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Measurement of the Direct CP Asymmetry in $b \to s\gamma$ Decays

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We describe a measurement of the direct *CP* asymmetry between inclusive $b \to s\gamma$ and $\overline{b} \to \overline{s}\gamma$ decays. This asymmetry is expected to be less than 0.01 in the standard model, but could be enhanced up to about 0.10 by new physics contributions. We use a sample of 89×10^6 $B\overline{B}$ pairs recorded with the

BABAR detector at SLAC PEP-II, from which we reconstruct a set of 12 exclusive $b \to s\gamma$ final states containing one charged or neutral kaon and one to three pions. We measure an asymmetry of $A_{CP}(b \to s\gamma) = 0.025 \pm 0.050(\text{stat}) \pm 0.015(\text{syst})$, corresponding to an allowed range of $-0.06 < A_{CP}(b \to s\gamma) < +0.11$ at 90% confidence level.

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The inclusive decay $b \to s\gamma$ is a flavor-changing neutral current process described by a radiative penguin loop diagram. The world average branching fraction is $(3.3 \pm 0.4) \times 10^{-4}$ [1] in good agreement with recent theoretical predictions [2]. Earlier experimental values of the branching fraction have been used to constrain new physics beyond the standard model [3]. A measurement of the direct *CP* asymmetry between $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$ decays provides an independent and significant test of these predictions. In the standard model the dominant loop contribution contains a top quark, with other contributions being suppressed by Cabibbo-Kobayashi-Maskawa (CKM) factors and the Glashow-Iliopoulos-Maiani mechanism. The lack of interference between comparable amplitude contributions leads to a rather small predicted asymmetry [4]:

$$A_{CP}^{TH} = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)} = 0.0044^{+0.0024}_{-0.0014}, \quad (1)$$

which has little sensitivity to the photon energy cutoff or to the distribution of hadronic final states. The dominant errors are due to the uncertainty of the charm quark mass and the choice of the perturbative scale. The inclusion of contributions to the loop beyond the standard model can increase the predicted asymmetry up to about 0.10 [4].

There is a previous measurement of direct *CP* asymmetry [5] in a sum of $b \to s\gamma$ and $b \to d\gamma$ decays. In the standard model, the total of the $b \to s\gamma$ and $b \to d\gamma$ asymmetries is exactly zero in the U-spin symmetry limit, $m_d = m_s$, as a consequence of CKM unitarity [6]. The measurement in Ref. [5] gives $-0.27 < 0.965 \times A_{CP}(b \to s\gamma) + 0.02 \times A_{CP}(b \to d\gamma) < 0.10$.

We use a sample of $(88.9 \pm 1.0) \times 10^6$ $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the SLAC PEP-II asymmetric e^+e^- collider. A detailed description of the detector can be found elsewhere [7]. For this analysis the most important detector elements are the 40-layer drift chamber, situated in a 1.5 T solenoidal magnetic field, which measures charged particle momenta, the CsI(Tl) electromagnetic calorimeter, which measures the energies of the photons, and the detector of internally reflected Cherenkov light (DIRC), which is used to identify charged kaons.

We reconstruct $b \to s\gamma$ decays as the sum of 12 exclusive final states:

$$B^- \to K^-\pi^0\gamma, K^-\pi^+\pi^-\gamma, K^-\pi^0\pi^0\gamma, K^-\pi^+\pi^-\pi^0\gamma,$$
$$\bar{B}^0 \to K^-\pi^+\gamma, K^-\pi^+\pi^0\gamma, K^-\pi^+\pi^0\pi^0\gamma, K^-\pi^+\pi^-\pi^+\gamma,$$
$$B^- \to K_S^0\pi^-\gamma, K_S^0\pi^-\pi^0\gamma, K_S^0\pi^-\pi^0\pi^0\gamma, K_S^0\pi^-\pi^+\pi^-\gamma,$$

and measure the yield asymmetry with respect to their charge conjugate decays $\bar{b} \to \bar{s}\gamma$. The identification of charged kaons removes $b \to d\gamma$ decays. We do not use $\bar{B}^0$ decays to final states with K_S^0 to determine the direct *CP* asymmetry, since these are not flavor specific, but we study them to understand systematic effects.

