COLO – HEP – 345
June 2, 1994

RARE DECAYS OF B MESONS *

Karen Lingel
University of Colorado
Boulder, CO 80309-0390
U.S.A.

Abstract

Rare decays of B mesons are discussed. These decays include penguin decays (electromagnetic and hadronic), $b \to u$ decays, and purely leptonic decays.

INTRODUCTION

With the profusion of heavy meson samples becoming available, more and more effort is being turned toward the study of rare decays of these mesons. These rare decays are getting attention for two basic reasons. First, by studying rare decays we can get insight into the Standard Model — Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, one-loop penguin decays, CP violation. Secondly, by looking for anomalous effects in rare decays, we can infer whether there are non-Standard Model contributions: extra Higgs particles, supersymmetric particles, flavor changing neutral currents, leptoquarks.

The B meson is an ideal place to look for rare decays. Since $|V_{cb}|$ is small (approximately 0.05) we expect the favored $b \to c$ decays to be somewhat less than 100% of the decay width. Rare decays will make up the remainder. Secondly, the large top quark mass and the large coupling between t and b quarks ($|V_{tb}| \approx 1$) leads to large loop effects, a factor of 10^5 enhancement over one-loop kaon decays.

*Invited talk given at the 5th Conference on the Intersections of Particle and Nuclear Physics, St. Petersburg, Florida, 1–6 June 1994

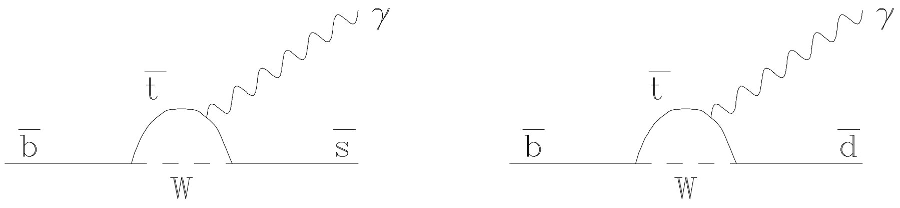

Figure 1: Electromagnetic penguin (one-loop) diagrams for $b \to s\gamma$ and $b \to d\gamma$.

ELECTROMAGNETIC PENGUINS

One-loop or "penguin" diagrams give rise to electromagnetic decays of the sort $b \to s\gamma$ and $b \to d\gamma$, shown in Fig. 1. The exclusive $b \to d\gamma$ decay channels $B \to \rho\gamma$ and $B \to \omega\gamma$ can be used in conjunction with the exclusive $b \to s\gamma$ decay channels $B \to K^*\gamma$ recently observed at CLEO [1] to measure $|V_{td}|/|V_{ts}|$:

$$\frac{\mathrm{B}(B^- \to \rho^-\gamma)}{\mathrm{B}(B^- \to K^{*-}\gamma)} = \frac{\mathrm{B}(B^0 \to \omega\gamma) + \mathrm{B}(B^0 \to \rho^0\gamma)}{\mathrm{B}(B^0 \to K^{*0}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \xi\ \Omega \tag{1}$$

where ξ is the form factor ratio, ≈ 0.9 [2], and $\Omega = 1.04$ is a phase space factor.

CLEO has searched for the decays $B \to \rho\gamma, \omega\gamma$. The main backgrounds are continuum production of light quarks and initial state radiation, which are suppressed with event shape cuts. In the ρ modes, there is also background from mis-identified $B \to K^*\gamma$ decays. This background is suppressed by a Neural Network technique which utilizes information contained in four variables: $\Delta E \equiv E_{\pi_1} + E_{\pi_2} + E_\gamma - E_{\mathrm{beam}}$, $M_{\pi\pi}$, $M_{K\pi}$, and the helicity angle of the "K". CLEO finds no evidence for any signals and finds upper limits on the branching fractions of $\mathrm{B}(B^0 \to \rho^0\gamma) < 3.1 \times 10^{-5}$, $\mathrm{B}(B^0 \to \omega\gamma) < 1.4 \times 10^{-5}$, and $\mathrm{B}(B^- \to \rho^-\gamma) < 1.8 \times 10^{-5}$ and a limit on the CKM matrix elements $|V_{td}|/|V_{ts}| < 0.6$.

