Observation of $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$

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We report observations of the $b \to d$ penguin-dominated decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ in 316 fb^{-1} of e^+e^- collision data collected with the *BABAR* detector. We measure the branching fractions $\mathcal{B}(B^+ \to \bar{K}^0 K^+) = (1.61 \pm 0.44 \pm 0.09) \times 10^{-6}$ and $\mathcal{B}(B^0 \to K^0 \bar{K}^0) = (1.08 \pm 0.28 \pm 0.11) \times 10^{-6}$ and the *CP*-violating charge asymmetry $\mathcal{A}_{CP}(\bar{K}^0 K^+) = 0.10 \pm 0.26 \pm 0.03$. Using a vertexing technique previously employed in several analyses of all-neutral final states containing kaons, we report the first measurement of time-dependent *CP*-violating asymmetries in $B^0 \to K^0_S K^0_S$, obtaining $S = -1.28^{+0.80+0.11}_{-0.73-0.16}$ and $C = -0.40 \pm 0.41 \pm 0.06$. We also report improved measurements of the branching fraction $\mathcal{B}(B^+ \to K^0 \pi^+) = (23.9 \pm 1.1 \pm 1.0) \times 10^{-6}$ and *CP*-violating charge asymmetry $\mathcal{A}_{CP}(K^0 \pi^+) = -0.029 \pm 0.039 \pm 0.010$.

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The decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ are expected to be dominated by the flavor-changing neutral-current process $b \to d\bar{s}s$, which is highly suppressed in the standard model and potentially sensitive to the presence of new particles in a way analogous to $b \to s\bar{s}s$ decays such as $B \to \phi K$ [1,2]. Assuming top-quark dominance in the virtual loop mediating the $b \to d$ transition [3], the charge asymmetry in $B^+ \to \bar{K}^0 K^+$ and the time-dependent *CP*-violating asymmetry parameters in $B^0 \to K^0_S K^0_S$ are expected to vanish, while contributions from lighter quarks or supersymmetric particles could induce observable asymmetries [4]. It has been noted [5] that the branching fraction and *CP* asymmetries in $B^0 \to K^0 \bar{K}^0$ are related in a nearly model-independent way, providing a sensitive test of the standard model description of *CP* violation.

In this Letter, we report observations of $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ using a data sample approximately 50% larger than the one used in our previous search [6]. (The use of charge-conjugate modes is implied throughout this Letter unless otherwise stated.) In addition to establishing these decay modes, we present measurements of the time-dependent *CP*-violating asymmetries in $B^0 \to K^0 \bar{K}^0$ for the first time. We also report updated measurements of the branching fraction and charge asymmetry in the $SU(3)$-related decay $B^+ \to K^0 \pi^+$.

The *CP* asymmetry in $B^0 \to K^0 \bar{K}^0$ (observed in the $K^0_S K^0_S$ final state) is determined from the difference in the time-dependent decay rates for B^0 and $\bar{B}^0$. In the process $e^+e^- \to \Upsilon(4S) \to B^0 \bar{B}^0$, the decay rate $f_+(f_-)$ is given by [7]

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

when the second B meson in the event (denoted $B_{\rm tag}$) is identified as $B^0(\bar{B}^0)$. Here Δt is the time difference between the decays of the signal and $B_{\rm tag}$ mesons, τ is the average B^0 lifetime, and Δm_d is the $B^0 - \bar{B}^0$ mixing frequency. The amplitude S describes *CP* violation in the interference between mixed and unmixed decays into the same final state, while C describes direct *CP* violation in decay.

The data sample used in this analysis contains $(347.5 \pm 3.8) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected by the *BABAR* detector [8] at the Stanford Linear Accelerator Center's (SLAC) PEP-II asymmetric-energy e^+e^- collider. The primary detector elements used in this analysis are a charged-particle tracking system, consisting of a five-layer silicon vertex tracker and a 40-layer drift chamber surrounded by a 1.5-T solenoidal magnet, and a dedicated particle-identification system, consisting of a detector of internally reflected Cherenkov light.