The high energy photon is detected from an isolated energy cluster in the calorimeter, with shape consistent with a single photon, and energy $E_\gamma^* > 1.8$ GeV in the e^+e^- center-of-mass frame. A veto is applied to the high energy photons that combined with another photon form either a π^0 within the mass range 117–150 MeV$/c^2$ or an η within the mass range 524–566 MeV$/c^2$.

Neutral kaons are reconstructed as $K_S^0 \to \pi^+\pi^-$ candidates with an invariant mass within 9 MeV$/c^2$ of the nominal mass [1], and a transverse flight distance > 2 mm from the primary event vertex. Charged kaons are tracks identified as kaons from information in the DIRC. The remaining tracks are considered to be charged pions. Both charged and neutral kaons are required to have a laboratory momentum > 0.7 GeV$/c$. Above this threshold the rate for charged pions to be misidentified as kaons is $<2.0\%$.

Neutral pions are reconstructed from pairs of photons with energies > 30 MeV. A π^0 mass cut is applied between 117 and 150 MeV$/c^2$. Charged and neutral pions are required to have laboratory momenta > 0.5, 0.3, or 0.2 GeV$/c$ for states with 1, 2, or 3 pions, respectively, to reject combinatoric background.

The mass of the hadronic system, X_s, formed from the kaon and pions is required to be between 0.6 GeV$/c^2$ and 2.3 GeV$/c^2$, corresponding to a photon energy threshold $E_\gamma > 2.14$ GeV in the B rest frame.

The signal Monte Carlo sample is generated according to Ref. [8], which predicts that $(83 \pm 5)\%$ of the $b \to s\gamma$ spectrum is above our photon energy threshold. The hadronic mass range below 1.1 GeV$/c^2$ is assigned to the exclusive final state $B \to K^*\gamma$ and modeled with the known branching fraction and K^* mass distribution [1]. Above 1.1 GeV$/c^2$ we use JETSET [9] to hadronize the system of the strange and spectator quarks. Within the selected hadronic mass range, the 12 final states constitute 48% of the total rate. If we were to include the $\bar{B}^0$ decays to K_S^0 and equate the decays to K_L^0 with those to K_S^0, this would increase to 73% of the total rate. As a part of our analysis, we check the dependence of the asymmetry on the hadronic mass and final state.

Most of the background in this analysis arises from continuum production of a high energy photon, either by initial state radiation, or from the decays of π^0 and η

mesons. We remove 86% of these backgrounds by selections on the angle between the thrust axis of the B meson candidate and the thrust axis of all the other particles of the event, $|\cos\theta_T^*| < 0.80$, and the angle between the B candidate and the beam axis, $|\cos\theta_B^*| < 0.80$, both defined in the e^+e^- center-of-mass system. We then use a neural network to combine information from a set of event shape variables, including a set of energy flow cones. This halves the continuum background compared to our initial selection.

In 12% of the signal events, we can identify an electron or muon from the decay of the other B [10]. This is a very effective signature for removing continuum background, so the remaining background in this sample comes mostly from other B decays. We present separately our results for the sample of events which are lepton tagged.

Exclusive $b \to s\gamma$ decays are characterized by two kinematic variables: the beam-energy substituted mass, $m_{ES} = \sqrt{(\sqrt{s}/2)^2 - p^{*2}B}$, and the energy difference between the B candidate and the beam energy, $\Delta E = E_B^* - (\sqrt{s}/2)$, where E_B^* and p_B^* are the energy and momentum of the B candidate in the e^+e^- center-of-mass frame, and $\sqrt{s}$ is the total center-of-mass energy. We require candidates to have $|\Delta E| < 0.10$ GeV, and remove multiple candidates in each event by selecting the one with the smallest value of $|\Delta E|$. This technique is $> 90\%$ efficient when the true $b \to s\gamma$ decay is among the reconstructed candidates. We then fit the m_{ES} distribution between 5.22 and 5.29 GeV$/c^2$ to extract the signal yield. When calculating m_{ES}, the value of p_B^* is corrected for the tail of the high energy photon response function by scaling the measured E_γ^* to the value that would give $\Delta E = 0$, the value expected for true signal.