CDF and CLEO search for decays of the type $b \to s\ell^+\ell^-$, an electromagnetic penguin where the emitted photon materializes as a lepton pair. This decay can also occur via a box diagram. Holes in the Dalitz plot caused by implicit or explicit lepton identification cuts, background suppression cuts, and a $B \to \psi^{(\prime)}K$; $\psi \to \ell^+\ell^-$ veto cause model dependence. Neither CDF nor CLEO see any evidence for any signals. Upper limits on the branching fractions are given in Table 1.

Table 1: Upper limits on $b \to s\ell\ell$ branching fractions

Branching fraction upper limits ($\times 10^{-5}$)						
mode	CLEO	mode	CLEO	CDF	mode	CLEO
$B^- \to K^- ee$	< 1.3	$B^- \to K^- \mu\mu$	< 1.8	< 3.2	$B^- \to K^- e\mu$	< 1.5
$B^0 \to K^{*0} ee$	< 1.9	$B^0 \to K^{*0} \mu\mu$	< 3.9		$B^0 \to K^{*0} e\mu$	< 1.8

HADRONIC DECAYS

The decays $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$ can proceed via a $b \to u$ spectator diagram or a $b \to d$ or $b \to s$ penguin diagram (Fig. 2). The $B^0 \to \pi^+\pi^-$ decay is of particular interest since the final state is a CP eigenstate and CP violation can arise from interference between the amplitude for the direct decay and that for the case where the B^0 mixes to a $\bar{B}^0$ and then decays [3]. Direct CP violation can occur if there is interference between the tree-level amplitude and the penguin amplitude [4]. This effect can spoil the $B^0 \to \pi^+\pi^-$ CP violation measurement via mixing and is known as "penguin pollution". However, one can get a handle on the penguin pollution effect by also measuring the rates of the $B^\pm \to \pi^\pm\pi^0$ and $B^0 \to \pi^0\pi^0$ channels [5]. Direct CP violation can be measured in $B^\pm \to K^\pm\pi^0$ if one also measures the rates of $B^\pm \to K^0\pi^\pm$ and $B^\pm \to \pi^\pm\pi^0$ [6]. Decay modes such as $B \to K\phi$ can occur only via penguin diagrams.

The CLEO search [7] for $B \to h^+h^-$ utilizes a maximum likelihood fit in 5 variables: M_B, $\Delta E \equiv E_{\pi_1} + E_{\pi_2} - E_{\rm beam}$, dE/dx_1, dE/dx_2, and an event shape parameter, $\mathcal{F}$. CLEO finds an excess in the sum of $K\pi$ and $\pi\pi$ with a significance of 4.2σ, however, CLEO cannot claim an observation in either individual signal. The M_B projection is shown in Fig. 3. Upper limits on the branching fractions are given in Table 2. ALEPH also searches [8] for B, B_s, or Λ_B decays to two light hadrons. The two light hadrons are required to have a vertex well-isolated from the interaction point, and to have an invariant mass above that allowed by $b \to c$ decays. The background in the signal region, predicted by Monte Carlo, is 0.07 events and ALEPH finds 3 signal candidates (Fig. 4), a significance of 3.5σ. Again, attributing the signal to specific modes is impossible, and ALEPH calculates the upper limits given in Table 2.

