Measurement of Time-Dependent $CP$ Asymmetry in $B^0 \to K_s^0 \pi^0 \gamma$ Decays

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We measure the time-dependent CP asymmetry in $B^0 \rightarrow K_S^0 \pi^0 \gamma$ decays for two regions of $K_S^0 \pi^0$ invariant mass, $m(K_S^0 \pi^0)$, using the final Babar data set of $467 \times 10^3$ $B \bar{B}$ pairs collected at the PEP-II $e^+e^-$ collider at SLAC. We find $339 \pm 24 B^0 \rightarrow K_S^0 \pi^0 \gamma$ candidates and measure $S_{K_S^0 \gamma} = -0.03 \pm 0.29 \pm 0.03 \pm 0.03$ and $C_{K_S^0 \gamma} = -0.14 \pm 0.16 \pm 0.03$. In the range $1.1 < m(K_S^0 \pi^0) < 1.8$ GeV/$c^2$ we find $133 \pm 20 B^0 \rightarrow K_S^0 \pi^0 \gamma$ candidates and measure $S_{K_S^0 \pi^0 \gamma} = -0.78 \pm 0.59 \pm 0.09$ and $C_{K_S^0 \pi^0 \gamma} = -0.36 \pm 0.33 \pm 0.04$. The uncertainties are statistical and systematic, respectively.

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The radiative decay $b \rightarrow s\gamma$ serves as a probe of physics beyond the standard model (SM). In the SM it proceeds at leading order through a loop diagram, making it sensitive to possible virtual contributions from as yet undiscovered particles. Because of parity violation in the weak interaction, the photon in $b \rightarrow s\gamma$ is predominantly left-handed, while it is right-handed in the charge-conjugate decay. The photon polarization can be determined indirectly through a measurement of time-dependent CP asymmetry in certain neutral decay channels. A non-zero asymmetry $S$ due to interference between $B^0$ and $\bar{B}^0$ decays is only present if both photon helicities as asymmetry in certain neutral decay channels. A non-zero asymmetry $S$ is expected to be approximately $-0.02$ in the SM [1, 2], though hadronic corrections might permit it to be as large as $\pm 0.1$ [3]. Several new physics scenarios yield large values of the asymmetry: these include left-right symmetric models [1, 4], supersymmetric models [5]. Because the SM asymmetry is small, any significant evidence of a large asymmetry would point to a source beyond the SM.

We present an updated measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^0_s\pi^0\gamma$ based on the final BaBar data set of $467 \times 10^6 \ U(AS) \rightarrow B\bar{B}$ decays collected at the PEP-II asymmetric-energy $e^+e^-$ storage rings at SLAC. Previous measurements have been performed by BaBar [6] and Belle [7]. Changes since BaBar’s last published result include doubling the data set, improved track reconstruction, better removal of background photons from $\pi^0$ and $\eta$ decays, better rejection of $B^+ \rightarrow K^{+}\gamma$ background [8], and an improved evaluation of the systematic uncertainties from non-signal $B$ decays. At leading order in the SM, the CP asymmetries of this mode do not depend on $m(K^0_s\pi^0)$ [9]. However, since the aforementioned hadronic corrections [8] or new physics could introduce this dependence, we split the data into two parts: the $K^+$ region with $0.8 < m(K^0_s\pi^0) < 1.0\ GeV/c^2$ and the non-$K^+$ region with $1.1 < m(K^0_s\pi^0) < 1.8\ GeV/c^2$.

Time-dependent CP asymmetries are determined using the difference of $B^0$ meson proper decay times $\Delta t = t_{\text{sig}} - t_{\text{tag}}$, where $t_{\text{sig}}$ is the proper decay time of the signal $B^0 \rightarrow K^0_s\pi^0\gamma$ candidate ($B_{\text{sig}}$) and $t_{\text{tag}}$ is that of the other $B$ ($B_{\text{tag}}$), which is partially reconstructed and flavor-tagged based on its daughter tracks. The $\Delta t$ distribution for $B_{\text{sig}}$ decaying to a $CP$ eigenstate is

$$P_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S \sin(\Delta m\Delta t) \mp C \cos(\Delta m\Delta t)],$$

(1)

where the upper and lower signs correspond to $B_{\text{tag}}$ having flavor $B^0$ and $\bar{B}^0$ respectively, $\tau$ is the $B^0$ lifetime, and $\Delta m$ is the $B^0,\bar{B}^0$ mixing frequency. The $C$ coefficient corresponds to the direct $CP$ asymmetry in decay, expected to be smaller than 1% in the SM [10].