In order to fit the m_{ES} distribution in data, we need to understand the different components of the signal and background events. We have identified the following four contributions as shown in Fig. 1. The signal events are described by a crystal ball function [11] with a resolution $\sigma(m_{ES}) = 2.2\ \mathrm{MeV}/c^2$. The continuum background is described by an ARGUS shape [12], which is cross checked by a fit to a sample of 9.6 fb^{-1} of data taken 40 MeV$/c^2$ below the $\Upsilon(4S)$ resonance. We use a $B\overline{B}$ Monte Carlo sample to model the background from B decays other than $b \to s\gamma$, which is significant for X_s masses above 1.9 GeV$/c^2$. This background is described by the sum of an ARGUS shape and a peaking component which is modeled by the signal shape.

The last background component is cross feed from incorrectly reconstructed $b \to s\gamma$ events. This is modeled by the signal Monte Carlo sample, where we identify events reconstructed in the wrong final state. Cross feed occurs when the true $b \to s\gamma$ decay is not among the reconstructed candidates, or in a multiple candidate event when the wrong candidate is chosen. The shape of the cross feed is described by the sum of an ARGUS shape

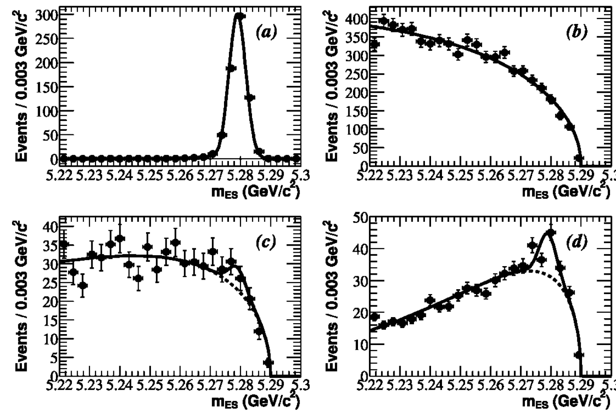

FIG. 1. Monte Carlo simulations of the four contributions to the beam-energy substituted mass distribution of events selected as $b \to s\gamma$, with the corresponding fits: (a) signal, (b) continuum, (c) $B\overline{B}$ decays, and (d) cross feed. The plots are normalized to the luminosity of our data sample.

and a peaking signal shape. We regard cross feed as a background to be subtracted.

We fit the data m_{ES} distributions separately for each flavor. For the total sample, the fit function is parametrized by two ARGUS shapes and a crystal ball function. One ARGUS shape is fixed to be as the continuum ARGUS shape, while the other one is free to represent the sum of the nonpeaking $B\overline{B}$ and cross-feed backgrounds. The crystal ball function fits the combination of the peaking components. For the lepton-tagged sample, we use only one free ARGUS shape and a crystal ball function. In all cases we use an unbinned maximum likelihood fit. The fitting technique has been validated with a large sample of Monte Carlo simulated events. In Fig. 2 we present the final fits to the m_{ES} distributions for

