_{ES} = \sqrt{(E^*_{beam})^2 - (p^*_{B^0})^2}\ , \tag{1}$$

$$\Delta E = E^*_{B^0} - E^*_{beam} \tag{2}$$

where E^*_{beam} is the beam energy and $p^*_{B^0}$ and $E^*_{B^0}$ are the reconstructed momentum and energy of the B^0 candidate in the CM frame. For signal events, the beam energy-substituted mass m_{ES} peaks at m_B. The quantity ΔE is used to determine whether a candidate system of particles has total energy consistent with the beam energy in the CM frame. Table 1 lists the m_{ES} and ΔE resolution for each decay mode. Note that the resolution is degraded for the $B^0 \to e^+e^-$ mode and, to a lesser extent, the $B^0 \to e^\pm\mu^\mp$ mode due to bremsstrahlung by the electrons. We define a signal box in the m_{ES}-ΔE plane whose dimensions are optimized for each mode to produce the best upper limit on the branching ratio. The various signal box dimensions are given in table 1. We also define a *Grand Sideband* (GSB) as 5.20

Work supported in part by Department of Energy Contract DE-AC03-76SF00515
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Table 1
The m_{ES} and ΔE resolution for each decay channel. Also shown are the dimensions of the signal box for each channel which have been optimized to produce the best upper limit.

	$B^0 \to e^+e^-$	$B^0 \to \mu^+\mu^-$	$B^0 \to e^\pm\mu^\mp$
$\sigma(m_{ES})$ [MeV/c^2]	3.0±0.2	2.6±0.1	2.7±0.1
$\sigma(\Delta E)$ [MeV]	29.3±0.9	24.7±0.3	26.8±0.4
Signal Box m_{ES} range [GeV/c^2]	5.273-5.285	5.274-5.285	5.274-5.284
Signal Box ΔE range [GeV]	-0.105-0.050	-0.050-0.050	-0.070-0.050

$< m_{ES} <$ 5.26 GeV/c^2 and -0.40 $< \Delta E <$ 0.40 GeV in which to study backgrounds.

Suppression of background from non-resonant $q\bar{q}$ production is provided by a series of topological requirements. We employ restrictions on the overall magnitude of the event thrust $|T|$ and on the magnitude of the cosine of the angle θ_T defined as the angle 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. We require $|T| < 0.9$ and $\cos\theta_T < 0.84$. The efficiencies for the full selection are given in table 2. The systematic error on the efficiency is determined by a comparison of the control sample $B^0 \to J/\psi K^0_s$ with $J/\psi \to e^+e^-$ for $B^0 \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ for $B^0 \to \mu^+\mu^-$. These comparisons indicate the dominant uncertainty on the signal efficiency to be the resolution and scale of ΔE, contributing 4.4% (2.6%) for the $B^0 \to e^+e^-$ ($B^0 \to \mu^+\mu^-$) channel.

We estimate the background in the signal box, N_{BG}, by assuming it is described by the ARGUS function[6] in m_{ES} and an exponential function in ΔE. These shapes are fit to the data in the sidebands and extrapolated into the signal box using the number of events in the GSB to determine the normalization. For the $B^0 \to e^+e^-$ channel, the background is dominated by pairs of true electrons from $c\bar{c}$ and two-photon events. For the $B^0 \to \mu^+\mu^-$ channel, about half of the total background is due to misidentified hadrons in combination with a real muon. For the $B^0 \to e^\pm\mu^\mp$ channel, the background is composed of real electrons and fake muons with two-photon processes contributing strongly. The expected background is roughly 0.5-0.6 events for all channels. In the signal box we observe 1 event in the $B^0 \to e^+e^-$ mode and no events in the other two modes as shown in figure 1. We therefore find no evidence for a signal and set upper limits at the 90% confidence level. For the purpose of setting upper limits, all observed events are assumed to be signal. These results are summarized in table 2.

2. $B \to K^+\nu\bar{\nu}$

The flavor changing neutral current decay $B^+ \to K^+\nu\bar{\nu}$ proceeds via Z^0 penguin and W box diagrams in the SM and is, therefore, highly suppressed. The predicted branching ratio for $B \to K^+\nu\bar{\nu}$ summed over all neutrino species is $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = 3.8^{+1.2}_{-0.6} \times 10^{-6}$ [7]. Since the decay is highly suppressed it can be used to probe the indirect effects of new particles and interactions emerging in the loop diagrams. New physics models which may enhance the rate of $B^+ \to K^+\nu\bar{\nu}$ include minimal supersymmetry(SUSY), multi-Higgs doublet models, leptoquarks, and SUSY models with R parity [7,8]. Moreover, the SM prediction for the inclusive process $b \to s\nu\bar{\nu}$ is nearly free from strong interaction effects and has very small theoretical uncertainty. The best previous experimental limit from the CLEO collaboration [9] is $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 2.4 \times 10^{-4}$ at 90% CL.