We evaluate our selection criteria with a detailed Monte Carlo (MC) simulation of the BaBar detector [11], using the EVTGEN generator [12] and the GEANT4 package [13]. We require photon candidates to have energy greater than 30 MeV and the expected lateral shower shapes in the electromagnetic calorimeter (EMC). The primary photon from the $B$ decay must be isolated by more than 25 cm from other charged and neutral clusters in the EMC. Primary-photon candidates that make a $\pi^0$ or $\eta$ candidate when combined with another photon in the event are discarded based on a likelihood formed from the diphoton mass and the energy of the second photon. We select $K^0_s \rightarrow \pi^+\pi^-$ candidates from oppositely-charged tracks for which the probability of a geometrical vertex fit is greater than 0.1%, the $\pi^+\pi^-$ invariant mass is between 487 and 508 MeV/c^2, and the reconstructed decay length is greater than 5 times its uncertainty. We select $\pi^0 \rightarrow \gamma\gamma$ candidates with invariant mass between 115 and 155 MeV/c^2 and energy greater than 590 MeV in the laboratory frame. For candidates in the $K^+$ region we require $|\cos\theta_{K^+}| < 0.9$, where $\theta_{K^+}$ is the angle between the $K^0_s$ and primary photon direction in the $K^+$ rest frame.

To identify signal decays we use the energy-substituted mass $m_{ES} = \sqrt{(s/2c^2 + p_0 \cdot p_B)^2 - \vec{p_0}^2 - |\vec{p_B}|^2/c^2}$ and the energy difference $\Delta E = E_{\gamma} - \sqrt{s}/2$, where $(E_0/c, p_0)$ and $(E_{\gamma}/c, p_{\gamma})$ are the four-momenta of the initial $e^+e^-$ system and the $B$ candidate, respectively, $\sqrt{s}$ is the center-of-mass (CM) energy, and the asterisk denotes the CM frame. The distributions of signal events show a peak in these variables. We require $5.2 < m_{ES} < 5.3\ GeV/c^2$ and $|\Delta E| < 250\ MeV$. To reduce $B^+ \rightarrow K^+\gamma$ background, we reconstruct $B^+ \rightarrow K^{++}(K^0_s\pi^+)\gamma$ candidates subject to the same requirements as $B^0$ candidates, and veto events for which $m_{ES}(B^+) > 5.27\ GeV/c^2$ and $0.8 < m(K^0_s\pi^+) < 1.0\ GeV/c^2$. To discriminate $B$ decays from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) background, we require $|\cos\theta_B| < 0.9$, where $\theta_B$ is the CM angle between the $B$ candidate and the $e^-$ beam direction. We require the ratio of event-shape moments $L_2/L_0$ to be less than 0.55, where $L_i = \sum_j |p_j^i||\cos\theta_j^i|$, $p_j^i$ is the CM momentum of each particle $j$ not used to reconstruct the $B$ candidate, and $\theta_j^i$ is the CM angle between $p_j^i$ and the thrust axis of the reconstructed $B$ candidate. After all selection criteria have been applied we find 10587 candidate events, 16% of which have more than one signal $B^0$ candidate. In these cases we select the one with $\pi^0\gamma$ mass closest to its nominal value [14], and if there is still an
ambiguity, we select the one with the $K_0^0$ mass closest to its nominal value. We find an overall selection efficiency of 16%.

For each reconstructed signal candidate we use the remaining tracks in the event to determine the decay vertex position and flavor of $B_{tag}$. The latter is determined by a neural network based on kinematic and particle identification information, the performance of which is evaluated using a sample of fully-reconstructed, self-tagging hadronic $B^0$ decays ($B_{had}^0$ sample) [13].

We determine the proper time difference between $B_{sig}$ and $B_{tag}$ from the spatial separation between their decay vertices in the same way as our previous analysis and a similar BaBar study of $B^0 \rightarrow K_S^0 \pi^0$ [16]. Because both the transverse flight length of the $B^0$ mesons and the transverse size of the interaction region are small compared to the $B^0$ flight length along the boost direction, we are able to determine a decay vertex from the intersection of the $K^0$ trajectory with the interaction region. We further improve the $\Delta t$ resolution by 11% over what is obtained using information from the interaction region alone by refitting the $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ system with the constraint that the average sum of decay times ($t_{sig} + t_{tag}$) be equal to twice the B lifetime with an uncertainty of $\sqrt{2} \tau_B$. Using MC simulation data we verify that this procedure gives an unbiased estimate of $\Delta t$. We define events as having good $\Delta t$ quality if each pion daughter of the $K^0_S$ creates at least 2 hits in the silicon vertex tracker (SVT), and if the $\Delta t$ uncertainty $\sigma_{\Delta t} < 2.5$ ps and $|\Delta t| < 20$ ps. About 70% of signal and background events pass these requirements. We split our data set and fitting procedure based on the $\Delta t$ quality such that flavor-tagged events with poor $\Delta t$ information do not contribute to the measurement of $S$, but do contribute to the measurement of $C$, which can be determined solely through tagging.

