Radiative B Decays — an Experimental Overview

Edward H. Thorndike
University of Rochester
Rochester, NY 14627, USA
CLEO Collaboration

1 Introduction

I'll give an informal, personal review of the status and direction of experiments on radiative B decays — $b \to s\gamma$ and $b \to d\gamma$. Let's start by listing the observables.

- the branching fractions for exclusive $b \to s\gamma$ decays, eg. $B \to K^*(892)\gamma$
- the branching fraction for the inclusive decay $b \to s\gamma$ (actually $B \to X_s\gamma$)
- the CP asymmetry in the inclusive decay and in exclusive decays: $a_{CP} \equiv (\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma))/(\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma))$
- the photon energy spectrum in inclusive decays $B \to X_s\gamma$
- in principle, all the same observables for $b \to d\gamma$

(In multibody final states, such as $B \to K\pi\pi\gamma$, there are additional observables, constructed from the particle momenta. I do not consider these observables here.)

What can each of these observables teach us? The branching fractions for exclusive $b \to s\gamma$ decays are the easiest of the observables, and CLEO's observation [1] of $B \to K^*(892)\gamma$ back in 1993 was the first penguin seen. But while that exclusive decay was fine for the 'existence proof', the rates for exclusive decays are not useful for searching for New Physics, because form factors are poorly known.

In contrast, the branching fraction for the inclusive decay $B \to X_s\gamma$ (X_s a sum over all final states containing an s quark), is ideal for revealing or limiting New Physics. Forbidden at tree level by GIM, the process proceeds via penguin diagrams. In the Standard Model, the loop contains $W^{\pm}$ and t, both heavy, and so New Physics penguins with, eg., squarks and winos in the loop, would give comparable contributions. Further, as a result of very hard theoretical work, the rate for $b \to s\gamma$ can be reliably calculated, both within the Standard Model and with New Physics.

CP asymmetries are very small in the Standard Model, 1% or less. They can reach 10 - 20 % in some New Physics proposals. The asymmetry for the inclusive

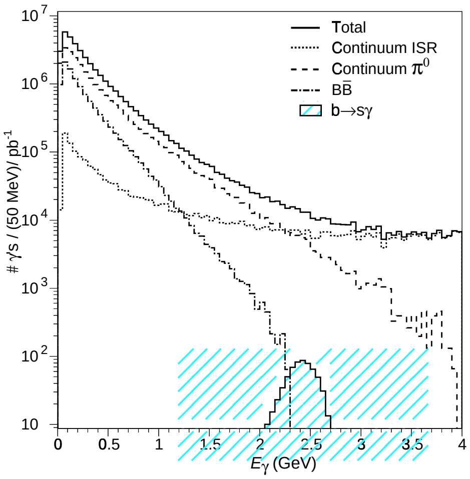

Figure 1: Photon energy spectrum expected from $b \to s\gamma$, other B decay processes, and from the continuum under the $\Upsilon(4S)$.

process is more reliably calculated than that for an exclusive process, but if a large CP asymmetry is found in either, that will be clear evidence of New Physics.

In contrast to branching fractions, the photon energy spectrum in $B \to X_s\gamma$ is very insensitive to New Physics. The basic process, $b \to s\gamma$, is a two-body decay, and hence gives a line in the b quark rest frame, broadened a bit by gluon bremsstrahlung. The photon energy spectrum for $B \to X_s\gamma$ thus depends on the mass and Fermi momentum of the b quark within the B meson. From the spectrum one can learn the B light cone shape function, useful for obtaining $|V_{ub}|$ from the endpoint lepton yield in $b \to u\ell\nu$. Also, the spectrum helps determine HQET OPE expansion parameters, needed for obtaining a precision value of $|V_{cb}|$ from the $b \to c\ell\nu$ inclusive rate.