Since the signal mode contains two neutrinos there are only minimal kinematic constraints that can be applied. Therefore, the identification of the signal mode demands the reconstruction and removal of the decay products of the other B in the event. The particles not used in the reconstruction of the companion or *tag* B may then be compared with the signature expected for $B^+ \to K^+\nu\bar{\nu}$. The low multiplicity of the signal decay greatly reduces the combinatorial back-

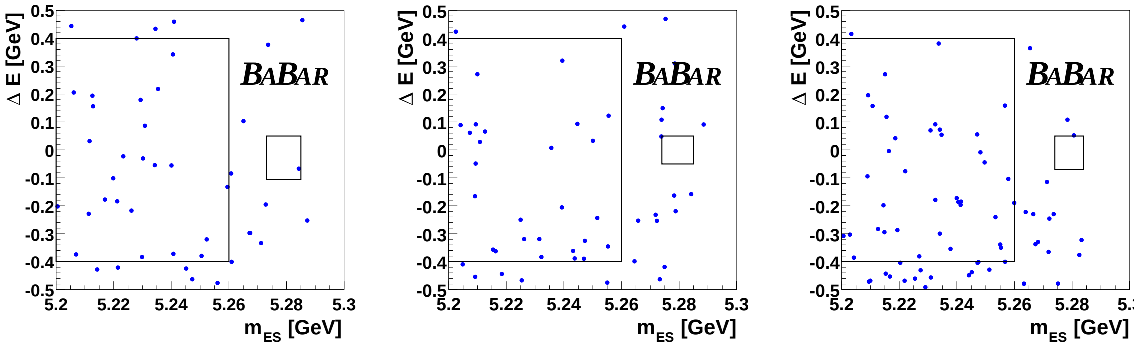

Figure 1. Distribution from data of m_{ES} vs ΔE for $B^0 \to e^+e^-$ (left), $B^0 \to \mu^+\mu^-$ (middle), and $B^0 \to e^\pm\mu^\mp$ (right).

Table 2
Results of the $B \to \ell^+\ell^-$ search. Shown are the number of events in the Grand Sideband, N_{GSB}, number of events in the signal box, N_{SigBox}, number of background events expected, N_{BG}, total signal efficiency, and 90% CL upper limit on the branching ratio.

mode	N_{GSB}	N_{SigBox}	N_{BG}	efficiency[%]	Upper Limit (90% CL)
$B \to e^+e^-$	25	1	0.60±0.24	19.3±0.4	3.3×10^{-7}
$B \to \mu^+\mu^-$	26	0	0.49±0.19	18.8±0.3	2.0×10^{-7}
$B \to e^\pm\mu^\mp$	37	0	0.51±0.17	18.3±0.4	2.1×10^{-7}

ground in the tag reconstruction, allowing the use of decay modes that would not be sufficiently clean under other circumstances. Therefore, the companion B is reconstructed in the decay mode $B^- \to D^0\ell^-\bar{\nu}X$ with the D^0 reconstructed in the $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$ modes. The X system is kinematically constrained to be either nothing or a soft transition pion or photon from a higher mass charm state. This method results in roughly 0.5% of B^- decays being reconstructed as tags.

The following kinematic requirements are imposed on the tag B candidate: $p^*_{D^0} > 0.5$ GeV/c and $m_{D\ell} > 3$ GeV/c^2 where $p^*_{D^0}$ is the CM frame momentum of the D^0 candidate and $m_{D\ell}$ is the invariant mass of the $D^0\ell^-$ combination. We also require $-2.5 < \cos\theta_{B,D\ell} < 1.1$ where,

$$\cos\theta_{B,D\ell} = \frac{2E_B E_{D\ell} - m_B^2 - m_{D\ell}^2}{2|\vec{p}_B||\vec{p}_{D\ell}|}. \qquad (3)$$

Here E_B and $|\vec{p}_B|$ are the known energy and momentum of the B in the $\Upsilon(4S)$ frame. This requirement on $\cos\theta_{B,D\ell}$ is the most important for restricting the kinematics of the $D^0\ell^-$ to be consistent with a semileptonic B decay.

