Measurement of the $CP$ Asymmetry in $B \to X_s \gamma$

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Abstract

Direct CP violation in the $b \rightarrow s \gamma$ process is a sensitive probe of physics beyond the Standard Model. We report a measurement of the $CP$ asymmetry in $B \rightarrow X_s \gamma$, where the hadronic recoil system $X_s$ is reconstructed using a pseudo-reconstruction technique. In this approach there is negligible contamination from $b \rightarrow d \gamma$ decays, which are expected to have a much larger $CP$ asymmetry. We find $A_{CP} = 0.002 \pm 0.050$ (stat.) $\pm 0.030$ (syst.) for $B \rightarrow X_s \gamma$ events having recoil mass smaller than $2.1$ GeV/$c^2$. The analysis is based on a data sample of $140 \text{ fb}^{-1}$ recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB $e^+e^-$ storage ring.

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Radiative $B$ decays, which proceed mainly through the $b \to s\gamma$ process, have played an important role in the search for physics beyond the Standard Model (SM). The inclusive branching fraction has been measured by CLEO [1], ALEPH [2] and Belle [3], giving results consistent with the recent theoretical prediction of $(3.57 \pm 0.30) \times 10^{-4}$ [4]. The SM predicts very small direct $CP$ violation in $b \to s\gamma$; the $CP$ asymmetry,

$$A_{CP}(b \to s\gamma) = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)},$$

is about +0.5% in the SM, while some new physics, such as supersymmetry, allows the $CP$ asymmetry to be above 10% without changing the inclusive branching fraction [5]. Thus, measurement of $A_{CP}$ may provide information on new physics that cannot be extracted from the measurement of the branching fraction. Previously, CLEO measured $-0.27 < 0.965 A_{CP}(b \to s\gamma) + 0.02 A_{CP}(b \to d\gamma) < 0.10$ at 90% confidence level [6]; however $b \to d\gamma$ is expected to cancel the $CP$ asymmetry in $b \to s\gamma$ [7]. The measurement presented here has negligible $b \to d\gamma$ contamination.

In this paper, we report on a measurement of the $CP$ asymmetry in $B \to X_s\gamma$, where the hadronic recoil system $X_s$ is reconstructed using a pseudo-reconstruction technique. The analysis is based on 140 fb$^{-1}$ of data taken at the $\Upsilon(4S)$ resonance (on-resonance) and 15 fb$^{-1}$ at an energy 60 MeV below the resonance (off-resonance), which was recorded by the Belle detector [8] at the KEKB asymmetric $e^+e^-$ collider (3.5 GeV on 8 GeV) [9]. The on-resonance data correspond to 152 million $B\bar{B}$ events. The Belle detector has a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An instrumented iron flux-return for $K_L/\mu$ detection is located outside the coil.

We form the hadronic recoil system, $X_s$, with a mass up to 2.1 GeV/$c^2$, by combining one charged or neutral kaon with one to four pions, where at most one pion can be neutral. We also reconstruct $X_s$ via $K^\pm K^\mp K^\pm (\pi^\pm)$ and $K^0_s K^\pm K^\pm (\pi^\pm)$ including the $B \to K\phi\gamma$ decays that were observed recently by Belle [10].

Each of the primary charged tracks is required to have a momentum in the $e^+e^-$ center-of-mass (CM) frame that is greater than 100 MeV$/c$, and to have an impact parameter within $\pm 5$ cm of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. These tracks are identified as pion or kaon candidates according to a likelihood ratio based on the light yield in the ACC, the TOF information and the specific ionization measurements in the CDC. For the selection applied on the likelihood ratio, we obtain an efficiency (pion misidentification probability) of 90% (7%) for charged kaon candidates, and an efficiency (kaon misidentification probability) of 93% (7%) for charged pion candidates. Tracks that are identified as an electron or muon are excluded.