The initial interest in $b \to d\gamma$ will be in determining $|V_{td}|$ from the rates for exclusive decays $B \to \rho\gamma$, $B \to \omega\gamma$. But here one must watch out for long distance effects and for additional CKM factors from c- and u-quark loops.

The experimental problems in studying radiative B decays are illustrated in Fig. 1. There one sees the photon energy spectrum expected from radiative B decays, from other B decay processes, and from the continuum under $\Upsilon(4S)$ – photons from initial state radiation and from decay of hadrons (dominantly from $\pi^0 \to \gamma\gamma$). While $b \to s\gamma$ can be distinguished from other B decay processes by measuring the yield above 2.2 GeV, the contribution from the continuum – two orders of magnitude larger than the signal – is a major challenge. Techniques for suppressing the continuum background are a MUST. With such techniques, and the power of full B reconstruction, exclusive decay modes stand out above the continuum background. For the inclusive process $B \to X_s\gamma$, it is essential to measure and subtract the continuum background, by running below the $\Upsilon(4S)$.

While $b \to s\gamma$ can be separated from other B decay processes by considering only the yield above 2.2 GeV, that approach is inadequate for the precision of today's $b \to s\gamma$ inclusive branching fraction measurements, and also for obtaining a useful photon spectrum. For these, one must go down to at least 2.0 GeV, understanding and removing the substantial yield from other B decay processes between 2.0 and 2.2 GeV.

In subsequent sections I discuss branching fractions for exclusive $b \to s\gamma$ decays; the branching fraction for the inclusive $b \to s\gamma$ decay; CP asymmetries; the photon energy spectrum; $b \to d\gamma$ decays. In Section 7, I summarize and give conclusions.

2 Branching Fractions for Exclusive $b \to s\gamma$ Decays

CLEO's 1993 observation [1] of eight $B^0 \to K^{*0}\gamma$ events and five $B^+ \to K^{*+}\gamma$ events was based on 1.4 fb^{-1} of 4S luminosity. With an order of magnitude more luminosity, CLEO [2], BaBar [3], and Belle [4] now all have 10-20% measurements of both charged and neutral decays. Results are given in Table 1. Agreement among measurements is good. Branching fractions for charged and neutral decays agree well.

	$B^0 \to K^{*0}\gamma$	$B^+ \to K^{*+}\gamma$
CLEO '93[1]	$4.0 \pm 1.7 \pm 0.8$	$5.7 \pm 3.1 \pm 1.1$
CLEO '00[2]	$4.55 \pm 0.70 \pm 0.34$	$3.76 \pm 0.86 \pm 0.28$
BaBar '02[3]	$4.23 \pm 0.40 \pm 0.22$	$3.83 \pm 0.62 \pm 0.22$
Belle(prelim)[4]	$4.08 \pm 0.34 \pm 0.26$	$4.92 \pm 0.57 \pm 0.38$
Average	$4.21 \pm 0.25 \pm 0.26$	$4.32 \pm 0.38 \pm 0.30$

Table 1: $B \to K^*\gamma$ branching fractions (10^{-5})

In addition to $K^*(892)$, CLEO [2] and Belle [5, 4] have observed $B \to K_2^*(1430)\gamma$, with branching fractions of $1.66 \pm 0.56 \pm 0.13 \times 10^{-5}$ and $1.50 \pm 0.56 \pm 0.12 \times 10^{-5}$, in good agreement and of comparable accuracy. Belle has also [5] observed $B^+ \to K^+\pi^-\pi^+\gamma$ ($2.4 \pm 0.5 \pm 0.3 \times 10^{-5}$), and deduced substructures $B^+ \to K^{*0}\pi^+\gamma$ ($2.0 \pm 0.65 \pm 0.2 \times 10^{-5}$), $B^+ \to K^+\rho^0\gamma$ ($1.0 \pm 0.5 \pm 0.25 \times 10^{-5}$). There is no evidence of a nonresonant component, with upper limit $\mathcal{B}(B^+ \to K^+\pi^-\pi^+\gamma)NR < 0.9 \times 10^{-5}$.

