SLAC-PUB-10222
October 2003

Studies of Radiative Penguin Decays at *BABAR*.

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The electromagnetic radiative "penguin" decays $b \to s\gamma$, $b \to d\gamma$ are sensitive to physics beyond the Standard Model. We present recent studies made with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring.

1. Introduction

The radiative $b \to s\gamma$, $b \to d\gamma$ transitions occur by the electromagetic "penguin " loop diagram in the Standard Model. These decays are sensitive to the CKM matrix elements V_{td} and V_{ts} and to new virtual high mass particles such as a charged Higgs appearing in the loop causing deviations in the rate [1] and possibly introducing a new CP-violating phase. The Standard Model predictions [2] for the leading exclusive decays $B \to K^*\gamma$ ($b \to s\gamma$) and the as yet unobserved $B \to \rho\gamma$ ($b \to d\gamma$) decay suffer from large uncertainties compromising the sensitivity to both CKM matrix elements and new physics. However in the ratio $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$ some of these uncertainties cancel and a competitive measurement of V_{ts}/V_{td} is possible. We present measurements of the exclusive decay, $\mathcal{B}(B \to K^*\gamma)$ [5], the CP-violating charge asymmetry, $A_{cp}(B \to K^*\gamma)$ and results of a search for $B \to \rho\gamma$ and $B \to \omega\gamma$ [6].

The predictions for the inclusive rates [3] are more precise as quark-hadron duality is believed to be a good approximation so that $B \to X_s\gamma = b \to s\gamma$. We present two measurements of $\mathcal{B}(B \to X_s\gamma)$ using both a semi-inclusive [8] and a fully inclusive technique [7]. The photon energy spectrum from the $B \to X_s\gamma$ measured with the semi-inclusive technique is also used to extract values for the HQET parameters $\overline{\lambda}$ and λ_1.

The data were collected with the *BABAR* detector [9] at the PEP-II asymmetric $e^+(3.1\,\mathrm{GeV})$ – $e^-(9\,\mathrm{GeV})$ storage ring. We use Monte Carlo simulations of the *BABAR* detector based on GEANT 4.0 [10] to optimize our selection criteria,to determine signal efficiencies, and in some cases to estimate backgrounds. These simulations take account of varying detector conditions and beam backgrounds.

The event selection for both the exclusive and inclusive analysis begins by requiring a high-energy radiative photon candidate. A photon candidate is defined as a localized energy maximum in the calorimeter. It must be isolated by from any other photon candidate or track and have a lateral energy profile consistent with a photon shower. We veto photons from a $\pi^0(\eta)$.

2. $\mathcal{B}(B \to K^*\gamma)$ and $A_{cp}(B \to K^*\gamma)$

The details of the event selection are described in [5]. The K^* is reconstructed from K^+, K^0_S, π^- and π^0 candidates through the four modes $K^{*0} \to K^+\pi^-$, $K^0_S\pi^0$ and $K^{*+} \to K^+\pi^0$, $K^0_S\pi^+$ and combined with a high energy photon to form a B meson candidate. The dominant background is from continuum production from continuum $q\overline{q}$ production, where q can be a u,d,s or c quark, with the high-energy photon originating from initial-state radiation or from π^0 and η decays. The continuum background is produced above threshold and so is lorentz boosted to a "jet-like" topology in contrast to the signal which is produced isotropically. Event topology variables are used to suppress the background. Finally we construct from the B candidates two independent variables ΔE and m_{ES} used to extract the signal yield. We define $\Delta E = E^*_B - E_{beam}$ and $m_{\mathrm{ES}} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$ where E^*_B and p^*_B are the energy and momentum of the reconstructed

Work supported in part by the Department of Energycontract DE-AC03-76SF00515.
Presented at the 31st International Conference on High EnergyPhysics (ICHEP 2002),
7/24/2002 - 7/31/2002, Amsterdam, The Netherlands

B, computed in the center of mass frame of the e^+e^- and E_{beam} is the precisely known beam energy. These variables exploit the fact that the beam energy is equal to the energy of the produced B but more accurately known than the detector reconstructed energy measurement.