After the tag B is selected, there must be exactly one remaining charged track in the event whose charge is opposite that of the tag lepton and it must satisfy the particle identification criteria for charged kaons. The kaon from the decay $B^+ \to K^+\nu\bar{\nu}$ has a stiff momentum spectrum in the $\Upsilon(4S)$ rest frame while the background peaks at small momenta. Therefore, we require $p^*_K > 1.5$ GeV/c. We also require the angle between the kaon and lepton to satisfy $-0.9 < \cos\theta^*_{K,\ell} < 0.8$ in the CM frame since $e^+e^- \to q\bar{q}$ and $e^+e^- \to \tau^+\tau^-$ backgrounds tend to peak in the forward and backward directions.

The $B^+ \to K^+\nu\bar{\nu}$ signal leaves very little neutral energy (calorimeter energy not associated with a charged track) in the detector and does not contain any neutral hadrons. We therefore require that the remaining neutral energy detected in the electromagnetic calorimeter, E_{left}, be less than 0.5 GeV and that there be no neutral clusters consistent with neutral hadrons located in the muon system. A signal box is defined by the requirements $E_{left} < 0.5$ GeV and $|m_D - m_D^{fit}| < 3\sigma_D^{fit}$ where m_D is the nominal D^0 mass and m_D^{fit} and σ_D^{fit} are the reconstructed D^0 mass and resolution respectively. The expected background in the signal box from the simulation is 2.2 events.

Systematic errors are evaluated by comparing data with the simulation in two E_{left} vs $(m_D - m_D^{fit})$ sideband regions. In addition to the sideband samples, we use events in which both the B^+ and B^- are reconstructed in the tag mode $B^- \to D^0 \ell^- \bar{\nu} X$. These "double tagged" events are used to quantify the uncertainty in the efficiency of our signal selection. Systematic errors on the total number of $\Upsilon(4S)$ events, tagging efficiency, kaon selection and momentum, E_{left} and neutral hadron multiplicity have all been studied. The total relative uncertainty on the selection efficiency is found to be 8.7%.

As shown in figure 2, the signal region contains two events, consistent with the 2.2 background events predicted by the simulation. For the purpose of setting a limit, each candidate is assumed to be signal. We therefore find $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 9.4 \times 10^{-5}$ at 90% CL.

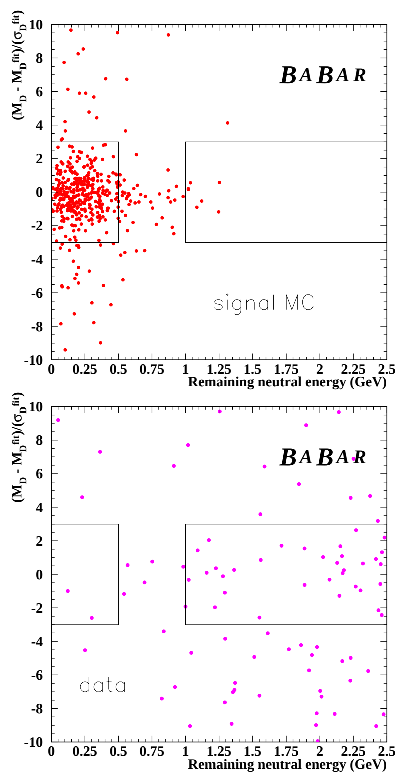

Figure 2. The distribution of events in the $(m_D - m_D^{fit})$ vs E_{left} plane for signal Monte Carlo (top) and data (bottom).

3. CONCLUSIONS

We see no evidence for a signal in either the $B \to \ell^+\ell^-$ or $B \to K^+\nu\bar{\nu}$ decay modes and set the following upper limits at the 90% CL: $\mathcal{B}(B^0 \to e^+e^-) < 3.3 \times 10^{-7}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.0 \times 10^{-7}$, $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 2.1 \times 10^{-7}$, and $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 9.4 \times 10^{-5}$.

REFERENCES

1. CLEO Collaboration, T. Bergfeld *et al.*, *Phys. Rev.* D **62**, 091102 (2000)
2. Belle Collaboration, K. Abe *et al.*, BELLE-CONF-0127, (2001)
3. J.L. Hewitt, S. Nandi, and T.G. Rizzo, *Phys. Rev.* D **39**, 250 (1989)
4. Y. Nir and D. Silverman, *Phys. Rev.* D **42**, 1477 (1990)
5. J. Pati and A. Salam, *Phys. Rev.* D **10**, 275 (1974)
6. H. Albrecht *et al.* *Phys. Lett.* B **241**, 278 (1990)
7. G. Buchalla, G. Hiller, and G. Isidori, *Phys. Rev.* D **63**, 014015 (2001)
8. Y. Grossman, Z. Ligeti, and E. Nardi, *Nucl. Phys.* B **465**, 369 (1996)
9. T.E. Browder *et al.*, *Phys. Rev. Lett.* **86**, 2950 (2001)