3 Branching Fraction for Inclusive $b \to s\gamma$ Decay

For a study of the inclusive process $B \to X_s\gamma$, lacking the discrimination that comes from full B reconstruction, continuum suppression is very important. In the 'first observation of inclusive' analysis, CLEO [6] used two approaches. The first was to choose several (eight) "shape variables", each with some power to discriminate between $b \to s\gamma$ signal and continuum background (either ISR or γ's from hadrons), and combine them into a single variable using a neural net. (This was CLEO's first use of a neural net, and I was initially very negative about the approach. Its success made me a convert.)

The second approach, dubbed "pseudoreconstruction", at first sight appears just like full reconstruction. Events containing a high energy photon are searched for combinations of particles that satisfy $B \to X_s\gamma$. For X_s, we try one kaon ($K^\pm$ or $K^0_s \to \pi^+\pi^-$), and 1 to 4 pions (of which at most one may be a π^0). The measure of "satisfying $B \to X_s\gamma$" is closeness of M and E to the proper values, as given by $\chi^2_B \equiv (E - E_{beam})^2/\sigma^2_E + (M - M_B)^2/\sigma^2_M$. A $\chi^2_B < 20$ is deemed an acceptible pseudoreconstruction. What makes this "pseudoreconstruction", rather than full reconstruction, is our lack of concern as to whether we "have all the pieces right." True $B \to X_s\gamma$ events are much more likely to pseudoreconstruct than are continuum background events, and this remains true with one or two mis-chosen pions. Further, $\cos\theta_{tt}$, the cosine of the angle between the thrust axis of the particles that pseudoreconstruct and the thrust axis of the rest of the event, is strongly peaked for the jet-like continuum events, but isotropic for signal events. (I was initially *very* dubious about this technique, fearing that it would be very sensitive to the choice of model for $B \to X_s\gamma$, but this proved not to be the case.)

In CLEO's 1995 publication [6], we performed two separate analyses, one using shape variables with a neural net, the other using pseudoreconstruction. We then averaged the two branching fractions so obtained. In CLEO's latest publication [7], we did a fully integrated analysis. For all events with a high energy photon, we obtained a combined shape variable parameter from the neural net (8 inputs, 1 output). For the subset of events that had a pseudoreconstruction with $\chi^2_B < 20$, we obtained two additional discriminating parameters, χ^2_B and $|\cos\theta_{tt}|$. For the subset that contained a lepton (e or μ), we used the energy of the lepton and the angle between lepton and high energy photon as additional discriminating parameters. Armed with these discriminating parameters (sometimes only 1, sometimes 3, sometimes 5), we determined the probability that an event with a high energy photon was $b \to s\gamma$ rather than continuum background, and assigned it a weight according to that probability.

The distribution in weights so obtained *vs.* photon energy is shown in Fig. 2. The upper panel shows On-resonance and scaled Off-resonance data. The success of the continuum suppression is apparent, in that the continuum background is now a mere factor of 4 larger than the signal, rather than the two orders of magnitude in Fig. 1.

The lower panel in Fig. 2 shows the yield in weights *vs.* photon energy after the continuum background has been subtracted, using Off-resonance data. There one sees clear evidence for $b \to s\gamma$ in the 2.2 - 2.6 GeV range, and also the increasing importance of the other B decay processes below 2.2 GeV.