$K^0_s$ candidates are formed from $\pi^+\pi^-$ combinations whose invariant mass is within 8 MeV/$c^2$ of the nominal $K^0_s$ mass. The two pions are required to have a common vertex that is displaced from the interaction point. The $K^0_s$ momentum direction is also required to be consistent with the $K^0_s$ flight direction. Neutral pion candidates are formed from pairs of photons that have an invariant mass within 16 MeV/$c^2$ of the nominal $\pi^0$ mass and an opening angle smaller than 60°. Each photon is required to have an energy greater than 50 MeV. A mass constrained fit is then performed to obtain the $\pi^0$ momentum.

The $B$ meson candidates are reconstructed from the $X_s$ system and the highest energy photon with a CM energy between 1.8 and 3.4 GeV within the acceptance of the barrel ECL.
(33° < θ∗ < 128°, where θ∗ is the polar angle of the photon in the laboratory frame). In order to reduce the background from decays of π0 and η mesons, we combine the photon candidate with all other photons in the event and reject the event if the invariant mass of any pair is within 18 MeV/c² (32 MeV/c²) of the nominal π0 (η) mass.

We use two independent kinematic variables for the B reconstruction: the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{beam}^* / c^2)^2 - (|\vec{p}_{X_s}^* + \vec{p}_γ^*| / c)^2}$ and $\Delta E \equiv E_{X_s}^* + E_γ^* - E_{beam}^*$, where $E_{beam}^*$ is the beam energy, and $|\vec{p}_γ^*|$, $E_γ^*$, $\vec{p}_{X_s}^*$, $E_{X_s}^*$ are the momenta and energies of the photon and the $X_s$ system, respectively, calculated in the CM frame. In the $M_{bc}$ calculation, the photon momentum is rescaled so that $|\vec{p}_γ^*| = (E_{beam}^* - E_{X_s}^*) / c$ is satisfied; this improves the $M_{bc}$ resolution to 2.9 MeV/c². We require $M_{bc} > 5.24$ GeV/c² and $-150$ MeV < $\Delta E$ < 80 MeV. We define the signal region to be $M_{bc} > 5.27$ GeV/c².

The largest source of background originates from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) production including contributions from initial state radiation ($e^+e^- \rightarrow q\bar{q}γ$). In order to suppress this background, we require the presence of a high energy lepton from the opposite $B$. The lepton can be either an electron with a CM momentum greater than 0.8 GeV/c or a muon with a laboratory momentum greater than 1.0 GeV/c. In both cases, the opening angle $\theta_{γ,τ}$ between the high energy photon from the signal $B$ meson and the lepton, calculated in the CM frame, must satisfy $|\cos θ_{γ,τ}| < 0.8$. In addition to this lepton requirement, we use the likelihood ratio described in Ref. [11], which utilizes the information from a Fisher discriminant [12] formed from six modified Fox-Wolfram moments [13] and the cosine of the angle between the $B$ meson flight direction and the beam axis. The lepton requirement (likelihood ratio selection) retains 15% (92%) of the signal, rejecting 98.5% (55%) of the $q\bar{q}$ background.

When multiple $B$ candidates are found in the same event, we take the candidate that gives the highest confidence level when we fit the $X_s$ decay vertex, constrained to the profile of the measured interaction region. The confidence level for the $K^0_s\pi^0γ$ mode is set to zero, because we do not determine the vertex. If multiple $B$ candidates appear in an event according to the inclusion or omission of different $π^0$ mesons in the $X_s$ recoil system, we take the candidate that has the minimum $|\Delta E|$.

We fit the $M_{bc}$ distribution to extract the signal yield. The $M_{bc}$ distribution of the $q\bar{q}$ background is modeled by an ARGUS function [14] whose shape is determined from the off-resonance data. (The lepton requirement is not applied to the off-resonance data in order to compensate for the limited amount of data in that sample.) Background from $B$ decay is divided into two components. $B$ decays through $b \rightarrow c$ transitions (except color-suppressed $B$ decays such as $B^0 \rightarrow D^0 π^0$), which we call $B\bar{B}$ background in this paper, have a non-peaking $M_{bc}$ distribution which is modeled by another ARGUS function. Rare $B$ decays, i.e. $B$ decays through $b \rightarrow s$ and $b \rightarrow u$ transitions (charmless $B$ decay) and color-suppressed $B$ decays, are not negligible and have peaks at the $B$ mass in the $M_{bc}$ distribution. The sum of these distributions is modeled by a Gaussian plus an ARGUS function. The shape of the distributions is determined by a corresponding Monte Carlo (MC) sample.