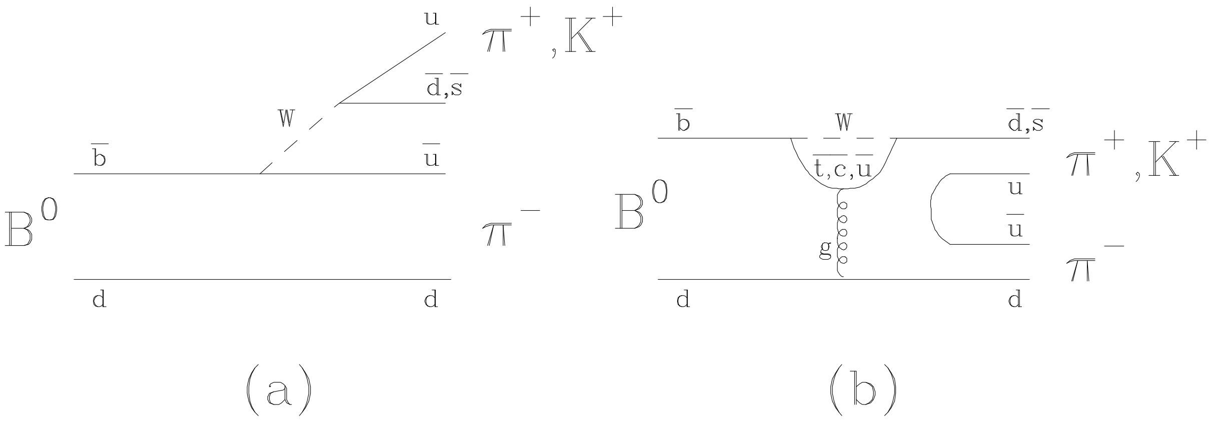

Figure 2: (a) tree and (b) penguin diagrams for $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$.

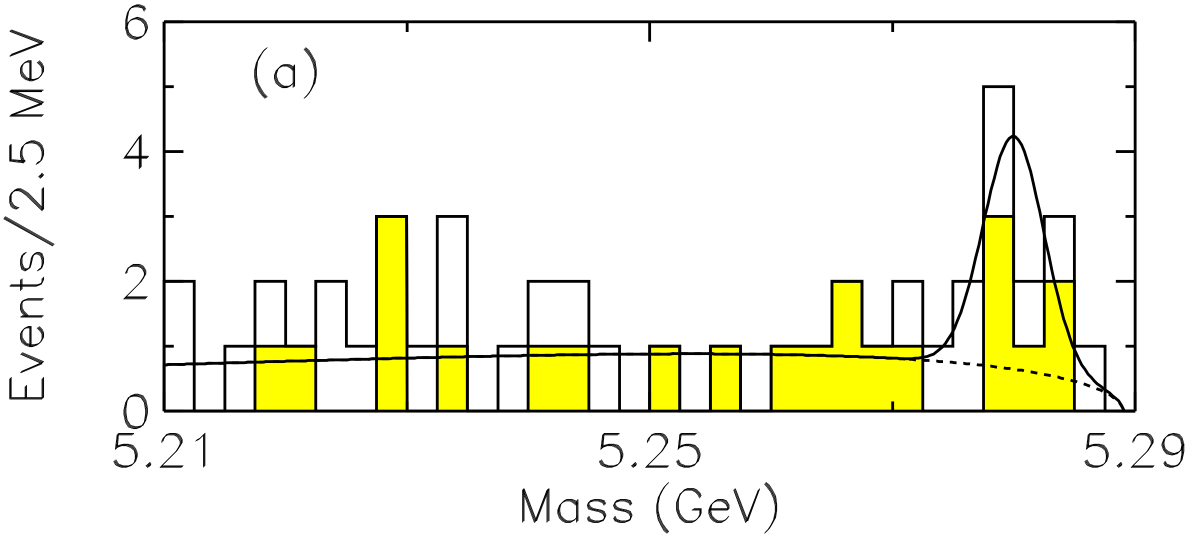

Figure 3: The CLEO M_B distribution for $B^0 \to \pi^+\pi^-$ (shaded) and $B^0 \to K^+\pi^-$ (unshaded). The projection of the maximum likelihood fit is superimposed.