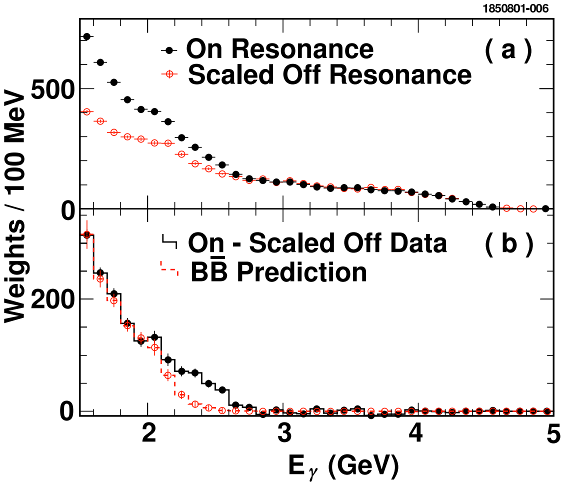

Figure 2: CLEO's [7] photon energy spectrum: (a) On resonance and scaled Off resonance; (b) On minus scaled Off, and prediction for $B\overline{B}$ processes other than $b \to s\gamma$ and $b \to d\gamma$.

In its first measurement [6], CLEO placed a cut on photon energy at 2.2 GeV, using theoretical models to account for the fraction of $b \to s\gamma$ rate below 2.2 GeV, and accepting a systematic error for this model dependence. In the recent measurement [7], by making a strenuous effort to understand background from B decay processes, CLEO lowered its photon energy cut to 2.0 GeV, thereby accepting ~90% of the rate, and reducing the systematic error from model dependence. To be competitive, future measurements will have to accept photons down to at least 2.0 GeV.

In addition to CLEO's two published measurements, there have been measurements by ALEPH [8] and Belle [9]. All four results are shown in Fig. 3. Difficult as the measurement is at the $\Upsilon(4S)$, it seems to me to be near impossible at the Z^0, and ALEPH's efforts must be characterized as heroic. Their result is consistent with the $\Upsilon(4S)$ measurements, but their error is twice that of the recent CLEO measurement. The Belle measurement, based on only 6 fb^{-1}, and with the now no-longer-acceptible 2.2 GeV photon energy cut, should be viewed as a warmup exercise.

The Standard Model theoretical expectation, as given most recently by Buras *et al.* [10], is also shown in Fig. 3. It should be mentioned that there have recently been questions raised [11] as to the appropriate value of m_c/m_b to use in the calculation. Buras *et al.* have used $m_c/m_b = m_c^{\overline{MS}}(\mu)/m_b^{1S} = 0.22$, while earlier work used $m_c/m_b = m_c^{pole}/m_b^{pole} = 0.29$, and obtained a branching fraction lower by 0.25×10^{-4}. My impression is that the theoretical community is not of a single mind as to the appropriate value of m_c/m_b to use, and so the SM theory value might come down by 10%. In any case, experiment and SM theory are in fine agreement.

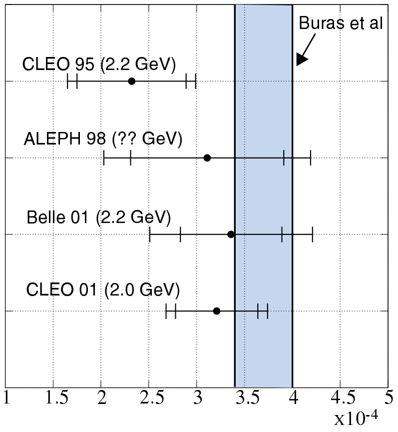

Figure 3: Measurements of the branching fraction for the inclusive process $b \to s\gamma$, by CLEO in 1995 [6], ALEPH [8], Belle [9], and CLEO in 2001 [7]. The Standard Model prediction of Buras *et al.* [10] is also shown .

4 CP Asymmetries

There have been measurements of the CP asymmetry in $B \to K^*(892)\gamma$ by CLEO [2], BaBar [3], and Belle [4], and a measurement of the CP asymmetry in $B \to X_s\gamma$ plus $B \to X_d\gamma$ inclusive by CLEO [12]. The *sign convention*, to my knowledge so far used in all measurements of B CP asymmetries, is b quark minus $\overline{b}$ quark (B^- minus B^+, $\overline{B}^0$ minus B^0). For the cases at hand, that means $a_{CP} \equiv (\Gamma(b \to s\gamma) - \Gamma(\overline{b} \to \overline{s}\gamma)/(\Gamma(b \to s\gamma) + \Gamma(\overline{b} \to \overline{s}\gamma)$, and similarly with the exclusive decays.

