

Measurement of The Time-Dependent CP Asymmetry in $B^0 \rightarrow K^{*0}\gamma$ Decays

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^{*0}(K_S^0\pi^0)\gamma$ decays based on $431 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. In a sample containing 316 ± 22 signal events we measure $S_{K^*\gamma} = -0.08 \pm 0.31 \pm 0.05$ and $C_{K^*\gamma} = -0.15 \pm 0.17 \pm 0.03$. The uncertainties are statistical and systematic, respectively.

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The radiative decay $b \rightarrow s\gamma$ [1] serves as a probe of physics beyond the standard model (SM) [2]. In the SM it proceeds at leading order through a loop diagram involving a virtual W^- boson and t quark. Because weak interactions involve only left-handed fermions and right-handed anti-fermions, the photon in $b \rightarrow s\gamma$ is predominantly left-handed while in $\bar{b} \rightarrow \bar{s}\gamma$ it is right-handed. Any possible interference between the direct decay $B^0 \rightarrow K^{*0}(K_s^0\pi^0)\gamma$ and the decay via B^0 mixing, $B^0 \rightarrow \bar{B}^0 \rightarrow K^{*0}\gamma$, is suppressed by the small rate of $b \rightarrow s\gamma_R$ relative to $b \rightarrow s\gamma_L$, which is of the order m_s/m_b . SM predictions of the CP asymmetry due to interference between mixing and decay are expected to be about -0.02 [3]. As discussed in Ref. [2], left-right symmetric models [4] could conceivably produce mixing-induced CP asymmetries larger than 0.5. Some supersymmetric models without left-right symmetry [5] have also been shown to permit CP asymmetries of $\mathcal{O}(1)$. Because the SM asymmetry is quite small, any significant evidence of a larger asymmetry would point to a source beyond the SM.

Here we report a preliminary updated measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^{*0}\gamma$ based on $431 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. Previous measurements of this mode were performed by *BABAR* [6] and Belle [7].

The *BABAR* detector is described in detail elsewhere [8]. Most important to this analysis are the five-layer, double-sided silicon microstrip detector (SVT), the 40-layer drift chamber, and the CsI(Tl) electromagnetic calorimeter (EMC). A detailed Monte Carlo (MC) simulation of signal and background processes was performed using the *EVTGEN* [9] generator and the *GEANT4* package [10].

Time-dependent CP asymmetries are determined using the difference of B^0 meson proper decay times $\Delta t \equiv t_{\text{sig}} - t_{\text{tag}}$, where t_{sig} is the proper decay time of the signal B (B_{sig}) and t_{tag} is that of the other B (B_{tag}). The Δt for B_{sig} decaying to a final state f is distributed according to

$$\mathcal{P}_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times [1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)], \quad (1)$$

where the upper and lower signs correspond to the tag-side B having flavor B^0 and \bar{B}^0 respectively, τ_B is the B^0 lifetime, and Δm_d is the $B^0 - \bar{B}^0$ mixing frequency. The C_f coefficient is associated with the difference in decay amplitudes for $B^0 \rightarrow f$ and $\bar{B}^0 \rightarrow f$, while the S_f coefficient involves interference between the $B^0 - \bar{B}^0$ mixing and decay amplitudes. We note that direct CP violation in $B^0 \rightarrow K^{*0}\gamma$ decays is predicted to be smaller than 1% in the SM [11]. The current evidence is consistent with this, based on self-tagging $B \rightarrow K^*\gamma$ decays [12].