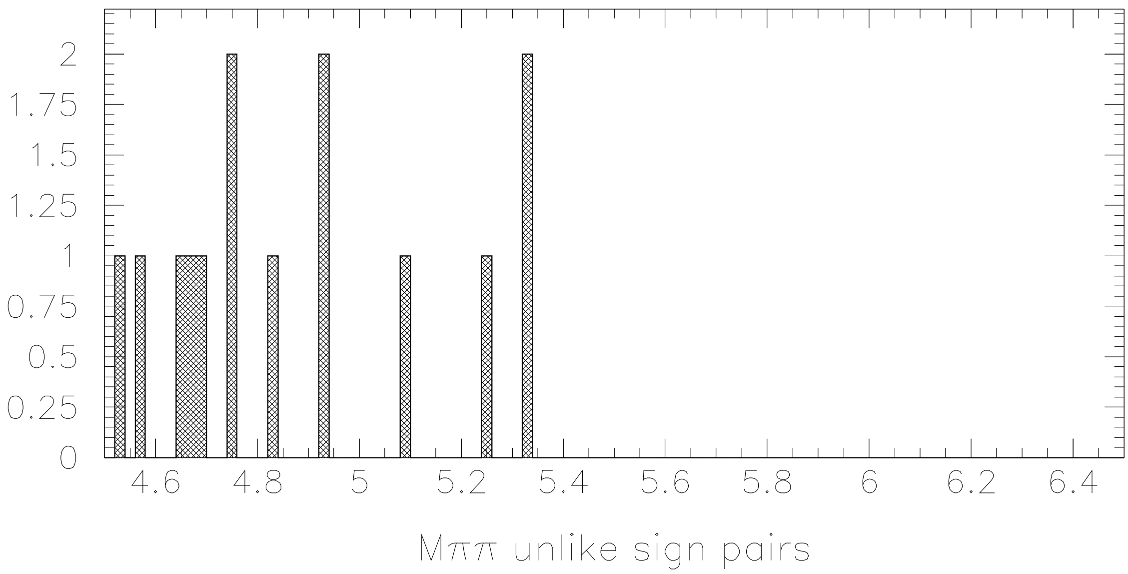

Figure 4: The ALEPH $\pi^+\pi^-$ invariant mass distribution. The signal region is approximately 5.1 to 5.7 GeV. Background from $b \to c$ decays occurs below 5.0 GeV.

Table 2: Summary of rare hadronic decays

	BR ($\times 10^{-5}$)		
mode	CLEO	ALEPH	DELPHI
$B^0 \to \pi^+\pi^-$	< 2.9	< 7.5	< 15
$B^0 \to K^+\pi^-$	< 2.6	< 7.5	< 15
$B^0 \to K^+K^-$	< 0.7		
$B^0 \to \pi^0\pi^0$	< 2.6		
$B^+ \to \pi^+\pi^0$	< 4.3		
$B^+ \to K^+\pi^0$	< 2.5		
$B^+ \to K^+\phi$	< 2.1		
$B^+ \to K^{*+}(892)\phi$	< 12		
$B^0 \to K^0\phi$	< 12		
$B^0 \to K^{*0}(892)\phi$	< 6.0		
$B^0 \to \phi\phi$	< 4.1		
$B_s^0 \to K^+\pi^-$		< 25	
$B_s^0 \to K^+K^-$		< 11	< 15
$\Lambda_b \to p^+h^-$		< 16	

PURELY LEPTONIC DECAYS

Purely leptonic decays of B^+, such as $B^+ \to e^+\nu_e$, $B^+ \to \mu^+\nu_\mu$, and $B^+ \to \tau^+\nu_\tau$ can occur via an annihilation diagram. The width of this decay is given by

$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 M_B M_\ell^2}{8\pi}\left(1 - \frac{M_\ell^2}{M_B^2}\right)\ f_B^2\ |V_{ub}|^2. \tag{2}$$

If $|V_{ub}|$ is measured from other sources, then the purely leptonic decays will give information about the B decay constant, f_B. Using the measurement of $B^0\bar{B}^0$ mixing and f_B, one can derive the CKM matrix element $|V_{td}|$. The decay constant has not yet been measured; theoretical estimates range from 130 MeV from QCD sum rules [9] to 300 MeV from lattice QCD calculations [10]. The width also depends on the mass of the lepton in the decay; the branching ratio $\mathrm{B}(B \to \tau\nu_\tau)$ is expected to be about 1×10^{-4}, $\mathrm{B}(B \to \mu\nu_\mu)$ about 4×10^{-7}, and $\mathrm{B}(B \to e\nu_e)$ about 9×10^{-12}. The τ channel appears to be the place to start.