We identify two separate event samples corresponding to the decays $B^+ \to K^0_S h^+$ and $B^0 \to K^0_S K^0_S$, where h^+ is either a pion or a kaon. Neutral kaons are reconstructed in the mode $K^0_S \to \pi^+\pi^-$ by combining pairs of oppositely charged tracks originating from a common decay point and satisfying selection requirements on their invariant mass and proper decay time. Candidate h^+ tracks are assigned the pion mass and are required to originate from the interaction region and to have a well-measured Cherenkov angle (θ_c) consistent with either the pion or kaon particle hypothesis.

For each B^0 candidate, we require the absolute value of the difference ΔE between its reconstructed energy in the center-of-mass (c.m.) frame and the beam energy ($\sqrt{s}/2$) to be less than 100 MeV. For B^+ candidates, we require $-115 < \Delta E < 75$ MeV, where the lower limit accounts for an average shift in ΔE of -45 MeV in the $\bar{K}^0 K^+$ mode due to the assignment of the pion mass to the K^+ candidate. We also define a beam-energy substituted mass $m_{\rm ES} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where the B-candidate momentum $\mathbf{p}_B$ and the four-momentum of the initial e^+e^- state (E_i, $\mathbf{p}_i$) are calculated in the laboratory frame. We require $5.20 < m_{\rm ES} < 5.29$ GeV$/c^2$ for B candidates in both samples. To suppress the dominant background arising from the process $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$), we calculate the c.m. angle θ^*_S between the sphericity axis [9] of the B candidate and the sphericity axis of the remaining charged and neutral particles in the event and require $|\cos\theta^*_S| < 0.8$.

After applying all of the above requirements, we find 2321 (30 159) candidates in the B^0 (B^+) sample. The total detection efficiencies are given in Table I and include the branching fraction for $K^0_S \to \pi^+\pi^-$ [11] and a probability of 50% for $K^0\bar{K}^0 \to K^0_S K^0_S$ [12]. We use data and simulated Monte Carlo samples [13] to verify that backgrounds from other B decays are negligible.

TABLE I. Summary of results for the total detection efficiencies ε, fitted signal yields n, signal-yield significances s (including systematic uncertainty), charge-averaged branching fractions $\mathcal{B}$, and charge asymmetries $\mathcal{A}_{CP}$ (including 90% confidence intervals). The efficiencies include the branching fraction for $K_S^0 \to \pi^+\pi^-$ and the probability of 50% for $K^0\bar{K}^0 \to K_S^0 K_S^0$. Branching fractions are calculated assuming equal rates for $\Upsilon(4S) \to B^0\bar{B}^0$ and B^+B^- [10].

Mode	ε (%)	n	$s(\sigma)$	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$ (90% C.L.)
$B^+ \to K^0\pi^+$	12.9 ± 0.4	$1072 \pm 46^{+32}_{-37}$		$23.9 \pm 1.1 \pm 1.0$	$-0.029 \pm 0.039 \pm 0.010$	$[-0.092, 0.036]$
$B^+ \to \bar{K}^0K^+$	12.6 ± 0.4	$71 \pm 19 \pm 4$	5.3	$1.61 \pm 0.44 \pm 0.09$	$0.10 \pm 0.26 \pm 0.03$	$[-0.31, 0.54]$
$B^0 \to K^0\bar{K}^0$	8.5 ± 0.3	$32 \pm 8 \pm 3$	7.3	$1.08 \pm 0.28 \pm 0.11$		

A multivariate technique [14] is employed to determine the flavor of the $B_{\rm tag}$ meson in the B^0 sample. Separate neural networks are trained to identify primary leptons, kaons, low-momentum pions from D^* decays, and high-momentum charged particles from B decays. Events are assigned to one of six mutually exclusive "tagging" categories. The quality of tagging is expressed in terms of the effective efficiency $Q = \sum_k \epsilon_k (1\text{–}2w_k)^2$, where ϵ_k and w_k are the efficiencies and mistag probabilities, respectively, for events tagged in category k. We measure the tagging performance in a data sample of fully reconstructed neutral B decays ($B_{\rm flav}$) to $D^{(*)-}(\pi^+, \rho^+, a_1^+)$, where the flavor of the decaying B meson is known, and find a total effective efficiency of $Q = (30.4 \pm 0.3)\%$.