We search for $B^0 \rightarrow K^{*0}(K_s^0\pi^0)\gamma$ candidates based on the following criteria, all but one of which were used in the previous result. Photon candidates are required to have energy greater than 30 MeV and must have the expected shower shapes in the EMC. The photon from the B decay, also called the primary photon, is required to have an energy between 1.5 and 3.5 GeV in the e^+e^- center of mass (CM) frame to be consistent with $b \rightarrow s\gamma$ decays [13]. It must be isolated from other charged and neutral clusters in the EMC. Primary photon candidates that form $\pi^0 \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$ candidates of invariant mass $115 < m_{\gamma\gamma} < 155 \text{ MeV}/c^2$ or $470 < m_{\gamma\gamma} < 620 \text{ MeV}/c^2$, respectively, when combined with another photon of energy greater than 50 MeV for π^0 or 250 MeV for η are discarded. We select $K_s^0 \rightarrow \pi^+\pi^-$ candidates from oppositely charged tracks for which the confidence level of the vertex fit is greater than 0.1%, the $\pi^+\pi^-$ invariant mass is between 487 and 508 MeV/c^2 (about 3σ), 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 (about 3σ) and energy greater than 590 MeV in the lab frame. We require the invariant $K_s^0\pi^0$ mass $m(K_s^0\pi^0)$ to be within $0.8 - 1.0 \text{ GeV}/c^2$, and later use its shape in a maximum likelihood fit. We require

$|\cos\theta_{K^*}| < 0.9$, where θ_{K^*} is the angle between the K_S^0 and the primary photon in the $K_S^0\pi^0$ rest frame. Along with signal candidates, we also reconstruct $B^+ \rightarrow K^{*+}(K_S^0\pi^+)\gamma$ candidates subject to the same requirements as B^0 candidates, and veto events for which the invariant $K_S^0\pi^+$ mass is within $0.8 - 1.0 \text{ GeV}/c^2$. This is new since the last result, and it removes 12% of the background due to non-signal B decays.

We identify signal decays using two Lorentz-invariant quantities: the energy-substituted mass $m_{\text{ES}} = \left(\sqrt{(s/2 + c^2\mathbf{p}_{e^+e^-} \cdot \mathbf{p}_B)^2/E_{e^+e^-}^2 - |p_B|^2}\right)/c^2$ and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$, where $(E_{e^+e^-}, c\mathbf{p}_{e^+e^-})$ and $p_B \equiv (E_B, c\mathbf{p}_B)$ are the four-momenta of the initial e^+e^- system and the B candidate, respectively, \sqrt{s} is the CM energy, and the asterisk denotes the CM frame. We require $5.2 < m_{\text{ES}} < 5.3 \text{ GeV}/c^2$ and $|\Delta E| < 250 \text{ MeV}$. To discriminate B decays against continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) background we require $|\cos\theta_B^*| < 0.9$, where θ_B^* is the CM angle between the B candidate and the e^- beam direction. We also exploit event topology by requiring the ratio of Legendre moments L_2/L_0 to be less than 0.55, where $L_i = \sum_j |p_j^*| |\cos\theta_j^*|^i$, p_j^* is the CM momentum of each particle j not used to reconstruct the B candidate, and θ_j^* is the CM angle between p_j^* and the thrust axis of the reconstructed B candidate.

After all selection criteria have been applied we find the average candidate multiplicity in events with at least one candidate is 1.15. In these cases we select the candidate with π^0 mass closest to its nominal value [14], and if there is an ambiguity then we select the one with the K_S^0 mass closest to its nominal value. We evaluate the selection efficiency using simulated events. We find it is about 16%, and combined with the $B^0 \rightarrow K^{*0}\gamma$ branching fraction, $\mathcal{B}(B^0 \rightarrow K^{*0}\gamma) = (4.01 \pm 0.20) \times 10^{-5}$ [12], we expect 312 ± 24 signal events. We also expect approximately 35 events originating from non-signal B decays ($B\bar{B}$ background). The rest of the 3677 selected events come from continuum background. These two background types are treated separately below.

For each reconstructed $B^0 \rightarrow K^{*0}\gamma$ candidate we use the remaining tracks in the event to determine the decay vertex position and flavor of B_{tag} . A neural network based on kinematic and particle identification information assigns each event to one of seven mutually exclusive tagging categories [15], including a category for events in which a flavor tag is not determined. The performance of this algorithm is determined using a data sample (B_{flav} sample) of fully-reconstructed $B^0 \rightarrow D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The average tagging efficiency is measured to be $Q = \sum_c \epsilon^c(1 - 2w^c)^2 = (31.2 \pm 0.3)\%$, where ϵ^c and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category c .