The search for $B \to \tau\nu$ presents quite an experimental challenge, due to the number of unobserved neutrinos expected in the final state. The CLEO search [11] for $B \to \tau\nu$ uses a tagged sample of 749 ± 40 fully reconstructed B^+ decays. Using 1-prong tau decays, which have a total branching fraction of about 48%, CLEO searches the tagged sample for events which have exactly one charged track and zero neutral showers leftover after removing the tracks and showers belonging to the fully reconstructed B^+. No signal events are observed, and CLEO sets an upper limit of $\mathrm{B}(B \to \tau\nu) < 1.3\%$, still two orders of magnitude away from the theoretical expectation. The limit obtained for the decay constant, $f_B < 2100$ MeV, is also an order of magnitude away from the theoretical expectation.

Although the theoretical branching fraction for $B \to \tau\nu$ is the most promising of the fully leptonic modes, the experimental challenges destroy this advantage. CLEO also looks for the more experimentally clear-cut decay modes $B \to \mu\nu$ and $B \to e\nu$ [11]. CLEO finds 2 $\mu\nu$ candidates and no $e\nu$ candidates, giving branching fraction upper limits of $\mathrm{B}(B \to \mu\nu) < 2.0 \times 10^{-5}$ and $\mathrm{B}(B \to e\nu) < 1.3 \times 10^{-5}$. The limit on f_B from the muon channel is $f_B < 1300$ MeV, a stricter limit than that from the tau channel. The "limit" from the electron channel is $f_B < 230000$ MeV!

The decays $B^0 \to e^+e^-, B^0 \to \mu^+\mu^-$ can occur in the Standard Model via box or Z-penguin diagrams shown in Fig. 5. The branching fractions are expected to be $\sim 10^{-15}$ and $\sim 10^{-10}$, respectively [12]. However, tree-level flavor-changing neutral currents (FCNC) provide a simple tree-level alternative (Fig. 5). FCNC decays are forbidden in the Standard Model, however, there are many models which allow FCNC, and in fact, it is fairly difficult to construct a model which disallows FCNC; in general, discreet symmetries are added by hand to remove them.

CLEO finds no candidates in either mode, and the branching fraction upper limits are $\mathrm{B}(B \to ee) < 5.9 \times 10^{-6}$, and $\mathrm{B}(B \to \mu\mu) < 5.9 \times 10^{-6}$.

CLEO also searches for the lepton number-violating decays $B^0 \to e^\pm\mu^\mp$, $e^\pm\tau^\mp$, $\mu^\pm\tau^\mp$ [13]. Again, the tau channels provide the biggest experimental challenges. CLEO concentrates on the tau decay mode $\tau^+ \to \pi^+\nu$, which has only one neutrino in the final state, and thus some constraints are preserved. CLEO defines a signal region in lepton momentum and $\Delta E \equiv E_\ell + E_\pi + E_\nu - E_{\mathrm{beam}}$ where $E_\nu = p_\nu = |\overrightarrow{p_B} - \overrightarrow{p_\ell} - \overrightarrow{p_\pi}|$ and using the approximation $p_B = 0$. No evidence for any signals is observed and CLEO sets upper limits on the branching fractions of $\mathrm{B}(B \to e^\pm\mu^\mp) < 5.9 \times 10^{-6}$, $\mathrm{B}(B^0 \to e^\pm\tau^\mp) < 5.3 \times 10^{-4}$, and $\mathrm{B}(B^0 \to \mu^\pm\tau^\mp) < 8.3 \times 10^{-4}$.