The time difference $\Delta t \equiv \Delta z/\beta\gamma c$ is obtained from the known boost of the e^+e^- system ($\beta\gamma = 0.56$) and the measured distance Δz along the beam (z) axis between the $B^0 \to K_S^0 K_S^0$ and $B_{\rm tag}$ decay vertices. The position of the $B_{\rm tag}$ vertex is determined from the remaining charged particles in the event after removing the four tracks composing the signal candidate. Despite the relatively long lifetime of the K_S^0 mesons, the z position of the B-candidate decay point is obtained reliably by exploiting the precise knowledge of the interaction point using the technique described in Ref. [15]. We compute Δt and its error from a combined fit to the $\Upsilon(4S) \to B^0\bar{B}^0$ decay, including the constraint from the known average lifetime of the B^0 meson. Approximately 82% of signal events contain a K_S^0 reconstructed from pions that each have at least two hits in the silicon vertex tracker, providing sufficiently small Δt uncertainty (0.9 ps) to perform the measurement. We require $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the uncertainty on Δt determined separately for each event. The resolution function for signal candidates is a sum of three Gaussian distributions with parameters determined from the $B_{\rm flav}$ sample [14]. The background Δt distribution has the same functional form as the signal resolution function, with parameters determined directly from data.

To obtain the yields and CP violating asymmetry parameters in each sample, we apply separate unbinned maximum-likelihood fits incorporating discriminating variables that account for differences between $B\bar{B}$ and $q\bar{q}$ events. In addition to the kinematic variables $m_{\rm ES}$ and ΔE, we include a Fisher discriminant $\mathcal{F}$ [16], defined as an optimized linear combination of the event-shape variables $\sum_i p_i^*$ and $\sum_i p_i^* \cos^2\theta_i^*$, where p_i^* is the c.m. momentum of particle i, θ_i^* is the c.m. angle between the momentum of particle i and the B-candidate thrust axis, and the sum is over all particles in the event excluding the B daughters. For the fit to the B^+ sample, we include the Cherenkov angle measurement to separate $K_S^0\pi^+$ and $K_S^0K^+$ decays. For the B^0 sample, we include Δt to determine the CP-violating asymmetry parameters S and C simultaneously with the signal yield.

The likelihood function to be maximized is defined as $\mathcal{L} = \exp(-\sum_i n_i) \prod_{j=1}^N [\sum_i n_i \mathcal{P}_i]$, where n_i and $\mathcal{P}_i$ are the yield and probability density function (PDF) for each component i in the fit, and N is the total number of events in the sample. For the B^0 sample, there are two components (signal and background), and the total PDF is calculated as the product of the individual PDFs for $m_{\rm ES}$, ΔE, $\mathcal{F}$, and Δt. The signal Δt PDF is derived from Eq. (1), modified to take into account the mistag probability, and convolved with the resolution function. We combine B^+ and B^- candidates in a single fit and include the PDF for θ_c to determine separate yields and charge asymmetries for the two signal components $K_S^0\pi$ and K_S^0K and two corresponding background components. For both signal and background, the $K_S^0h^\pm$ yields are parametrized as $n_\pm = n(1 \mp \mathcal{A}_{CP})/2$; we fit directly for the total yield n and the charge asymmetry $\mathcal{A}_{CP}$. We have found correlations among the PDF variables in the fit to be negligible in both the B^0 and the B^+ samples.

The parametrizations of the PDFs are determined from data wherever possible. In both samples, we exploit the large sideband regions in $m_{\rm ES}$ and ΔE to determine all background PDF parameters simultaneously with the yields and CP asymmetries in the fits. For the B^+ sample, the large signal $K_S^0\pi^+$ component allows for an accurate determination of the peak positions for $m_{\rm ES}$ and ΔE, as well as the parameters describing the shape of the PDF for $\mathcal{F}$. The remaining shape parameters describing $m_{\rm ES}$ and ΔE are determined from simulated Monte Carlo samples and are fixed in the fit. We use the $K_S^0\pi^+$ parameters to describe signal $K_S^0K^+$ PDFs in $m_{\rm ES}$, ΔE, and $\mathcal{F}$, taking into account the known shift in the mean of ΔE due to the pion-mass hypothesis. For both signal and background, the θ_c PDFs are obtained from a sample of $D^{*+} \to D^0\pi^+ (D^0 \to K^-\pi^+)$ decays reconstructed in data, as described in

Ref. [17]. For the B^0 sample, all shape parameters describing the $m_{\rm ES}$, ΔE, and $\mathcal{F}$ signal PDFs are fixed to the values determined from Monte Carlo simulation except the peak position for ΔE, which is derived from the results of the fit to the B^+ sample.