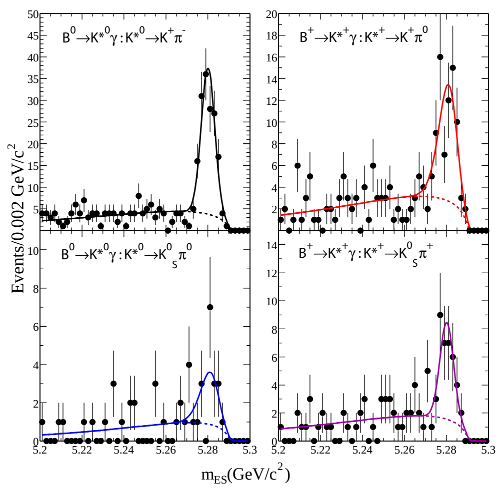

Figure 1. m_{ES} for the $B \to K^*\gamma$ candidates. The solid and dashed curves show respectively the fitted signal-plus-background and the background alone.

The analysis is performed on 22.7 million $B\overline{B}$ pairs. Figure 1 shows the m_{ES} distributions for the four decay modes. The signal is extracted from a maximum likelihood fit. The background is modeled by a threshold function [4]. The measured branching fractions and $CP-violating$ charge asymmetries are summarised in Table 1. The branching fractions are roughly a factor of two lower than the next-to-leading order Standard Model predictions and in agreement with previous measurements [11].

3. Search for $B \to \rho\gamma$ and $B \to \omega\gamma$

The analysis, described in detail in reference [6], is considerably more challenging than the $B \to K^*\gamma$ measurements. The signal rate is expected to be of order 50 times smaller than $B \to K^*\gamma$ ($\mathcal{B}[B^+ \to \rho^+\gamma] = (0.9-1.5)\times 10^{-6}$ [2]) with significantly higher continuum backgrounds and additional backgrounds from $b \to s\gamma$ processes. The decay $B \to \rho\gamma$ is reconstructed with $\rho^0 \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$, while $B^0 \to \omega\gamma$ is reconstructed with $\omega \to \pi^+\pi^-\pi^0$. Continuum backgrounds are suppressed with event topology variables, vertexing and flavor tagging. The variables are combined into a neural net, trained on Monte Carlo, and validated with several data control samples. A dedicated pion selector has been developed for this analysis optimized to reject the kaon fake background from $b \to s\gamma$ processes. The analysis was performed “blind” on 84.4 million BB pairs. Figure 2 shows the ΔE,m_{ES} dsitributions for the data after all cuts. The signal yield is estimated from a multi-dimensional maximum likelihood fit. The results are given in table 2. No signal is observed and we set 90 % confidence limits.

Table 1
The measured branching fraction $\mathcal{B}(B \to K^*\gamma)$ and A_{CP} for each of the decay modes.

Mode	$\mathcal{B}(B \to K^*\gamma)$ -±stat. ± sys. $\times 10^{-5}$	A_{CP}(signal) (±stat. ± sys.)
$K^+\pi^-$	$4.24 \pm 0.41 \pm 0.22$	$-0.049 \pm 0.094 \pm 0.012$
$K^0_S\pi^0$	$4.10 \pm 1.71 \pm 0.42$	
$K^0_S\pi^+$	$3.01 \pm 0.76 \pm 0.21$	$-0.190 \pm 0.210 \pm 0.012$
$K^+\pi^0$	$5.52 \pm 1.07 \pm 0.38$	$0.044 \pm 0.155 \pm 0.021$

Table 2
The signal yields and errors obtained from the signal extraction fit, and the 90 % Confidence Limit.

Mode	Yield (Events)	90% C.L. $\times 10^{-6}$
$B^0 \to \rho^0\gamma$	4.8 ± 5.2	1.4
$B^+ \to \rho^+\gamma$	6.2 ± 5.5	2.3
$B^0 \to \omega\gamma$	0.1 ± 2.3	1.9

The limits for the individual modes can be combined assuming isospin symetry to give $\mathcal{B}(B \to \rho\gamma) < 1.9 \times 10^{-6}$ at 90 % C.L.. In addition this limit can be compared to the measured $\mathcal{B}(B \to$