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 measurement. The B_{sig} vertex is reconstructed by combining the K_S^0 trajectory with the knowledge of the average interaction point (IP), which is calculated every ten minutes based on two-track events during data-taking. The B_{tag} vertex is reconstructed from the remaining charged tracks in the event [16]. We compute Δt and its uncertainty from a geometric fit [17] to the $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ system, which takes the IP constraint [18] into account. The resolution of Δt is improved by constraining the average sum of the two B decay times ($t_{\text{sig}} + t_{\text{tag}}$) to equal $2\tau_{B^0}$, with an uncertainty of $\sqrt{2}\tau_{B^0}$. We have verified in signal MC that no bias on $S_{K^*\gamma}$ or $C_{K^*\gamma}$ results from this procedure.

The Δt resolution strongly depends on the number of SVT layers traversed by the pions from the K_S^0 . In order for the Δt information to be useful, we require that each pion have at least 2 hits in the SVT, and that $\sigma_{\Delta t} < 2.5 \text{ ps}$ and $|\Delta t| < 20 \text{ ps}$. About 70% of the events in the data sample pass these requirements. The events for which the Δt information is not used can still contribute to the measurement of the $C_{K^*\gamma}$ parameter as long as they have flavor tagging information.

We extract signal yields and CP asymmetries using an unbinned maximum likelihood fit to

m_{ES} , ΔE , L_2/L_0 , $m(K_s^0\pi^0)$, flavor tag, Δt , and $\sigma_{\Delta t}$. As stated earlier, we expect a significant contribution from $B\bar{B}$ background, so we extract the event yield from this source as well as continuum background. The likelihood function is the same one used in the previous version of this analysis, and is described in detail in Ref. [18]. We assume that the correlation among the observables is small enough that the likelihood function can be constructed as a product of one-dimensional probability density functions (PDF). A systematic correction is applied later as a result of this assumption. All signal PDF parameters are determined using simulated events, except for the flavor tag efficiencies, mistag probabilities, and Δt resolution function parameters, which are determined from the B_{flav} sample. $B\bar{B}$ background shapes are also determined from simulation. We use the large fraction of background events in the fitted data sample to determine continuum background PDF parameters.

The Δt PDF for signal events and $B\bar{B}$ background is obtained from the convolution of Eq. 1 with a resolution function $\mathcal{R}(\delta t \equiv (\Delta t - \Delta t_{\text{true}}), \sigma_{\Delta t})$. The CP asymmetries for the $B\bar{B}$ background, $S_{B\bar{B}}$ and $C_{B\bar{B}}$, are fixed to zero in the fit, and we account for a possible deviation from zero in the systematic uncertainty. The resolution function is parameterized as the sum of three gaussian distributions [16]. The first two have a nonzero mean proportional to the reconstructed $\sigma_{\Delta t}$, accounting for a small bias in Δt from charm decays of the B_{tag} . Their width is also proportional to $\sigma_{\Delta t}$. The third gaussian is centered at zero with a fixed width of 8 ps. We have verified in simulation that the parameters of the resolution function for $B^0 \rightarrow K^{*0}\gamma$ events are compatible with those obtained from the B_{flav} sample. Therefore we use the B_{flav} parameters for better precision. We assume that the continuum background contains only prompt decays and find that the Δt distribution is well-described by a resolution function of the same form used by the signal PDF. The parameters of the background resolution function are determined in the fit to data.

Figure 1 shows the background-subtracted distributions for m_{ES} and ΔE for $B^0 \rightarrow K^{*0}\gamma$ candidates. The background subtraction is performed using the sPlot event weighting technique described in Ref. [19]. The curves in the figure represent the signal PDFs used in the fit. Figure 2 shows the background-subtracted distributions of Δt for B^0 - and \bar{B}^0 -tagged events, and the asymmetry as a function Δt .