Several cross-checks were performed to validate the fitting technique before data in the signal region were examined. We checked for biases by performing pseudoexperiments where simulated Monte Carlo signal events were mixed with background events generated directly from the PDFs according to the expected yields in the data. The resulting small biases on the yields include effects of incorrect particle identification and are accounted for in the systematic uncertainties.

The fit results supersede our previous measurements of these quantities and are summarized in Table I. The signal yields for $B^+ \to K_S^0 K^+$ and $B^0 \to K_S^0 K_S^0$ correspond to significances of 5.3σ and 7.3σ (including systematic uncertainties), respectively, and are consistent with our previous measurements [6], as well as with recent results by the Belle Collaboration [18]. The significances are computed by taking the square root of the change in $2\ln\mathcal{L}$ when the appropriate yield is fixed to zero. The fit to the B^0 sample yields $S = -1.28^{+0.80+0.11}_{-0.73-0.16}$ and $C = -0.40 \pm 0.41 \pm 0.06$, where the first errors are statistical and the second are systematic. The linear correlation coefficient between S and C is -32%.

In Fig. 1, we compare data and PDFs using the event-weighting technique described in Ref. [19]. We perform fits excluding the variable being shown; the covariance matrix and remaining PDFs are used to determine a weight that each event is either signal (main plot) or background (inset). The resulting distributions (points with errors) are normalized to the appropriate yield and can be directly compared with the PDFs (solid curves) used in the fits. We find good agreement between data and the assumed shapes in both $m_{\rm ES}$ and ΔE. In Fig. 2, we display the Δt distributions for $K_S^0 K_S^0$ events tagged as B^0 or $\bar{B}^0$ and the asymmetry $\mathcal{A} = (N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$. The projections are enhanced in signal decays by selecting on probability ratios calculated from the signal and background PDFs (excluding Δt). The likelihood function in the $B^0 \to K_S^0 K_S^0$ fit is used to derive Bayesian confidence-level contours in the C vs S plane by fixing (S, C) to specific values, refitting the data, and recording the change in $-2\log\mathcal{L}$. Figure 2 shows the resulting $n\sigma$ contours in the physical region defined by $S^2 + C^2 < 1$.

Systematic uncertainties on the signal yields are primarily due to the imperfect knowledge of the PDF shapes. We evaluate this uncertainty by varying the PDF parameters that are fixed in the fit within their statistical errors and by substituting different functional forms for the PDF shapes. For the charged modes, the largest contribution is due to the signal parametrization of $m_{\rm ES}$ and ΔE (3% for $K_S^0\pi^+$, 4% for $K_S^0 K^+$), while for the neutral mode it is due to the potential fit bias (8.6%) determined from the pseudoexperiments. We use the larger of the value or uncertainty on the background asymmetries to set the systematic uncertainty on $\mathcal{A}_{CP}$ due to potential charge bias [17]. We measure background asymmetries $\mathcal{A}_{CP}(K_S^0\pi^+) = -0.010 \pm 0.008$