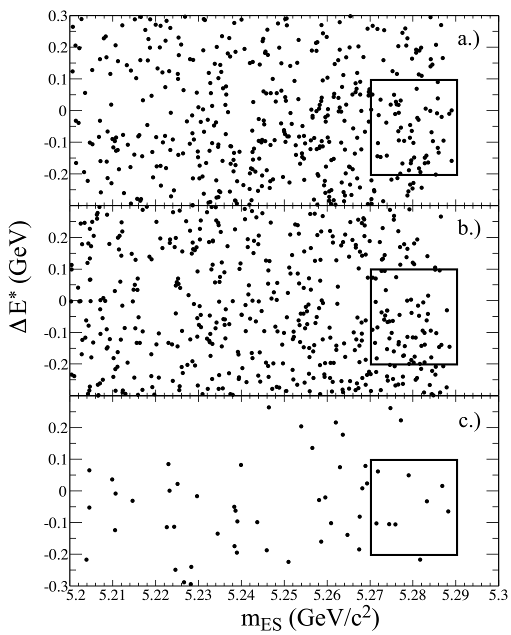

Figure 2. ΔE vs. $m_{\rm ES}$ for a.) $B^0 \to \rho^0\gamma$, b.) $B^+ \to \rho^+\gamma$ and c.) $B^0 \to \omega\gamma$ candidates. The boxes indicate the blinded region.

$K^*\gamma$) above to give $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma) < 0.047$ at 90 % C.L.

4. Measurement of $\mathcal{B}(B \to X_s\gamma)$ using a "semi-inclusive" technique

The fragmentation of the s-quark in the $b \to s\gamma$ transistion results in final states, X_s, containing kaons and pions proceeding through a complicated resonance structure. One technique to measure the inclusive rate is to attempt to reconstruct all possible X_s states. However, we are not sensitive to states containing a K^0_L while the prohibitively large combinatorics from high multiplicity modes and modes with $K^0_S \to \pi^0\pi^0$ limit the fraction of accessible modes to approximately 50 %. We recomstruct the $X_s$in the $K^+\pi^-$, $K^0_S\pi^0$, $K^+\pi^-\pi^0$, $K^0_S\pi^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, $K^0_S\pi^+\pi^-\pi^0$ $K^+\pi^0$, $K^0_S\pi^+$, $K^+\pi^-\pi^+$, $K^0_S\pi^+\pi^0$, $K^+\pi^-\pi^+\pi^0$, $K^0_S\pi^+\pi^-\pi^+$ modes in 22.7 million $B\overline{B}$ pairs. The basic reconstruction technique is

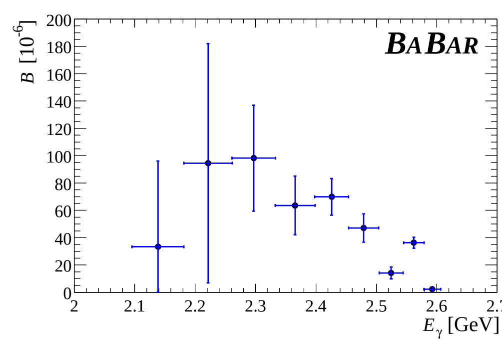

Figure 3. Branching fraction as a function of E_γ. The errors are purely statistical.

essentially the same as for the $B \to K^*\gamma$ analysis described above, except that there are additional backgrounds from $B\overline{B}$ decays and cross-feed between the modes. The analysis is described in detail in reference [8]. The $X_s$is divided into several m_{X_s}(dual to E^*_γ) bins and the signal yield extracted from a fit to $m_{\rm ES}$ for each of these bins. Figures 3 and 4 show the resultant $E^*_\gamma$and

m_{X_s}spectra respectively. The first moment of the E^*_γ spectra can be used to extract a measurement of the HQET parameter $\overline{\Lambda}(\alpha_s^2, 1/M_B^3)$ [13]. We find $< E_\gamma > |_{E_\gamma > 2.094 \text{ GeV}} = 2.35 \pm 0.04$ $(stat) \pm 0.04$ $(syst)$ GeV from which we derive $\overline{\Lambda} = 0.37 \pm 0.09$ $(stat) \pm 0.07$ $(syst) \pm 0.10$ $(model)$ GeV. The parameter $\overline{\Lambda}$ then provides information to help constrain the parameters in the fit to the m_{X_s}spectrum shown in fig 4 used to extract $\mathcal{B}(b \to s\gamma) = 4.3 \pm 0.5$ $(stat) \pm 0.8$ $(syst) \pm 1.3$ $(model) \cdot 10^{-4}$ and $\lambda_1 = -0.24^{+0.03}_{-0.04}$ $(stat) \pm 0.02$ $(syst)^{+0.15}_{-0.21}$ $(model)$ $[\text{GeV}/c^2]^2$. consistent with standard model predictions [3] and previous measurements [12]. Note that this technique gives large systematic errors due to uncertainties in the fragmentation model and resonance structure of the X_s.