We find 316 ± 22 signal events with

$$S_{K^{*}\gamma} = -0.08 \pm 0.31 \pm 0.05$$

and

$$C_{K^{*}\gamma} = -0.15 \pm 0.17 \pm 0.03,$$

where the first error is statistical and the second systematic. We discuss systematic uncertainties below. The statistical uncertainties have been increased beyond what was reported in the fit result because we have determined them to be underestimated, using an ensemble of simulated experiments in which events were generated from the likelihood PDFs. The scaling factors for $S_{K^{*}\gamma}$ and $C_{K^{*}\gamma}$ are 1.097 and 1.035 respectively. Because the uncertainty of $C_{K^{*}\gamma}$ is larger than that obtained from the partial rate asymmetry in self-tagging $B \rightarrow K^{*}\gamma$ decays [12], we also perform the fit with $C_{K^{*}\gamma}$ fixed to zero and find

$$S_{K^{*}\gamma}(C_{K^{*}\gamma} = 0) = -0.07 \pm 0.32 \pm 0.05.$$

The linear correlation coefficient between $S_{K^{*}\gamma}$ and $C_{K^{*}\gamma}$ is 0.046.

We consider several sources of systematic uncertainties related to the level and possible asymmetry of the background contribution from other B decays. We evaluate this contribution using

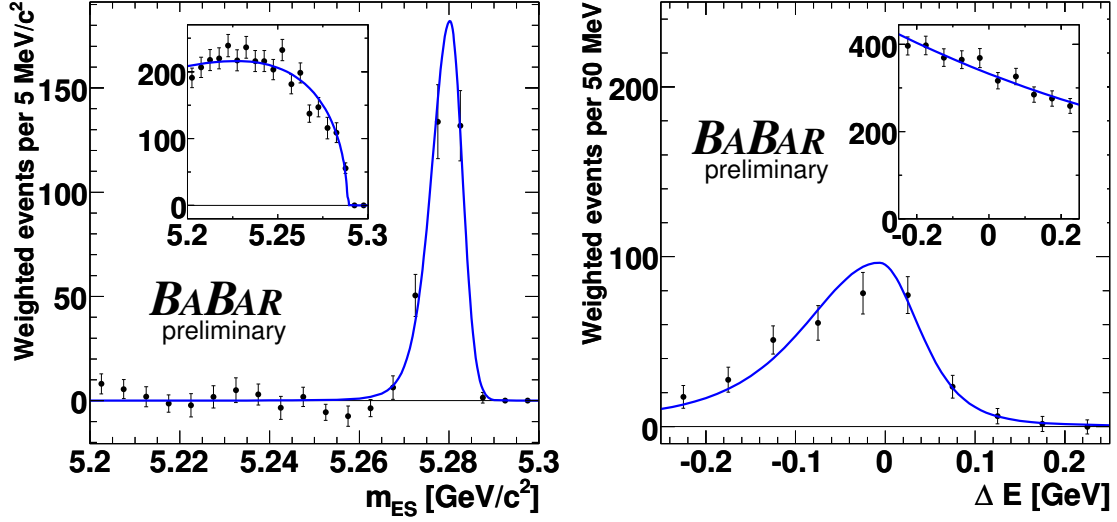


Figure 1: Signal and background (inset) distributions for m_{ES} (left) and ΔE (right) obtained with the weighting technique described in Ref. [19]. The curves represent the PDFs used in the fit, normalized to the fitted yield.