Results for the exclusive decays are shown in Table 2. CLEO's inclusive result, a combination of $b \to s\gamma$ and $b \to d\gamma$, is $(0.965a(b \to s\gamma) + 0.02a(b \to d\gamma)) = -0.079 \pm 0.108 \pm 0.022$. All these results, including the average of the three exclusive measurements, are consistent with zero, the Standard Model expectation.

	$a_{CP}(B \to K^*\gamma)$
CLEO '00[2]	+0.08 ± 0.13 ± 0.03
BaBar '02[3]	–0.044 ± 0.076 ± 0.012
Belle(prelim)[4]	+0.032 ± 0.069 ± 0.020
Average	+0.009 ± 0.048 ± 0.018

Table 2: $B \to K^*\gamma$ CP asymmetries

5 The Photon Energy Spectrum

As can be seen from Fig. 2, in order to obtain the photon energy spectrum for the inclusive $B \to X_s\gamma$ process, to photon energies of 2.0 GeV and below, one must understand backgrounds from B decay processes. Unlike those from continuum processes, these cannot be directly measured. CLEO [7] has proceeded as follows.

The dominant component of the background, accounting for 90%, is photons from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ that have escaped the π^0 and η vetoes. These backgrounds are determined by measuring π^0 (η) yields, treating the π^0 (η) as if it were a γ, applying all cuts and determining the event weight, just as in the $b \to s\gamma$ analysis. Monte Carlo is then used to determine the π^0 (η) veto inefficiency.

Photons from other sources are small by comparison to those from π^0 and η, and with modest efforts to have the Monte Carlo event generator accurate, one can (CLEO does) trust the Monte Carlo. Processes considered include $\omega \to \pi^0\gamma$, $\eta' \to \rho^0\gamma$, radiative ψ decay, $\rho \to \pi\gamma$, $a_1 \to \pi\gamma$, final state radiation. In addition to the dominant $b \to c$ decays, $b \to u$ processes and $b \to sg$ processes were considered.

Neutral hadrons, in particular antineutrons and K-longs, by interacting in the calorimeter, cause high energy clusters, above 1.5 GeV. Their contribution to the B decay background was determined by fitting the lateral distribution of the shower (E9/E25, for those familiar with this notation).

CLEO's observed laboratory frame photon energy spectrum for On-resonance minus scaled Off-resonance minus B backgrounds (the $b \to s\gamma$ plus $b \to d\gamma$ signal) is shown in Fig. 4.

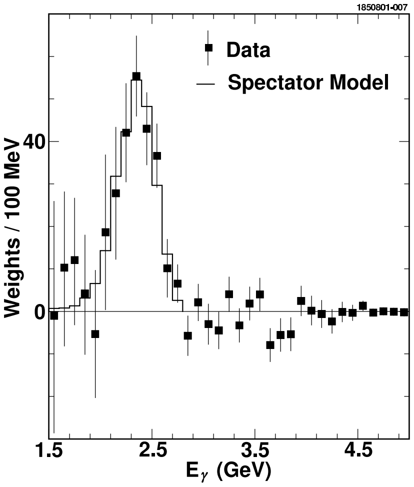

Figure 4: CLEO's [7] observed laboratory frame photon energy spectrum for On minus scaled Off minus B backgrounds, the putative $b \to s\gamma$ plus $b \to d\gamma$ signal.

From the measured spectrum CLEO has obtained first and second moments, in the B rest frame, for $E_\gamma^{restframe} > 2.0$ GeV, finding

$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011$ GeV, and

$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.0226 \pm 0.0066 \pm 0.0020 \;\; \mathrm{GeV}^2$.

