SLACPUB-9700
April 2003

# Recent Results on Rare $B$ Decays from BaBar and Belle

B. Brau[a*],

[a] Laboratory for Nuclear Science, Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA, 02139

The PEP-II and KEK asymmetric $B$ factories are providing the BaBar and BELLE collaborations large samples of $B$ mesons, enabling high-statistics searches for rare $B$ decays. The rates for some of these decays can be enhanced by contributions from new physics, while others can provide constraints on the Unitarity Triangle. I will review a variety of recent results on rare $B$ decays from these two experiments.

## 1. Introduction

Heavy quark systems have been studied for many years experimentally. They are also relatively accessible theoretically, in particular because the mass of the $b$ quark is much greater than the QCD scale parameter $\lambda_{QCD}$ and thus the $b\overline{q}$ system can often be treated perturbatively. In addition, in decays for which the tree processes involve $b \to u$ transitions, the penguin amplitudes can play a significant role in determining the overall rate. For this reason, it is possible that new physics in the equivalent penguin diagrams could contribute significantly. The large samples of $B$ decays recorded by BaBar and Belle are now providing the statistics necessary to study rare decays like the $b \to u$ transition. Finally, some kind of new physics could manifest itself as direct CP violation in the interference between the penguin and tree amplitudes.

There are many $B$ decays which are classified as 'rare'. Rather than try to cover the complete spectrum of topics, I have chosen to focus on several measurements for which BaBar and Belle have recently publicized new results.

## 2. $B$ Reconstruction

All of the measurements I will discuss use similar techniques to reconstruct $B$ candidates. All observed particles combined to form a $B$ candidate are required to be in the active detector fiducial volume. To improve resolution, and maximize the use of available information, the well-known beam energy is used to form two kinematic variables. They are the energy difference between the $B$ candidate and the beam energy, $\Delta E = E_{\rm candidate} - E_{beam}$, and the energy-substituted $B$ mass, $m_{ES} = \sqrt{E_{beam}^2 - \sum_i p_i^2}$, in which the $p_i$ are the $B$ candidates daughters. These variables are mostly uncorrelated. Correctly reconstructed signal candidates cluster in the region around $\Delta E = 0$ and $m_{ES} = 5.28$ GeV, the nominal $B$ mass.

## 3. $b \to s l^+ l^-$

The decay $B \to K^{(*)} l^+ l^-$ proceeds via the two flavor changing electroweak diagrams shown in Figure 1. The inclusive rate for $B \to X_s \mu^+ \mu^-$

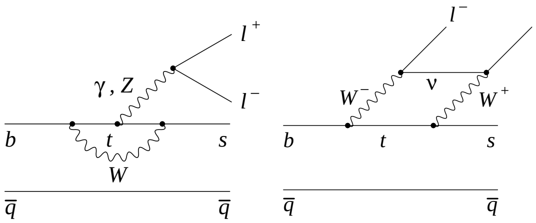

Figure 1. Standard Model 2nd order electroweak diagrams for $B \to K^{(*)} l^+ l^-$.

---

[*] Now at Ohio State University, Dept. of Physics, 174 W.18th Ave. Columbus, OH 43210

* Representing the BABAR Collaboration at the Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by the Department of Energy contract DE-AC03-76SF00515.
Presented at the 10th Advanced Accelerator Concepts Workshop (ACC 2002), 6/23/2002-6/28/2002, Mandalay Beach, CA

is predicted to be $(4.15 \pm 0.70) \times 10^{-6}$, and the rate for $B \rightarrow X_s e^+e^-$ is predicted to be $(6.89 \pm 0.10) \times 10^{-6}$ [1]. New physics at the electroweak scale (e.g. SUSY, Technicolor, fourth-generation quarks), could compete with the small Standard Model rate. Some SUSY models predict an enhancement of the rates by up to a factor of two[2].

Belle first observed $B \rightarrow K\mu^+\mu^-$ in the fall of 2001[3]. Both BaBar and Belle have new results on $b \rightarrow sl^+l^-$. Belle recently presented a measurement of the inclusive rate for $B \rightarrow X_s l^+l^-$, and BaBar has updated its search for the exclusive $B \rightarrow K^{(*)}l^+l^-$ modes and now confirms Belle's observation.

