Evidence for $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$, and Measurement of the Branching Fraction and Search for Direct CP Violation in $B^+ \to K^0 \pi^+$

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We present evidence for the $b \to d$ penguin-dominated decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ in 227×10^6 $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector. We measure the branching fractions $\mathcal{B}(B^+ \to \bar{K}^0 K^+) = (1.5 \pm 0.5 \pm 0.1) \times 10^{-6} (< 2.4 \times 10^{-6})$ and $\mathcal{B}(B^0 \to K^0 \bar{K}^0) = (1.19^{+0.40}_{-0.35} \pm 0.13) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively. We also present improved measurements of the charge-averaged branching fraction $\mathcal{B}(B^+ \to K^0 \pi^+) = (26.0 \pm 1.3 \pm 1.0) \times 10^{-6}$ and CP-violating charge asymmetry $\mathcal{A}_{CP}(K^0 \pi^+) = -0.09 \pm 0.05 \pm 0.01$, where the uncertainties are statistical and systematic, respectively.

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Flavor-changing neutral currents are forbidden at first order in the standard model, but can proceed through weak interactions that are described by one-loop Feynman diagrams commonly referred to as "penguins" (see Fig. 1 in Ref. [1]). Such decay processes were first established in the B system more than a decade ago through observation of the radiative decay $B \to K^* \gamma$ [1], which is dominated by the $b \to s\gamma$ electromagnetic-penguin amplitude. Recently, the analogous gluonic-penguin process $b \to sg(g \to s\bar{s})$ has been used extensively to test the standard model predictions for the CP-violating asymmetry amplitudes of decay modes such as $B^0 \to \phi K^0_S$ [2]. To date, no direct evidence has been found for decays dominated by the corresponding $b \to dg$ transition, whose amplitude is suppressed relative to that for the $b \to sg$ process by the small ratio $V_{\rm td}/V_{\rm ts}$ involving elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [3].

In this Letter, we report evidence for the decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$, which are expected to be dominated by the $b \to dg(g \to s\bar{s})$ penguin diagram, and an updated measurement of the branching fraction and direct CP-violating charge asymmetry for $B^+ \to K^0 \pi^+$ (the use of charge conjugate modes is implied throughout this paper unless otherwise stated). Our previous search for $B \to KK^0$ yielded branching-fraction upper limits at the level of 2×10^{-6} [4], which are consistent with recent theoretical estimates based on perturbative calculations [5], as well as the lower bounds implied by $SU(3)$ symmetry [6].

Once the decay $B^0 \to K^0 \bar{K}^0$ has been established, a measurement of its time-dependent CP-violating asymmetry (through the technique described in Ref. [7]) could provide important constraints on physics beyond the standard model. Assuming top-quark dominance in the penguin loop, the asymmetry is expected to vanish in the standard model [8], while contributions from supersymmetric particles could be significant [9]. Although soft rescattering effects could weaken the sensitivity to new physics in this mode [10], the ratio of decay rates for $B^+ \to \bar{K}^0 K^+, K^0 \pi^+$ can be used to constrain the relative size of such effects [11].

Recent measurements of the partial-rate asymmetry in $B^0 \to K^+ \pi^-$ decays by the *BABAR* [12] and Belle [13] experiments have established direct CP violation in the B system. In this Letter, we search for direct CP violation in the decays $B^+ \to K^0 \pi^+, \bar{K}^0 K^+$ through measurement of the charge asymmetry

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)},$$

where $f^\pm = K^0_S \pi^\pm, K^0_S K^\pm$. The decay $B^- \to \bar{K}^0 \pi^-$ is dominated by the $b \to s$ penguin process and, neglecting rescattering effects [11], is expected to yield $\mathcal{A}_{CP} \sim 1\%$ [5,14]. Observation of a significant charge asymmetry could therefore indicate new physics entering the penguin loop [15]. The decay rate and charge asymmetry in $K^0_S \pi^+$ can also be used to constrain the angle γ of the unitarity triangle [16].

The data sample used in this analysis contains $(226.6 \pm 2.5) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected by the *BABAR* detector [17] at the 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 (DIRC).

We identify two separate event samples corresponding to the decay topologies $B^0 \to K^0_S K^0_S$ and $B^+ \to K^0_S h^+$, where $h^\pm$ 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 having a $\pi^+\pi^-$ invariant mass within 11.2 MeV$/c^2$ of the nominal K^0_S mass [18]. To reduce combinatorial background, we require the measured proper decay time of the K^0_S to be greater than 5 times its uncertainty. Candidate h^+ tracks are assigned the pion mass and are required to originate from the interaction region and to have an associated Cherenkov angle (θ_c) measurement with at least six signal photons detected in the DIRC. To reduce backgrounds from protons and leptons, we require θ_c to be within 4 standard deviations (σ) of the expectation for either the pion or kaon particle hypothesis. The B^0 sample is formed by combining pairs of K^0_S candidates, while the B^+ sample is formed by combining K^0_S and h^+ candidates.