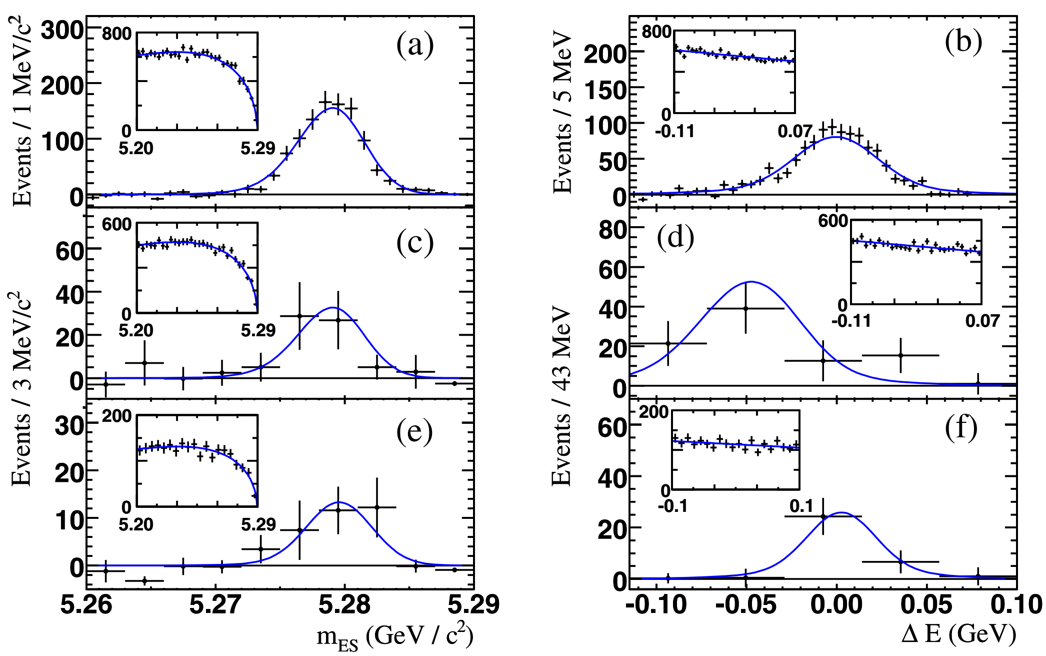

FIG. 1 (color online). Distributions of (left) $m_{\rm ES}$ and (right) ΔE for signal (main plot) and background (inset) (a),(b) $K_S^0\pi^+$, (c),(d) $K_S^0 K^+$, and (e),(f) $K_S^0 K_S^0$ candidates (points with error bars) in data obtained with the weighting technique described in the text. The solid curves represent the assumed shapes used in the fits.

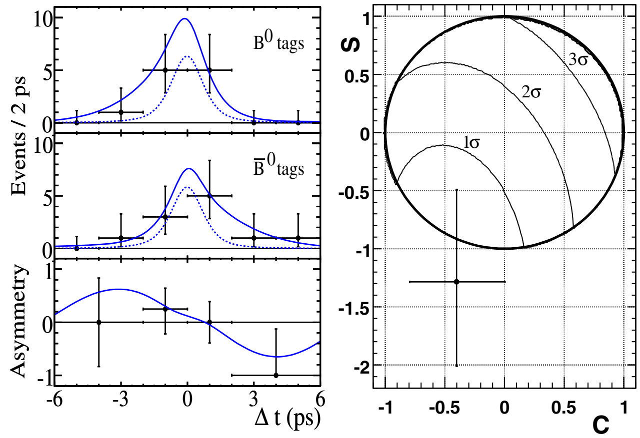

FIG. 2 (color online). Left: Distributions of Δt for $B^0 \to K^0_S K^0_S$ decays in data tagged as B^0 (top) or $\bar{B}^0$(middle) and the asymmetry (bottom). The data are enhanced in signal decays using requirements on probability ratios. The solid curve represents the PDF projection for the sum of signal and background, while the dotted curve shows the contribution from background only. Right: Likelihood contours in the S vs C plane, where $n\sigma$ corresponds to a change in $-2\log\mathcal{L}$ of 2.3 for $n = 1$, 6.2 for $n = 2$, and 11.8 for $n = 3$. The circle indicates the physically allowed region, while the point with error bars denotes the result of the fit to the data.

and $\mathcal{A}_{CP}(K^0_S K^+) = -0.005 \pm 0.009$, which are consistent with no bias and lead to a systematic uncertainty of 0.010. The dominant sources of systematic uncertainty on S and C are due to the positions of the means in $m_{\rm ES}$ and ΔE. The statistical uncertainties of the measured values of the CP parameters are in good agreement with the expected error values (0.8 ± 0.3 for S and 0.6 ± 0.2 for C), while Monte Carlo studies confirm that the fit technique is unbiased for large values of the CP parameters.

In summary, we have observed the decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ with significances of 5.3σ and 7.3σ, respectively. The observed branching fractions are consistent with recent theoretical estimates [5,20]. The measured values of the time-dependent CP-violating asymmetry parameters in the $B^0 \to K^0_S K^0_S$ mode reported here indicate that large positive values of S are disfavored, although more data will be needed to confirm this result. We have also improved our measurements of the branching fraction and CP-violating charge asymmetry in $B^+ \to K^0_S \pi^+$; both are consistent with previous measurements by other experiments [21].

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