### 3.1. Belle Measurement of $B \rightarrow X_s l^+l^-$

Belle reconstructs candidates for $B \rightarrow X_s l^+l^-$ by combining opposite sign lepton pairs with $X_s$ candidates, where $X_s$ formed by combining a $K^+$ or $K_s^0$ with zero to four pions, of which up to one $\pi^0$ is allowed, and the invariant mass of the $X_s$ candidate must satisfy $M_{X_s} < 2.1$GeV. The best candidate in each event is chosen using $\Delta E$, vertex quality, $B$ flight direction, and $K - l$ angular correlation information. The analysis was performed on a sample of 43 fb$^{-1}$.

Background from $B \rightarrow X_s h^+h^-$ needs to be controlled carefully in this analysis because it peaks near the $B$ mass in the $m_{ES}$ spectrum. For this reason, Belle estimates this background with data by using a sample of reconstructed $B \rightarrow X_s h^+h^-$ events selected as signal, but without any lepton identification requirements. The yield from this sample is multiplied by the momentum-dependent measured lepton fake rate for each pion to estimate the background from this source. Belle estimates it has $2.4^{+0.5}_{-0.4}$ background events from this source in its 43 fb$^{-1}$ sample and subtracts this amount from the signal yield.

Resonant background from $B \rightarrow J/\psi(\rightarrow l^+l^-)K^{(*)}$ is explicitly vetoed by removing candidates which have a di-lepton invariant mass near the $J/\psi$ or $\psi(2S)$ nominal mass.

The signal distributions are shown in Figure 2. Belle observes $16.6^{+8.0+3.9}_{-7.3-3.8}$ events in the $X_s e^+e^-$ channel, and sets an upper limit of $\mathcal{B}(B \rightarrow X_s e^+e^-) < 11.0 \times 10^{-6}$ at the 90% confidence level. Belle observes $30.7^{+7.9+5.4}_{-7.4-3.8}$ events in the $X_s\mu^+\mu^-$ channel, and measures the branching fraction to be $(8.9^{+2.3+1.6}_{-2.1-1.7}) \times 10^{-6}$. By combining the two lepton modes, Belle obtains a yield of $47.6^{+11.0+9.6}_{-10.4-8.0}$ for $X_s l^+l^-$, and measures the inclusive rate to be $(7.1^{+1.6+1.4}_{-1.6-1.2}) \times 10^{-6}$[4]. All results are in agreement with predicted rates.

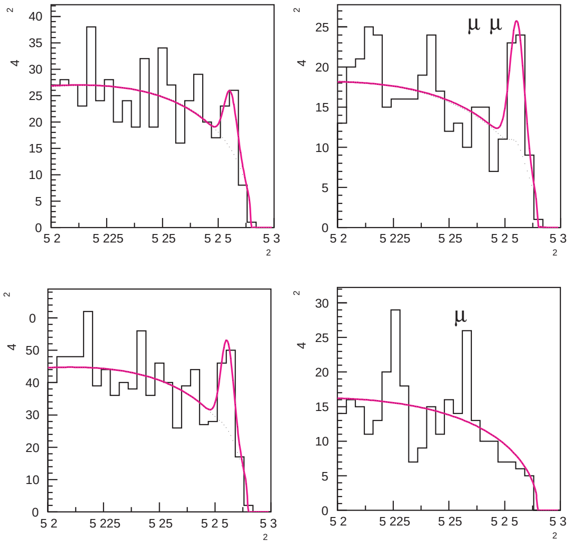

Figure 2. Signal distributions for Belle analysis of $B \rightarrow X_s l^+l^-$ Top left: $X_s e^+e^-$ candidates, top right: $X_s\mu^+\mu^-$ candidates, bottom left: combined $X_s l^+l^-$ candidates, and bottom right: $X_s e^\pm\mu^\mp$.