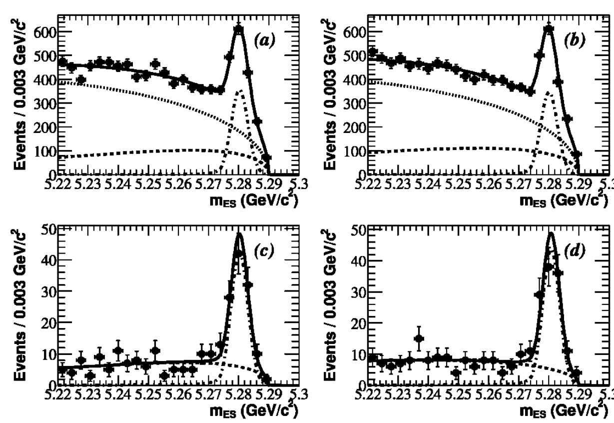

FIG. 2. Fits to the beam-energy substituted mass distributions in data events for: (a) all $b \to s\gamma$, (b) all $\overline{b} \to \overline{s}\gamma$, (c) lepton-tagged $b \to s\gamma$, and (d) lepton-tagged $\overline{b} \to \overline{s}\gamma$ decays. Contributions are shown from peaking crystal ball (dot-dashed), fixed continuum ARGUS shape (dotted) and free $B\overline{B}$ and cross-feed ARGUS shape (dashed).

$b \to s\gamma$ and $\overline{b} \to \overline{s}\gamma$ events. The lower plots are for the lepton-tagged sample. All the fits have χ^2 per degree-of-freedom close to 1, if we make a fit to a binned distribution as shown in Fig. 2. The sum of events in the b and $\overline{b}$ peaks is 1644 ± 72, of which 201 ± 18 are lepton tagged. To get the true signal yields these have to be corrected for the predicted yield of peaking $B\overline{B}$ and cross-feed backgrounds from Monte Carlo samples (see Fig. 1), which is 88 ± 27, where 10 ± 8 are lepton tagged.

The direct CP asymmetry is calculated from:

$$A_{CP} = \frac{1}{\langle D \rangle}\left[\frac{(n - \bar{n})}{(n + \bar{n})} - \frac{\Delta D}{2}\right] - A_{CP}^{\mathrm{DET}}, \qquad (2)$$

where n and $\bar{n}$ are the numbers of observed $b \to s\gamma$ and $\overline{b} \to \overline{s}\gamma$ events after the peaking background is subtracted, $\Delta D = 2(\bar{w} - w)$ is the difference in the wrong flavor fraction between b and $\overline{b}$ decays, and $\langle D \rangle = 1 - (w + \bar{w})$ is the dilution factor from the average wrong flavor fraction. A_{CP}^{DET} is the flavor asymmetry of the detector. We find $\Delta D = 0.001 \pm 0.002$ and $\langle D \rangle = 0.989 \pm 0.001$ from Monte Carlo samples. The small wrong flavor fraction is due to charged pions misidentified as charged kaons.

We need to correct the measured value of A_{CP} for the flavor asymmetry of the detector A_{CP}^{DET}. While it is known that the kaon-nucleon cross sections are asymmetric at low momenta, there are few accurate measurements [1]. This means that our Monte Carlo sample is not expected to model correctly the asymmetries due to the interactions of kaons with the inner part of the detector. The kaon identification efficiency of the DIRC for reconstructed tracks is measured with a control sample of kaons from D^* decays. Averaging over the kaon spectrum in $b \to s\gamma$ events we obtain a small asymmetry of -0.002 ± 0.001 from particle identification. We measure the overall detector asymmetry of the data events in our m_{ES} and ΔE sidebands, increasing the statistics by removing the neural network cut. Most of these events are from the continuum, where we do not expect any physics mechanism to generate a flavor asymmetry. We observe a significant asymmetry for kaon momenta below 1 GeV/c. The asymmetry as a function of the kaon momentum is applied to the signal Monte Carlo to determine what shift should be applied to the data. This gives an overall flavor-asymmetry correction $A_{CP}^{\mathrm{DET}} = -0.014 \pm 0.015$.

Table I presents the measured signal yields and corrected CP asymmetries. The lepton-tagged results are consistent with the results for the total sample. We divide the total sample into four bins in X_s mass, and observe no significant mass dependence of the asymmetry. The first bin corresponds to the $K^*(892)$ resonance, for which the world average asymmetry from studies of exclusive $B \to K^*\gamma$ decays is $A_{CP}(B \to K^*\gamma) = -0.01 \pm 0.07$ [1]. Our result is consistent with this average.