The $M_{bc}$ distribution of the signal component is also modeled by the sum of a Gaussian and an ARGUS function. All parameters are determined from the $B \rightarrow X_sγ$ signal MC simulation, except that the mean of the Gaussian is extracted from a fit to $B \rightarrow Dπ$ decays, described below. Our nominal signal MC contains a $B \rightarrow K^*(892)γ$ component and an inclusive $b \rightarrow sγ$ component with $M_{X_s} > 1.15$ GeV/c². The ratio of the two components is based on the branching fraction for $B \rightarrow K^*(892)γ$ measured by Belle [15] and the PDG value of $\text{BR}(B \rightarrow X_sγ)$ [16]. The $X_s$ system of $b \rightarrow sγ$ is modeled as an equal mixture of $sd$.
and $\bar{s}u$ quark pairs, and is hadronized using JETSET\(^{17}\). The $M_{X_s}$ spectrum is fitted to the model by Kagan and Neubert\(^{18}\) with the $b$ quark mass parameter $m_b = 4.75$ GeV/$c^2$.

Before discussing the extraction of $A_{CP}$, we elaborate on the signal modeling. We create alternative signal MC samples in which the $K^*(892)\gamma$ fraction is varied by $\pm \sigma$ or the $b$ quark mass parameter is varied by $\pm 0.15$ GeV/$c^2$. We account for the uncertainty in the hadronization process by preparing an alternate MC sample wherein $B$ candidates with $M_{X_s} > 1.15$ GeV/$c^2$ are selected or discarded at random to match the fractions of such candidates observed in the data having between one and four pions. We prepare other such samples wherein the proportion of selected $B$ candidates without a neutral kaon or pion matched the value seen in data; the correction is modest for all modes except $K\pi\gamma$ (which contributes 32% in the MC but 12% after correction). The systematic error estimate based on these samples is described below.

In the pseudo-reconstruction analysis of $B \rightarrow X_s\gamma$, the flavor of the $B$ meson is “self-tagged” when the net charge of the $X_s$ system is non-zero or the $X_s$ system contains an odd number of charged kaons. Otherwise the flavor is “ambiguous.” Because we have three possibilities for the flavor tag, there are three ways to tag the flavor incorrectly: $w_1$ is the probability of classifying a self-tagged event as a self-tagged event of the opposite flavor; $w_2$ is the probability to classify an ambiguous event as self-tagged; $w_3$ is the probability to classify a taggable event as ambiguous. For example, $w_2$ refers to the case when a $B^0 \rightarrow K^0_s\pi^+\pi^-\gamma$ event is tagged as a $K^0_s\pi^+\pi^0\gamma$ event, and $w_3$ refers to the case when a $B^+ \rightarrow K^0_s\pi^+\pi^0\gamma$ event is tagged as a $K^0_s\pi^+\pi^-\gamma$. The effect of the flavor dependence of the wrong tag fractions is negligibly small, and is included in the systematic error from the $B \rightarrow D\pi$ study described later.

The formula to calculate $A_{CP}$ is then $A_{CP} = DA_{CP}^{\text{raw}}$ with the dilution factor $D = (1 - w_2 - w_3)/[(1 - w_2)(1 - 2w_1 - w_3)]$ and the raw asymmetry $A_{CP}^{\text{raw}} = (N_+ - N_-)/[N_+ + N_- - (w_2/(1 - w_2))N_0]$, where $N_+$ ($N_-$) is the number of events tagged as originating from a $b$ ($\bar{b}$) quark, and $N_0$ is the number of events classified as ambiguous.