### 3.2. BaBar Measurement of $B \rightarrow K^{(*)}l^+l^-$

BaBar has an updated measurement of the rates for $B \rightarrow K^{(*)}l^+l^-$ using 56 fb$^{-1}$. Signal candidates are reconstructed in the final states $B^+ \rightarrow K^+l^+l^-$, $B^0 \rightarrow K_S^0 l^+l^-$, $B^+ \rightarrow K^{*+}l^+l^-$, $B^0 \rightarrow K_S^{*0}l^+l^-$; where $K^{*+} \rightarrow K_S^0\pi^+$, $K^{*0} \rightarrow K_S^+\pi^-$, and $l$ is either an electron or muon. The signal yield is extracted by an extended maximum likelihood fit in the $\Delta E$ versus $m_{ES}$ plane.

Resonant background from $B \rightarrow J/\psi(\rightarrow l^+l^-)K^{(*)}$ has the same topology as signal, and peaks in the signal region. This background therefore is explicitly vetoed by a correlated selection in the $\Delta E$ versus dilepton invariant mass plane as shown in Figure 3.

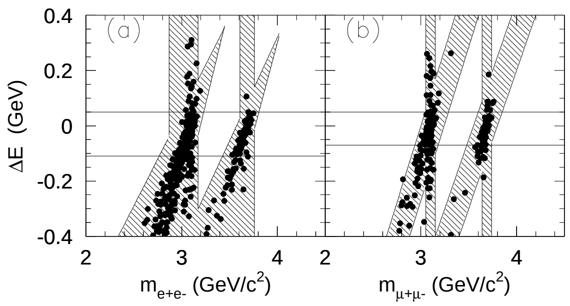

Figure 3. Veto in $\Delta E$ versus dilepton invariant mass plane for electrons (a) and muons (b). The shaded region is vetoed, and the points correspond to a Monte Carlo simulation of $B \to J/\Psi(\to e^+e^-)K$ and $B \to J/\Psi(\to \mu^+\mu^-)K$. Most signal events lie in the region between the horizontal lines near $\Delta E = 0$.

Signal yields in the $m_{ES}$ projection after a requirement that $-110 < \Delta E < 50$ MeV for the electron modes and $-70 < \Delta E < 50$ MeV for the muon modes are shown in Figure 4. By combining the electron and muon channels and imposing the theoretical condition that $\mathcal{B}(B \to K^*e^+e^-)/\mathcal{B}(B \to K^*\mu^+\mu^-) = 1.21$ [2], BaBar measures $\mathcal{B}(B \to Kl^+l^-) = (0.84^{+0.30+0.10}_{-0.24-0.18}) \times 10^{-6}$, and sets a limit for $\mathcal{B}(B \to K^*l^+l^-) < 3.5 \times 10^{-6}$ at the 90% confidence level[5].

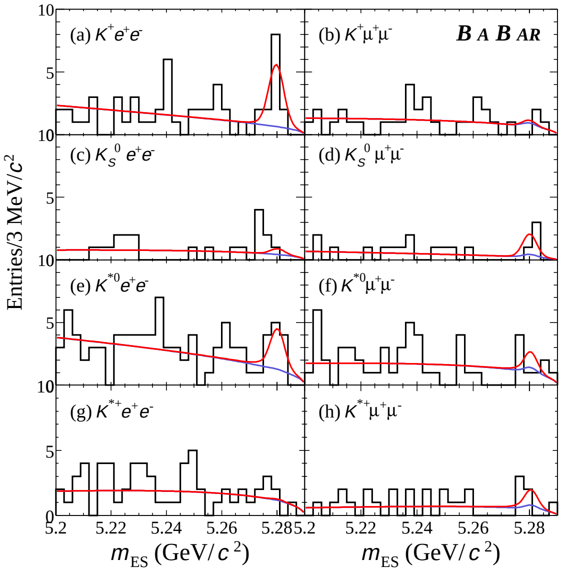

Figure 4. Signal yields and fit projections for $B \to K^{(*)}l^+l^-$.

## 4. Searches for $B \to \rho\gamma$

The decay $B \to \rho\gamma$ proceeds through a $b \to d$ penguin which is suppressed by $|V_{td}|^2/|V_{ts}|^2$ (approximately $10^{-2}$) with respect to $B \to K^*\gamma$. These two rates together can therefore be used to extract the ratio $|V_{td}|/|V_{ts}|$. The standard model predictions for the rates are $\mathcal{B}(B^0 \to \rho^0\gamma) = (0.49 \pm 0.21) \times 10^{-6}$ and $\mathcal{B}(B^+ \to \rho^+\gamma) = (0.85 \pm 0.40) \times 10^{-6}$ [6]. Again, these rates could be enhanced by new physics contributions in the loop, e.g. SUSY.