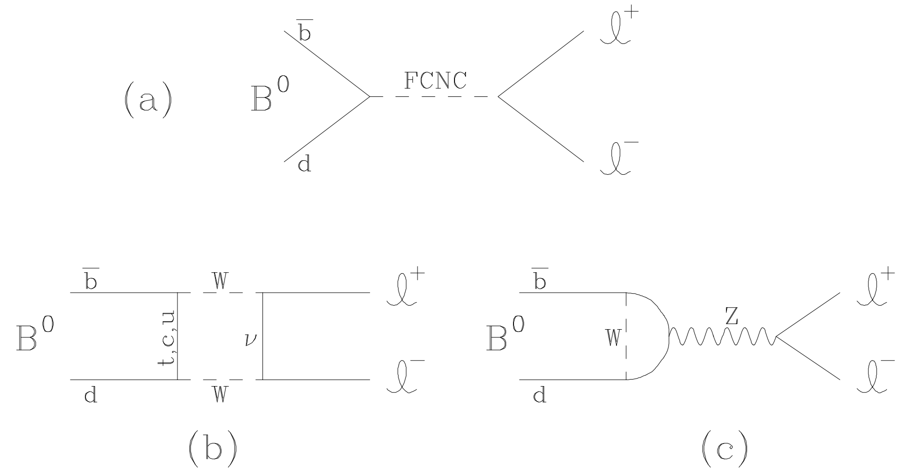

Figure 5: (a) Simple tree-level FCNC and (b) Standard Model box and (c) Z-penguin diagrams for $B^0 \to \ell^+\ell^-$.

Summary and Conclusions

The study of rare decays is a slow process and the rewards are few and far between. B^0 decays to either $\pi^+\pi^-$ or $K^+\pi^-$ or both have been discovered at CLEO. B (or Λ_b) $\rightarrow h^+h^-$ has also been seen at ALEPH. We are approaching Standard Model predictions in a number of other hadronic penguin and hadronic $b \rightarrow u$ modes. Purely leptonic modes such as $B \rightarrow \ell\nu_\ell$ and $B \rightarrow \ell\ell$ are a long way from the Standard Model predictions, but their continued study is useful to rule out non-Standard Model contributions. Or possibly find some!

REFERENCES

1. R. Ammar, *et al.,* Phys. Rev. Lett. **71**, 674 (1993).
2. J. M. Soares, Phys. Rev. D **49**, 283 (1994).
3. I. Dunietz, Ann. Phys. **184**, 350 (1988); M. Gronau, Phys. Rev. Lett. **63**, 1451 (1989).
4. J. M. Gerard and W. S. Hou, Phys. Rev. D **43**, 2909 (1991); H. Simma, G. Eilam, and D. Wyler, Nucl. Phys. B **352**, 367 (1991).
5. M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990); H. J. Lipkin, *et al.*, Phys. Rev. D **44**, 1454 (1991).
6. M. Gronau, J. L. Rosner, and D. London, TECHNION-PH-94-7, EFI-94-14, UdeM-LPN-TH-94-192.
7. M. Battle, *et. al.*, Phys. Rev. Lett. **71**, 3922 (1993).
8. G. Taylor, ALEPH Collaboration, *Proceedings of the Rencontres de Moriond*, 1994.
9. See, for example, J. L. Rosner, Phys. Rev. D **42**, 3732 (1990), and references therein.
10. C. R. Allton, *et al.*, Nucl. Phys. B **349**, 598 (1991); C. Alexandrou *et al.*, Phys. Lett. B **256**, 60 (1991).
11. D.Cinabro, *The Fermilab Meeting: DPF 1992*, eds. C. H. Albright, P. H. Kasper, R. Raja, and J. Yoh. (World Scientific, Singapore, 1993).
12. A. Ali, C. Greub, and T. Mannel, DESY-93-016 (1993).
13. R. Ammar, *et al.*, Cornell Report No. CLNS 93/1258, CLEO 93-21.