For each B^0 candidate, we require the difference ΔE between its reconstructed center-of-mass (c.m.) energy and

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 $K^0_S \to \pi^+\pi^-$ and the probability of 50% for $K^0\bar{K}^0 \to K^0_S K^0_S$. Branching fractions are calculated assuming equal rates for $\Upsilon(4S) \to B^0\bar{B}^0$ and B^+B^- [19]. For $\bar{K}^0 K^+$, we give both the central value of the branching fraction and, in parentheses, the 90% confidence-level (C.L.) upper limit.

Mode	ε (%)	n	$s(\sigma)$	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$ (90% C.L.)
$B^+ \to K^0\pi^+$	12.6 ± 0.3	744^{+37+21}_{-36-17}		$26.0 \pm 1.3 \pm 1.0$	$-0.09 \pm 0.05 \pm 0.01$	$[-0.16, -0.02]$
$B^+ \to \bar{K}^0 K^+$	12.5 ± 0.3	41^{+15+3}_{-13-2}	3.5	$1.5 \pm 0.5 \pm 0.1 (< 2.4)$	$0.15 \pm 0.33 \pm 0.03$	$[-0.43, 0.68]$
$B^0 \to K^0\bar{K}^0$	8.5 ± 0.6	$23^{+8}_{-7} \pm 2$	4.5	$1.19^{+0.40}_{-0.35} \pm 0.13$		

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^+. 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 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 1939 (20 441) candidates in the B^0 (B^+) samples, respectively. The fraction of events containing more than one B candidate is negligible (<0.5%). The total detection efficiencies are given in Table I and include the branching fraction for $K^0_S \to \pi^+\pi^-$ [18] and a probability of 50% for $K^0\bar{K}^0 \to K^0_S K^0_S$ [20]. We use data and simulated Monte Carlo samples [21] to verify that backgrounds from other B decays are negligible. The selected samples are therefore assumed to be composed of signal B decays and background candidates arising from random combinations of tracks and K^0_S mesons in $q\bar{q}$ events.

To determine signal yields 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 $\mathcal{F}$ [22] 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.

The likelihood function to be maximized is defined as

$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_{j=1}^{N} \left[\sum_i n_i \mathcal{P}_i\right],$$

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 only two components (signal and background), and the total PDF is calculated as the product of the individual PDFs for $m_{\rm ES}$, ΔE, and $\mathcal{F}$. 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, $K^0_S\pi$ and $K^0_S K$, and two corresponding background components. For both signal and background, the $K^0_S h^\pm$ 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 $\mathcal{A}_{CP}$.

The parametrizations of the PDFs are determined from data wherever possible. For the B^+ sample, the large signal $K^0_S\pi^+$ 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 $\mathcal{F}$. We therefore allow these parameters to vary freely in the fit. The remaining shape parameters describing $m_{\rm ES}$ and ΔE are determined from simulated Monte Carlo samples and are fixed in the fit. Except for the mean value of ΔE, which is shifted by our use of the pion mass hypothesis for the h^+ candidate, we use the $K^0_S\pi^+$ parameters to describe signal $K^0_S K^+$ decays. The parameters describing the background PDFs in $m_{\rm ES}$ and $\mathcal{F}$ are allowed to vary freely in the fit, while the ΔE parameters are determined in the signal-free region of $m_{\rm ES}$ ($5.20 < m_{\rm ES} < 5.26$ GeV$/c^2$) and fixed in the fit. 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. [12]. For the B^0 sample, all shape parameters describing the signal PDFs are fixed to the values determined from Monte Carlo simulation, while the peak positions for $m_{\rm ES}$ and ΔE are derived from the results of the fit to the B^+ sample. We allow the background $\mathcal{F}$ shape parameters to vary freely, while the PDF parameters for $m_{\rm ES}$ and ΔE are fixed to the values determined from data in the signal-free regions $100 < |\Delta E| < 300$ MeV (for $m_{\rm ES}$) and $5.20 < m_{\rm ES} < 5.26$ GeV$/c^2$ (for ΔE).