Both BaBar and Belle have recent preliminary measurements which place limits on the rates for these decays, and BaBar has used its limit to constrain $|V_{td}|^2/|V_{ts}|^2$.

Background from continuum and initial state radiation are suppressed in both BaBar and Belle by multivariate techniques which incorporate information from a variety of correlated sources including event shape, $B$ flight direction, $\cos\theta_{\text{thrust}}$, the angle between the thrust axis of the $B$ candidate and the rest of the event, and energy flow around the photon candidate in the center of mass. BaBar also includes information about the net flavor content of the event and $|\Delta z|$, the observed vertex separation of the $B$ candidate and the vertex reconstructed using the rest of the event. Belle combines the information into a likelihood ratio while BaBar uses a neural network. Both techniques provide a similar level of background suppression. The output of the neural network used by BaBar is shown in Figure 5.

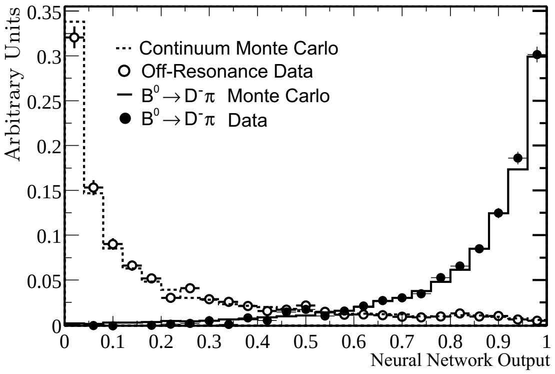

Figure 5. Neural Network output used for background suppression in BaBar's search for $B \to \rho\gamma$.

These limits set by both experiments are beginning to approach the theoretical predictions. The limits are summarized in Table 1.

Table 1
Measured limits for $\mathcal{B}(B \to \rho\gamma)$

| Decay Mode | Yield | Upper Limit 90% CL($\times 10^{-6}$) |
|---|---|---|
| | Belle: $45.1\times10^6 B\overline{B}$ | [8] |
| $B^0 \to \rho^0\gamma$ | $10.0^{+7.4}_{-6.2} \pm 1.0$ | $< 5.7$ |
| $B^+ \to \rho^+\gamma$ | $1.0^{+5.1}_{-3.9} \pm 1.0$ | $< 7.2$ |
| | BaBar $61.7\times10^6 B\overline{B}$ | [7] |
| $B^0 \to \rho^0\gamma$ | $3.1 \pm 4.2$ | $< 1.5$ |
| $B^+ \to \rho^+\gamma$ | $4.6 \pm 5.8$ | $< 2.8$ |

BaBar has used its limit, in combination with the world average for $\mathcal{B}(B \to K^*\gamma)$ to extract $|V_{td}|/|V_{ts}|$. BaBar finds $|V_{td}|/|V_{ts}| < 0.36$ at the 90% confidence level.

## 5. Measurements of $B \to \eta^{(\prime)}K^{(*)}$

The tree amplitude for the decays $B \to \eta^{(\prime)}K^{(*)}$ is CKM suppressed, and therefore the penguin diagrams play a significant role in the total rate. Rates which are larger than expected have been observed in the modes $B \to \eta^{\prime}K$ and $B \to \eta K^*$, first by CLEO[10] and later confirmed by Belle [11] and BaBar[12]. Belle measures $\mathcal{B}(B \to \eta^{\prime}K^+) = (79^{+12}_{-11} \pm 9) \times 10^{-6}$, $\mathcal{B}(B \to \eta^{\prime}K^0) = (55^{+19}_{-16} \pm 8) \times 10^{-6}$, and $\mathcal{B}(B \to \eta K^{*+}) = (26.5^{+7.8}_{-7.0} \pm 3.0) \times 10^{-6}$, $\mathcal{B}(B \to \eta K^{*0}) = (16.5^{+4.6}_{-4.2} \pm 1.2) \times 10^{-6}$. BaBar finds $\mathcal{B}(B \to \eta^{\prime}K^+) = (67 \pm 5 \pm 5) \times 10^{-6}$, $\mathcal{B}(B \to \eta^{\prime}K^0) = (46 \pm 6 \pm 4) \times 10^{-6}$, and $\mathcal{B}(B \to \eta K^{*+}) = (22.1^{+11.1}_{-9.2} \pm 3.2) \times 10^{-6}$, $\mathcal{B}(B \to \eta K^{*0}) = (19.8^{+6.5}_{-5.6} \pm 1.5) \times 10^{-6}$.