We extract signal yields and CP asymmetries using an unbinned maximum likelihood fit to $m_{ES}$, $\Delta E$, $L_2/L_0$, tag flavor, $\Delta t$, $\sigma_{\Delta t}$, and, in the $K^*$ region, $m(K_S^0 \pi^0)$. Continuum and $B \bar{B}$ backgrounds are also modeled in the fit. We construct the likelihood function for each contribution as the product of one-dimensional probability density functions (PDFs). The signal PDFs in $m_{ES}$ and $\Delta E$ are parametrized using the function

$$f(x) = \exp \left[ \frac{-(x-\mu)^2}{2\sigma^2 + \alpha(x-\mu)^2} \right],$$

where $\mu$ is the mean, $\sigma$ the core width, and $\alpha$ a tail parameter. The latter two parameters are allowed to be different on either side of the peak. The signal $m(K_S^0 \pi^0)$ shape is a relativistic Breit-Wigner, as nonresonant contributions in the $K^*$ region are negligible [17]. For continuum $m_{ES}$ we use an ARGUS [18] function, while for $\Delta E$ we use an exponential shape. The continuum and $B \bar{B}$ shape in $m(K_S^0 \pi^0)$ is a Breit-Wigner on top of a linear background. We parameterize the $B \bar{B}$ $m_{ES}$ shape as the sum of an ARGUS function and a Gaussian with different widths below and above the peak, and the $\Delta E$ shape as an exponential. The $L_2/L_0$ shapes are binned PDFs, and in those the signal and $B \bar{B}$ components share the same parameters. All signal and $B \bar{B}$ PDF parameters are determined using simulated events, except for the flavor tag efficiencies, mistag probabilities, and $\Delta t$ resolution function parameters, which are determined from the $B_{had}^0$ sample. The large number of continuum background events in the fit determine the continuum PDF parameters.

We obtain the $\Delta t$ PDF for signal events and $B \bar{B}$ background from Eq. 1, accounting for the mistag probability and convolving with the $\Delta t$ resolution function, which is the sum of three Gaussian distributions [13]. The effective CP asymmetries for the $B \bar{B}$ background, $S_{B \bar{B}}^{sig}$, and $C_{B \bar{B}}^{bkg}$, are fixed to zero in the fit, and we account for a possible deviation from zero in the systematic uncertainty. We verify in simulation that the parameters of the resolution function for signal events are compatible with those obtained from the $B_{had}^0$ sample. Therefore we use the $B_{had}^0$ parameters for better precision. We fit the continuum MC $\Delta t$ distribution and find that it is well-modeled by a prompt decay distribution consisting only of the $\Delta t$ resolution function shape. The parameters of the continuum $\Delta t$ PDF are determined in the fit to data.

In the fit to the $B^0 \rightarrow K^{*0}\gamma$ candidate sample of 3884 events we find $339 \pm 24$ (stat) signal events, $S_{K^*\gamma} = -0.03 \pm 0.29$ (stat) $\pm 0.03$ (syst) and $C_{K^*\gamma} = -0.10 \pm 0.16$ (stat) $\pm 0.03$ (syst). We also find $19 \pm 27$ (stat) $B \bar{B}$ background events. In the range $1 < m(K_S^0 \pi^0) < 1.8$ GeV/$c^2$ with 6703 events we measure $133 \pm 20$ (stat) signal events, $S_{K_S^0 \pi^0} = -0.78 \pm 0.59$ (stat) $\pm 0.09$ (syst) and $C_{K_S^0 \pi^0} = -0.36 \pm 0.33$ (stat) $\pm 0.04$ (syst). We find $167 \pm 49$ (stat) $B \bar{B}$ background events in this sample. The linear correlation coefficient between $S_{K^*\gamma}$ and $C_{K^*\gamma}$ is $+0.050$, while for $S_{K_S^0 \pi^0}$ and $C_{K_S^0 \pi^0}$ it is $+0.015$. Figure 1 shows signal-enhanced distributions for $m_{ES}$ and $\Delta E$ created by cutting on the likelihood of the unplotted fit variables.

We perform a cross-check because of the discrepancy between the projection of the fit model and the data in the non-$K^*$ region at low $m_{ES}$. A fit of the data sample with $m_{ES} > 5.22$ GeV/$c^2$ shows that the observed changes in $S$ and $C$ are consistent with statistical fluctuations, so the signal is not significantly affected. Additionally, we verified that the slope of the $m_{ES}$ background shape is not correlated with the other fit variables. MC simulations of common $B \bar{B}$ backgrounds, including the final states $K_S^0 \pi \pi \gamma$ and $K_S^0 \pi \pi \pi$, do not show any rising structure at low $m_{ES}$.