The three wrong tag fractions are estimated using signal MC, and thus are model dependent. We calculate the wrong tag fractions for the collection of signal MC samples described earlier, and extract the systematic errors in the wrong tag fractions from the changes in $w_i$ as the model is changed. We find $w_1 = 0.0206 \pm 0.0027$, $w_2 = 0.248 \pm 0.020$ and $w_3 = 0.0067 \pm 0.0013$, resulting in a dilution factor of $D = 1.041 \pm 0.006$.

Figure 4 shows the $M_{bc}$ distributions for events that are classified as $b$-tagged, $\bar{b}$-tagged and ambiguous, respectively. The distributions are fitted with signal, $q\bar{q}$, $BB$ and rare $B$ components. We assume the shapes of the three components are common for $b$- and $\bar{b}$-tagged classes, distinct from those for the ambiguous class. In the fit, the numbers of events from the $BB$ and rare $B$ background in the signal region are fixed to be 39.3 (9.2) and 35.4 (3.3) for the common $b$- and $\bar{b}$-tagged classes (ambiguous class) using the MC prediction, while the normalization of the $q\bar{q}$ component is allow to float. Signal yields are obtained by integrating the signal Gaussian and ARGUS functions in the signal region. We find the signal yield in each class to be $N_- = 393.2 \pm 25.9$, $N_+ = 392.0 \pm 25.9$ and $N_0 = 52.8 \pm 9.6$, resulting in $A_{CP} = 0.002 \pm 0.050$.

The systematic errors are studied using a $B \rightarrow D\pi$ control sample. $D$ mesons are reconstructed in the same final states as $X_s$ except for the final states to which $D$ cannot decay. Only a mild requirement on the invariant mass of the reconstructed $D$ mesons of less than 1.9 GeV/$c^2$ is applied, in order to allow cross-feeds between different $D$ decay channels. In the calculation of $M_{bc}$, the primary pion momentum is rescaled in the same way as the
to be dilution factor of DA decays. We divide these decays into two groups: those for which \( \sigma \) around 1
around the possible difference of sub-decay modes between \( b \) and \( \bar{b} \). We assign an
error of 23%.

The systematic error on \( A_{CP} \) due to the fitting procedure is estimated by varying the value of each fixed parameter by \( \pm 1\sigma \) and extracting new signal yields and \( A_{CP} \) for each case. We assign an additional 23% error obtained from \( B \to D\pi \) to the ratio of the Gaussian and ARGUS function. The ratio is also varied separately for \( N_+ \) and \( N_- \) to take into account
the possible difference of sub-decay modes between \( b \) and \( \bar{b} \). We also use the signal shape parameters obtained from each of the signal MC samples described earlier and extract \( A_{CP} \) for each case. We set the normalization of either the \( B\bar{B} \) or rare \( B \) backgrounds to zero and to twice its nominal value to account for its uncertainty. A 50% error is assigned to the Gaussian width and to the ratio of the Gaussian and ARGUS function for the rare \( B \) decays, to compensate for our limited knowledge of their branching fractions. The changes of \( A_{CP} \) for each procedure are added in quadrature, and are regarded as the systematic error. We obtain a systematic error of 0.014 due to the fitting procedure.

The \( B \to D\pi \) sample is also used to estimate the possible detector bias in \( A_{CP} \). We estimate \( A_{CP} \) for \( B \to D\pi \) using the same method as for \( B \to X_{s}\gamma \). The flavor is determined from that of the \( D \) candidate. From the MC study, we find the \( B \to D\pi \) wrong tag fractions to be \( w_1 = 0.0314 \pm 0.0039, w_2 = 0.285 \pm 0.024, \) and \( w_3 = 0.0225 \pm 0.0033 \), resulting in a dilution factor of \( D = 1.059 \pm 0.013 \). The signal yields are calculated by fitting the data \( M_{bc} \) distribution with signal, \( q\bar{q} \), and \( B\bar{B} \) components with fixed \( B\bar{B} \) normalization, and are found to be \( N_- = 2125 \pm 60, N_+ = 2105 \pm 60 \) and \( N_0 = 580 \pm 30 \), resulting in a \( CP \) “asymmetry” of \( A_{CP} = 0.006 \pm 0.022 \). We therefore assign 0.022 as the systematic error due to detector bias.