The neutral modes are CP eigenstates, and the same mechanism responsible for time-dependent CP violation in $B \to J/\psi K^0_S$ is also possible here. The penguin contribution in $\eta^{(\prime)}K^{(*)}$ complicates the situation, and in particular new physics contributions could possibly modify the measured CP phase with respect to the one measured in charmonium modes (which are tree-dominated).

Belle has presented a preliminary measurement of CP violation in $B^0 \to \eta^{\prime}K$, which is covered in Dan Marlow's talk[13]. BaBar has a measurement in progress. Both BaBar and Belle have updated their branching fraction measurements, and all continue to be consistent both with each other and with the results originally measured by CLEO.

Finally, both experiments have begun to search for direct CP violation in $B \to \eta^{(\prime)}K^{(*)}$, $B \to \omega\pi$, $B \to \omega K$, and $B \to \phi K^{(*)}$. Some of these modes in particular have generated theoretical interest. [9] So far, no significant CP asymmetry is observed in any of these modes.

## 6. Conclusions

The flavor changing neutral current $b$ to $s$ transitions $B \to K l^+ l^-$ first observed last fall by Belle have now also been observed by BaBar. The limit on $|V_{td}|/|V_{ts}|$ given by the limits on the rate for the decay $B \to \rho\gamma$ will soon approach a level of sensitivity which is complementary to the limits set by $\Delta m_d/\Delta m_s$. CP violation studies in $B \to \eta^{(')} K^{(*)}$ are beginning, and direct CP violation searches are maturing. Many other rare decays are being studied as both experiments continue to accumulate data.

## REFERENCES

1. A. Ali, E. Lunghi, C. Greub and G. Hiller, Phys. Rev. D **66**, 034002 (2002) [arXiv:hep-ph/0112300].
2. A. Ali, P. Ball, L. T. Handoko and G. Hiller, Phys. Rev. D **61**, 074024 (2000) [arXiv:hep-ph/9910221].
3. K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **88**, 021801 (2002) [arXiv:hep-ex/0109026].
4. K. Senyo, "$b \to s l^+ l^-$ at Belle", Talk presented at FPCP 2002, Philadelphia, PA.
5. J. Walsh, "Results from BABAR on the decays $B \to K l^+ l^-$ and $B \to K^* l^+ l^-$ ", Talk presented at FPCP 2002, Philadelphia, PA.
6. A. Ali and A. Y. Parkhomenko, Eur. Phys. J. C **23**, 89 (2002) [arXiv:hep-ph/0105302].
7. H. Tanaka, "Rare and Radiative $B$ Decays at BaBar ", Talk presented at 2001 Rencontres de Moriond on Electroweak Interactions
8. H. Kim, "Radiative $B$ decays from Belle ", Talk presented at DPF 2002, Williamsburg, VA.
9. A. Ali, G. Kramer and C. D. Lu, Phys. Rev. D **59**, 014005 (1999) [arXiv:hep-ph/9805403].
10. S. J. Richichi *et al.* [CLEO Collaboration], Phys. Rev. Lett. **85**, 520 (2000) [arXiv:hep-ex/9912059].
11. K. Abe *et al.* [Belle Collaboration], KEK-PREPRINT-2001-73 *Prepared for 20th International Symposium on Lepton and Photon Interactions at High Energies (LP 01), Rome, Italy, 23-28 Jul 2001.*
12. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **87**, 221802 (2001) [arXiv:hep-ex/0108017].
13. D. Marlow, "$\sin 2\phi_1$ Measurements from BELLE and BaBar", these proceedings.