HQET plus OPE allows inclusive observables to be written as double expansions, in powers of α_s and $1/M_B$. The parameter $\overline{\Lambda}$ enters at order $1/M_B$, λ_1 and λ_2 enter at $1/M_B^2$, and six more parameters, ρ_1, ρ_2 and $\mathcal{T}_1 - \mathcal{T}_4$ at $1/M_B^3$. Using expressions in the $\overline{MS}$ renormalization scheme, to order $1/M_B^3$ and order $\alpha_s^2\beta_0$, CLEO obtains $\overline{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV from the first moment. The expression for the second moment converges slowly in $1/M_B$, and CLEO did not extract parameters from it.

To lowest order in Λ_{QCD}/M_B, the hadron level $B \to X_s\gamma$ photon energy spectrum is given by a convolution of the parton level $b \to s\gamma$ photon energy spectrum with the $b \to lightquark$ light cone shape function of the B meson [13]. Again to lowest order in Λ_{QCD}/M_B, the same shape function describes $B \to X_u\ell\nu$, i.e., the hadron level $B \to X_u\ell\nu$ lepton energy spectrum is given by a convolution of the parton level $b \to u\ell\nu$ lepton energy spectrum with the same shape function [14]. CLEO has thus used their measured $B \to X_s\gamma$ photon energy spectrum to determine (to some accuracy) the light cone shape function, and from this predicted the fraction of the $B \to X_u\ell\nu$ lepton energy spectrum that lies above some cut near the endpoint. This, combined with a measurement of the $B \to X_u\ell\nu$ yield above that cut gives the total $B \to X_u\ell\nu$ yield, and that in turn gives $|V_{ub}|$ [15]. Corrections enter at next order in Λ_{QCD}/M_B, and these are currently the subject of active investigation [16, 17, 18].

6 $b \to d\gamma$

So far there is nothing on inclusive $b \to d\gamma$. On exclusive $b \to d\gamma$, there are upper limits on $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$. From isospin and SU(3) considerations, one expects $\mathcal{B}(B^+ \to \rho^+\gamma) = 2 \times \mathcal{B}(B^0 \to \rho^0\gamma) = 2 \times \mathcal{B}(B^0 \to \omega\gamma)$. Upper limits, from CLEO [2], Belle [19], and BaBar [20], are given in Table 3. The BaBar limit is by far the best. Since CLEO's first observation of $B \to K^*(892)\gamma$ was based on 1.4 fb^{-1}, and since $B^+ \to \rho^+\gamma$ is expected to be 20 times smaller than $B \to K^*\gamma$, one can anticipate an observation by BaBar and/or Belle in the near future.

From their limit, BaBar [20] obtains $[(1-\rho)^2 + \eta^2]^{1/2} < 1.6$. This limit, while not an improvement in the limit on $|V_{td}|$ over that obtained from the limit on $B_s - \overline{B}_s$ mixing, provides nice confirmation. But, I should repeat the warning that, as accuracy improves, one needs to watch out for long distance effects, and for contributions from c- and u-quark loops, carrying other CKM factors.

	B pairs (Million)	Branching Fraction Upper Limits (10^{-6})		
		$\mathcal{B}(B^+ \to \rho^+\gamma)$	$2 \times \mathcal{B}(B^0 \to \rho^0\gamma)$	$2 \times \mathcal{B}(B^0 \to \omega\gamma)$
CLEO '00[2]	9.7	13	34	18
Belle '01[19]	11	10	21	—
BaBar(prelim)[20]	63	2.8	3.0	—

Table 3: Upper limits on $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$ branching fractions

7 Summary and Conclusions

b → sγ Exclusive Branching Fractions
These are no longer of great fundamental interest. However, by identifying a larger fraction of the makeup of $B \to X_s\gamma$ decays, one will reduce some systematic errors on the branching fraction for the inclusive process $b \to s\gamma$. Belle has made progress on this front. Perhaps more important, their observation of $B \to K\pi\pi\gamma$ lays the groundwork for looking at correlations among the momentum vectors of the decay products, providing a way to "measure" the helicity of the photon.