In addition, we estimate the uncertainty due to possible asymmetries in charmless \( B \) decays. We divide these decays into two groups: those for which \( A_{CP} \) has been measured (\( B \to K^*\eta, K\pi^0 \) and \( K\rho \)), corresponding to about half of the selected charmless \( B \) events; and all other decay modes. We assign an \( A_{CP} \) of \( \pm 30\% \) to the first group (corresponding to around 1\( \sigma \) in each case), and \( \pm 100\% \) to the second, assuming the signs of \( A_{CP} \) are correlated.

FIG. 1: \( M_{bc} \) distributions for (a) events tagged as \( b \), (b) events tagged as \( \bar{b} \) and (c) events classified as ambiguous. Fit results are overlaid.

photon in the \( B \to X_{s}\gamma \) reconstruction.

In order to check the validity of the signal \( M_{bc} \) shape obtained from MC, we compare the \( M_{bc} \) distribution for \( B \to D\pi \) data and MC. The data \( M_{bc} \) distribution is fitted with the sum of a Gaussian and an ARGUS function plus \( q\bar{q} \) and \( B\bar{B} \) distributions. The \( q\bar{q} \) and \( B\bar{B} \) distributions are obtained from off-resonance data and MC simulation, respectively, where each normalization is scaled according to the luminosity. From this procedure, we determine the mean of the Gaussian used to model the signal \( M_{bc} \) distribution. We find that the ratio of the Gaussian and ARGUS function agrees between data and MC within the statistical error of 23%.

We assign an additional 23% error obtained from the fitting procedure as the systematic error due to the fitting procedure. We also use the signal shape obtained from MC, we compare the
and all other decay modes. We assign an \( A_{CP} \) of \( \pm 30\% \) to the first group (corresponding to around 1\( \sigma \) in each case), and \( \pm 100\% \) to the second, assuming the signs of \( A_{CP} \) are correlated.
The resulting contribution to the measured $A_{CP}$, 0.014, is taken as a systematic error.

The systematic error on $A_{CP}$ due to the uncertainty of the wrong tag fractions is found to be small. The contribution of the $b \rightarrow d\gamma$ process is negligible, because we require the existence of kaons in the final state. This is confirmed by examining MC samples of $B \rightarrow \rho\gamma$, $\omega\gamma$ and inclusive $b \rightarrow d\gamma$ process [19]; we expect that the contribution of $b \rightarrow d\gamma$ to $A_{CP}$ is less than 0.001. The total systematic error on $A_{CP}$ is then calculated to be 0.030 by adding in quadrature the errors mentioned earlier.

In order to examine the $M_{X_s}$ dependence of $A_{CP}$, we divide the data sample into six bins of measured $M_{X_s}$ and perform the $M_{bc}$ fit for each bin. Figure 2 shows the $A_{CP}$ distribution as a function of $M_{X_s}$. Here, the systematic error due to the detector bias and possible $CP$ asymmetry in charmless $B$ decays is not included in the error. We find that $A_{CP}$ is consistent with zero for all $M_{X_s}$ values in the distribution. From our MC study, about 2% of the events reconstructed with $M_{X_s} < 2.1$ GeV/c$^2$ are expected to have a true $X_s$ mass greater than 2.1 GeV/c$^2$.

In conclusion, the $CP$ asymmetry of $B \rightarrow X_s\gamma$ for events with $M_{X_s} < 2.1$ GeV/c$^2$ is measured to be

$$A_{CP}(B \rightarrow X_s\gamma; M_{X_s} < 2.1 \text{ GeV/c}^2) = 0.002 \pm 0.050(\text{stat.}) \pm 0.030(\text{syst.}),$$

consistent with no asymmetry. This corresponds to $-0.093 < A_{CP} < 0.096$ at the 90% confidence level, where we add the statistical and systematic errors in quadrature and assume Gaussian errors. The result can restrict the parameter space of new physics models that allow sizable $CP$ asymmetry in $b \rightarrow s\gamma$ [20].

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