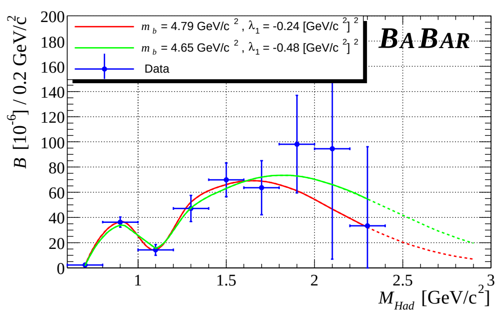

Figure 4. Superposition of the predicted spectrum for $m_b = 4.79$ GeV/c^2 and $m_b = 4.65$ GeV/c^2 on the observed hadronic mass spectrum.

5. Measurement of $\mathcal{B}(B \to X_s\gamma)$ using a "Fully-inclusive" technique

The semi-inclusive measurement of $\mathcal{B}(B \to X_s\gamma)$ offers a powerful technique to suppress backgrounds but the sensitivity to the details of the $X_s$fragmentation incurs large systematic uncertainties. A fully inclusive measurement sensitive to 100 % of the decay is highly desirable but complicated by the large backgrounds as shown in Figure 5. Here for pedagogical purposes we have selected a high energy photon using standard quality cuts from a sample of signal and continuum and $B\overline{B}$ Monte Carlo. To reduce

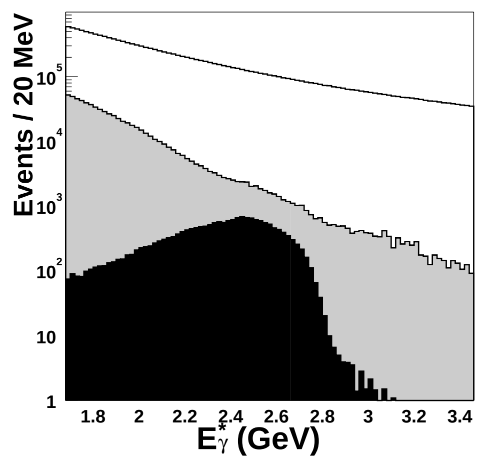

Figure 5. The energy distribution, in the $\Upsilon(4s)$ center of mass, of simulated photon candidates, after "photon quality" cuts. Shown are $B \to X_s\gamma$ signal (dark shading), $B\overline{B}$ background (grey shading) and continuum background (unshaded), all normalized to 54.6 Million BB.

these backgrounds while remaining insensitive to the $X_s$fragmentation we employ a lepton tagging technique. The analysis is described in detail in reference [7]. The tagging reduces the continuum background by 3 orders of magnitude but at a cost of low efficiency ($\approx 0.5\%$). Also a significant $B\overline{B}$ background remains which must be estimated by Monte Carlo. Figure 6 shows the E^*_γ spectrum for data with the estimated background. We find $\mathcal{B}(B \to X_s\gamma) = 3.88 \pm 0.36(stat.) \pm 0.37(syst.) \pm^{0.43}_{0.23} (model) \times 10^{-4}$. The dominant systematic uncertainty is from the modelling of the $B\overline{B}$ background which has been compared to data control samples. The measurement is consistent with both Standard Model expectations [3] and previous measurments [12]

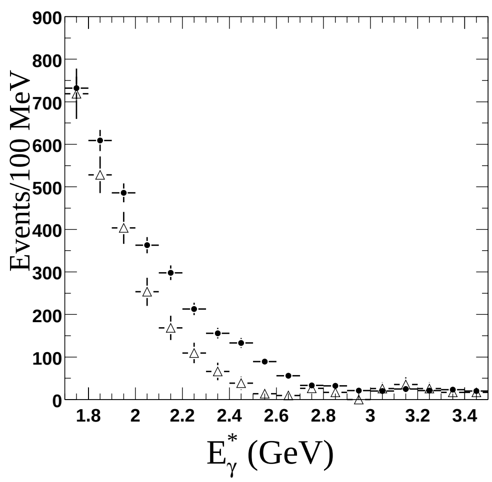

Figure 6. The E_γ^*distribution of on-resonance data (solid points) compared to background expectation. All errors are statistical only.

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