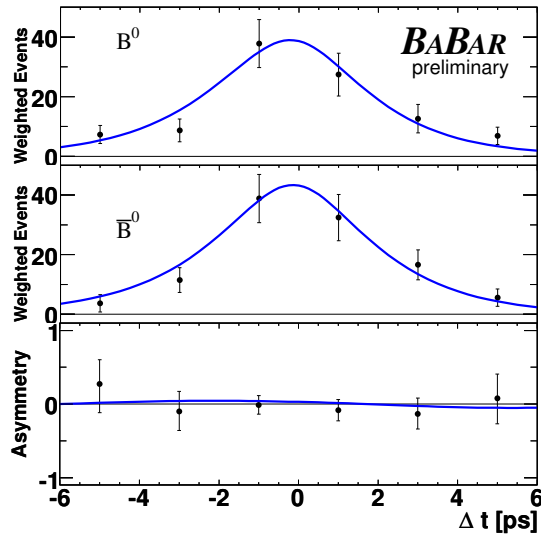


Figure 2: Signal distribution for Δt obtained with the weighting technique described in Ref. [19], with B_{tag} tagged as B^0 (top) or \bar{B}^0 (center), and the asymmetry (bottom). The curves represent the PDFs for signal decays in the likelihood fit, normalized to the final fit result.

Table 1: $B^0 \rightarrow K^{*0}\gamma$ systematic uncertainties.

Source	ΔS	ΔC
$B\bar{B}$ Background	0.029	0.018
Bias Uncertainty	0.034	0.015
Δt Resolution Function	0.011	0.018
Beamspot	0.004	0.001
SVT Alignment	0.002	0.001
PDF Uncertainty	0.025	0.010
DCS B_{tag} Decays	0.001	0.015
Total	0.052	0.035

simulated samples of non-signal $B \rightarrow X_s\gamma$ and other B decays. For the former we use the Kagan-Neubert model [20] to model the photon energy spectrum and JETSET for the fragmentation of the s quark. Since the final state multiplicity predicted by the fragmentation model is significantly different from *BABAR*'s measurement [21], we reweight events according to their multiplicity. From these studies we expect to find about 35 $B\bar{B}$ events, with approximately equal contributions from $B \rightarrow X_s\gamma$ decays and other generic B decays. The $B\bar{B}$ background yield extracted in the fit to the data is 22 ± 22 events. We vary $S_{B\bar{B}}$ and $C_{B\bar{B}}$ within a conservative range derived from the composition of the $B\bar{B}$ background sample and the CP asymmetry averages reported by the Heavy Flavor Averaging Group [12] to assign a systematic uncertainty due to the assumption of zero asymmetry in this source. Because the $B\bar{B}$ yield in data is smaller than expected, we fix it to the expected value when we vary its CP asymmetry within the $S_{B\bar{B}}$ range ± 0.41 and the $C_{B\bar{B}}$ range ± 0.33 . We assign uncertainties of 0.029 on $S_{K^*\gamma}$ and 0.018 on $C_{K^*\gamma}$ based on these variations.

In an ensemble of simulated experiments created by generating background events from the PDFs and embedding signal events from the full MC simulation, we determined there was bias in $S_{K^*\gamma}$ but not in $C_{K^*\gamma}$. We apply a correction of +0.067 to $S_{K^*\gamma}$, with a systematic uncertainty of half the shift. We also assign a systematic uncertainty of 0.015 to $C_{K^*\gamma}$ based on these tests.

Systematic effects due to uncertainties in the resolution function, beam spot position, and possible SVT misalignment are quantified in the same manner as Ref. [22]. We also include uncertainties due to imperfect knowledge of the fixed PDF parameters and shapes used in the fit, amounting to 0.025 on $S_{K^*\gamma}$ and 0.010 on $C_{K^*\gamma}$. Finally, uncertainties of 0.001 in $S_{K^*\gamma}$ and 0.015 in $C_{K^*\gamma}$ are included to account for doubly-Cabibbo-suppressed (DCS) decays of the B_{tag} [23]. The systematic uncertainties are summarized in Table 1.

In summary we have performed a new preliminary measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^{*0}(K_S^0\pi^0)\gamma$ decays. We have found it to be consistent with our previous result, as well as with the standard model expectation.

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