TABLE I. Signal yields and CP asymmetries for total and only lepton-tagged event samples. The total sample is also divided up into four bins in X_s mass in GeV/c^2, and into three types of decay modes. The errors on n and $\bar{n}$ are statistical only, while for A_{CP} we quote the additional systematic error from the detector asymmetry.

Sample	n	$\bar{n}$	A_{CP}
Total sample	787 ± 54	769 ± 54	$0.025 \pm 0.050 \pm 0.015$
Lepton tagged	91 ± 14	100 ± 13	$-0.04 \pm 0.10 \pm 0.02$
$M_{X_s} = 0.6$–1.1	378 ± 32	396 ± 33	$0.003 \pm 0.059 \pm 0.015$
$M_{X_s} = 1.1$–1.5	162 ± 22	136 ± 23	$0.11 \pm 0.11 \pm 0.02$
$M_{X_s} = 1.5$–1.9	139 ± 19	124 ± 21	$0.07 \pm 0.11 \pm 0.03$
$M_{X_s} = 1.9$–2.3	101 ± 29	67 ± 36	$0.23 \pm 0.30 \pm 0.04$
B^0	455 ± 36	447 ± 38	$0.015 \pm 0.059 \pm 0.014$
$B^\pm \to K^\pm$	229 ± 31	148 ± 30	$0.22 \pm 0.12 \pm 0.02$
$B^\pm \to K_S^0$	100 ± 24	166 ± 25	$-0.20 \pm 0.14 \pm 0.03$

We divide our total sample into three types of decay mode: $B^0(\overline{B}^0) \to K^\pm$, $B^\pm \to K^\pm$, and $B^\pm \to K_S^0$. We observe a discrepancy of 2.3σ between the two $B^\pm$ categories which we regard as a statistical fluctuation, since it is not correlated with a specific final state or hadronic mass bin. The combination of the $B^\pm$ samples is consistent with a null asymmetry, as is the B^0 sample.

The dominant systematic error in our measurement is the uncertainty of 0.015 in the flavor asymmetry of the detection efficiency for charged and neutral kaons. For the lepton-tagged sample we add an additional systematic uncertainty of 0.010 to account for a possible charge asymmetry in the lepton-tagging efficiency. This is derived from studies of control samples [10].

We have tested the effect of possible flavor asymmetries in the peaking cross-feed and $B\overline{B}$ backgrounds by varying them within the current experimental bounds (90% C.L.). We added a 0.10 asymmetry to the cross-feed events, and a 0.02 asymmetry to the peaking background from $B\overline{B}$ decays, which comes primarily from $B \to D^{(*)}\rho$ decays. The change in our measured asymmetry due to these changes in the cross feed and $B\overline{B}$ flavor asymmetries is 0.004, which gives a negligible contribution to the error.

We have checked that the parameters of the ARGUS shapes and crystal ball functions are the same for both flavors within 1σ, so the detector asymmetry is simply an overall normalization difference between the two samples. We have also checked that the neural net distributions for signal and continuum background are flavor symmetric.

Our estimates of the cross-feed background and the detector asymmetry correction, A_{CP}^{DET}, depend on the mix of final states in our signal Monte Carlo sample. We check these, also using information from $\overline{B}^0$ decays to final states with K_S^0, by varying the ratios of final states with K^+ or K_S^0, and π^0 to π^+ measured in our data by $\pm 3\sigma$. Note that the measured ratios are consistent with our signal Monte Carlo. Changing the ratios has no significant effect on the cross feed or the detector asymmetry correction.

Our final result for the direct CP asymmetry in $b \to s\gamma$ is $A_{CP} = 0.025 \pm 0.050 \pm 0.015$ for the total sample, and $A_{CP} = -0.04 \pm 0.10 \pm 0.02$ for the lepton-tagged sample. The total sample provides the best constraint, $-0.06 < A_{CP} < +0.11$ at 90% confidence level. This result begins to restrict the range of allowed new physics contributions in the flavor-changing penguin diagram.

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