Figure 2 shows the background-subtracted distributions of $\Delta t$ in the $K^*$ region, obtained with the sPlot event weighting technique. We show an sPlot of the $m(K_S^0 \pi^0)$ spectrum in Fig. 3. Using an ensemble of simulated experiments generated from the fitted likelihood function we find no bias in the $K^*$ region and a spread in $S$ and $C$ consistent with the statistical uncertainties. In the non-$K^*$ region we find a bias of $-0.06 \pm 0.03$ on $S$ and a spread in $C$ larger than the...
lated events in which the generated ensemble with 

are due to a measurement that is close to the physical 

statistical uncertainty reported by the fit. These effects 
are due to a measurement that is close to the physical 
boundary of $S^2 + C^2 < 1$, and they disappear if we gen-
erate the ensemble with $S_{K^0_s\pi^+\gamma} = C_{K^0_s\pi^+\gamma} = 0$. The bias on $S_{K^0_s\pi^+\gamma}$ is evaluated with several ensembles of simu-
lated events in which the generated $S_{K^0_s\pi^+\gamma}$ is varied. For 

the statistical uncertainty on $C$ we take the ensemble’s root-mean-square width of 0.33 instead of the 0.29 uncertainty determined by the fit to data.

Systematic uncertainties associated with our knowl-
edge of the beam spot position and possible SVT mis-
alignment are determined by varying the beam spot and 
SVT alignment parameters in MC. We bound the effects of uncertainties in the $\Delta t$ resolution function due to the vertexing method with a study from BABAR’s $B^0 \to K^0_s\pi^0$ analysis [20]. Resolution function differences between data and MC in control samples of $B^0 \to J/\psi K^0_s$ decays, in which the $J/\psi$ vertex information is ignored, lead to differences in $S$ and $C$ that we take as systematic uncertainties. Uncertainties from doubly-Cabibbo-suppressed (DCS) decays of the $B_{\text{tag}}$ are included as in Ref. [13].

We evaluate uncertainties due to the vertex reconstruc-
tion procedure and possible correlations among the ob-
ervables with an ensemble of simulated experiments cre-
ated by generating background events from the PDFs and embedding signal events from the full MC simula-
tion. No significant bias is observed in the $K^*$ region, and we bound uncertainties by the precision with which the potential bias is measured. In the non-$K^*$ region, no bias is observed in the signal MC.

Uncertainties due to limited knowledge of the fixed pa-
rameters in the fit are evaluated by varying them within 
their uncertainties. We evaluate differences between data and MC in the signal shape by fixing the background pa-
rameters to those determined in the fit to data and float-
ing the signal parameters separately for each observable.

We evaluate the effect of $S_{\text{bkg}}^{B_{\text{tag}}}$ and $C_{\text{bkg}}^{B_{\text{tag}}}$ by varying 
them over a range determined by the composition of the $B_{\text{tag}}$ background samples and $CP$ asymmetry measurements in the PDG listings. The systematic uncertainties are summarized in Table I.

In summary, we have measured the time-dependent $CP$ asymmetry in $B^0 \to K^0_s\pi^0\gamma$ decays using the full BABAR data set recorded at the $\Upsilon(4S)$ resonance. We find

\begin{align*}
S_{K^*\gamma} & = -0.03 \pm 0.29 \, \text{(stat)} \pm 0.03 \, \text{(syst)}, \\
C_{K^*\gamma} & = -0.14 \pm 0.16 \, \text{(stat)} \pm 0.03 \, \text{(syst)}, \\
S_{K^0_s\pi^+\gamma} & = -0.78 \pm 0.59 \, \text{(stat)} \pm 0.09 \, \text{(syst)},
\end{align*}
TABLE I: Summary of systematic uncertainties.

| Source                      | $K^+$ Region | Non-$K^+$ Region |
|-----------------------------|--------------|------------------|
|                             | $\Delta S$  | $\Delta C$  | $\Delta S$  | $\Delta C$  |
| Beamspot                    | 0.007        | 0.002          | 0.007        | 0.002        |
| SVT Alignment               | 0.010        | 0.010          | 0.010        | 0.010        |
| Resolution Function         | 0.011        | 0.018          | 0.011        | 0.018        |
| Bias Uncertainty            | 0.015        | 0.009          | 0.028        | 0.016        |
| PDF Uncertainty             | 0.015        | 0.013          | 0.060        | 0.019        |
| $C_{bkg}^{\pi^0}$ and $C_{bkg}^{\eta}$ | 0.008        | 0.002          | 0.060        | 0.018        |
| DCS $B_{tag}$ Decays        | 0.001        | 0.015          | 0.001        | 0.015        |
| Total                       | 0.028        | 0.030          | 0.091        | 0.040        |

$C_{K_S\pi^0\gamma} = -0.36 \pm 0.33$ (stat) $\pm 0.04$ (syst).

The measurement in each $m(K_S^0\pi^0)$ region is consistent within uncertainties with the predictions of the standard model.

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