b → sγ Inclusive Branching Fraction
Experiment agrees well with the predictions of the Standard Model, and places strong restrictions on New Physics. But there is really only one good measurement, CLEO's. BaBar and Belle need to get to work on this one. They will need to accept photons down to 2.0 GeV or lower – 2.2 GeV is no longer good enough. They will also need to take sufficient data at beam energies below the $\Upsilon(4S)$, as the continuum subtraction *must* be done with *data*.

CP Asymmetries
So far there is no hint of a non-zero value. Present limits place weak restrictions on some New Physics models. There is *plenty* of room for improvements, with BaBar and Belle's large data samples, before systematic error limitations set in. Asymmetry measurements for the *inclusive* decay are desirable (BaBar, Belle?).

Photon Energy Spectrum
CLEO's photon energy spectrum has helped provide a precise determination of $|V_{cb}|$ from the inclusive semileptonic decay branching fraction, and (more important) a good determination of $|V_{ub}|$ from the lepton endpoint yield in $b \to u\ell\nu$, with *quantifiable errors.* Measurements of the spectrum will be key for future determinations of $|V_{ub}|$ from inclusive $b \to u\ell\nu$. Improved measurements of the spectrum are highly desirable.

b → dγ Searches
So far there is nothing on inclusives, and only upper limits on exclusives. These limits are not yet an improvement in the limit on $|V_{td}|$ over that provided by the limit on $B_s - \overline{B}_s$ mixing. But with data samples of 100 fb^{-1}, BaBar and Belle should see

$B \to \rho\gamma$. Stay tuned.

I have benefitted from interactions with my many CLEO collegues. Particular thanks are due to Dan Cronin-Hennessy for his assistance in preparing this talk and writeup.

References

[1] R. Ammar *et al.* (CLEO), Phys. Rev. Lett. **71**, 674 (1993). $K^*\gamma$ discovery

[2] T. E. Coan *et al.* (CLEO), Phys. Rev. Lett. **84**, 5283 (2000).

[3] B. Aubert *et al.* (BaBar), Phys. Rev. Lett **88**, 101805 (2002).

[4] A. Ishikawa (Belle), XXXVIIth Rencontres de Moriond, March 10, 2002.

[5] S. Nishida *et al.* (Belle), hep-ex/0205025.

[6] M. S. Alam *et al.* (CLEO), Phys. Rev. Lett. **74**, 2885 (1995).

[7] S. Chen *et al.* (CLEO), Phys. Rev. Lett. **87**, 251807 (2001).

[8] R. Barate *et al.* (ALEPH), Phys. Lett. **B 429**, 169 (1998).

[9] K. Abe *et al.* (Belle) Phys. Lett. B **511**, 151 (2001).

[10] A. Buras, A. Czarnecki, M. Misiak, and J. Urban, hep-ph/0203135.

[11] P. Gambino and M. Misiak, hep-ph/0104034.

[12] T. E. Coan *et al.* (CLEO), Phys. Rev. Lett. **86**, 5661 (2001).

[13] A. L. Kagan and M. Neubert, Eur. Phys. J. C **7**, 5 (1999).

[14] F. De Fazio and M.Neubert, JHEP **06**, 017 (1999).

[15] A. Bornheim *et al.* (CLEO), Phys. Rev. Lett. **88**, 231803 (2002).

[16] C. Bauer, M. Luke, and T. Mannel, hep-ph/0205150.

[17] A.Leibovich, Z. Ligeti, and M. Wise, hep-ph/0205148.

[18] M. Neubert, private communication.

[19] Y. Ushiroda (Belle), hep-ex/0104045.

[20] H. Tanaka (BaBar), XXXVIIth Rencontres de Moriond, March 2002.