Several cross-checks were performed to validate the fitting technique before data in the signal region were examined. We confirmed the internal self-consistency of the fitting algorithm by generating and fitting a large set of pseudoexperiments where signal and background events were generated randomly from the PDFs with yields corresponding to the expected values based on our previous analysis of these modes [4]. Correlations among the discriminating variables in background data events are found to be negligible. To check for residual correlations between the discriminating variables in signal events, we performed a second test for the $K_S^0 K_S^0$ mode where simulated Monte Carlo samples of signal events were mixed with background events generated directly from the PDFs. We observed an average bias corresponding to approximately one event and include this effect in the systematic uncertainty on the fitted $K_S^0 K_S^0$ yield. Potential $K_S^0 \pi \to K_S^0 K$ cross-feed was evaluated by fitting large samples of simulated Monte Carlo signal events. The resulting small (<0.5%) biases are included in the systematic uncertainty on the fitted yields.

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 3.5σ and 4.5σ (including systematic uncertainties), respectively, and are consistent with our previous results [4], as well as with the results of other experiments [23]. The signal yield for $B^+ \to K_S^0 \pi^+$ is somewhat higher than expected from our previous result. A reanalysis of the first 88×10^6 $B\bar{B}$ events yields 285 ± 21 $K_S^0 \pi^+$ signal events, compared with 255 ± 20 reported in Ref. [4]. Approximately half of this difference is due to reprocessing of the data with improved calibration constants. The remaining difference is due to improved knowledge of the PDF parameters, which were the largest source of systematic uncertainty for the previous result. We find

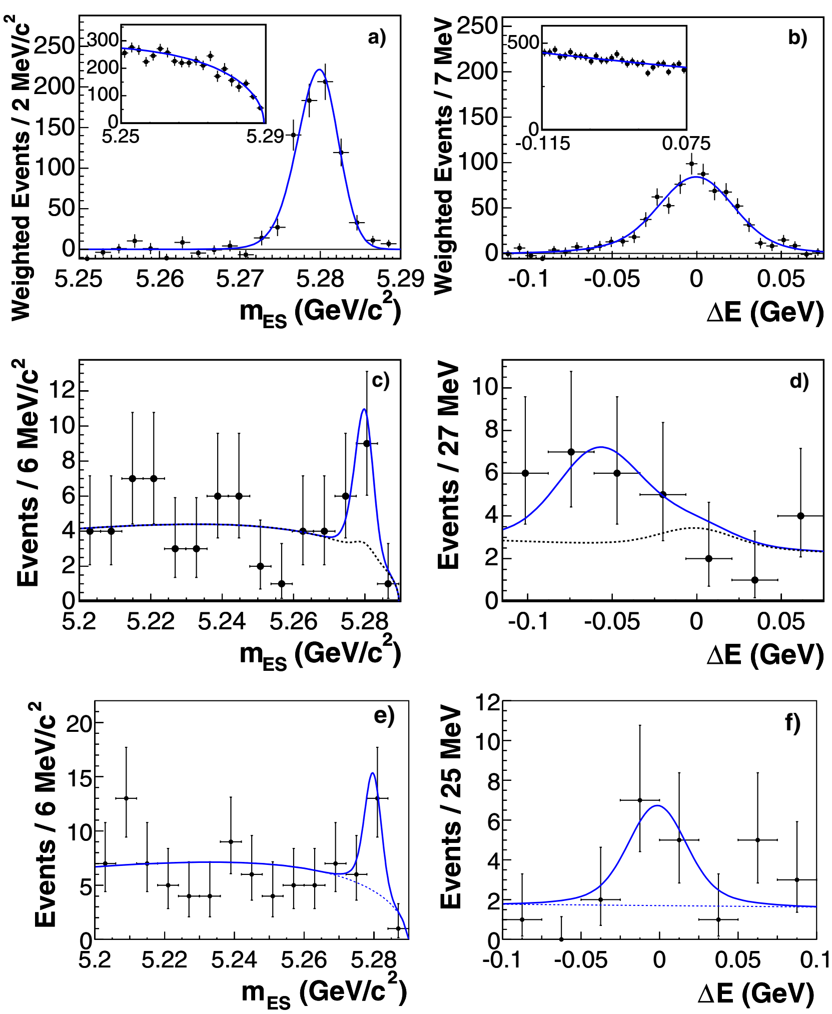

FIG. 1 (color online). Distributions of (a) m_{ES} and (b) ΔE for signal (main plot) and background (inset) $B^+ \to K_S^0 \pi^+$ candidates (points with error bars) using the weighting technique described in the text. Solid curves represent the corresponding PDFs used in the fit. In (c)–(f) we show projections of m_{ES} and ΔE for $K_S^0 K^+$ (c), (d) and $K_S^0 K_S^0$ (e), (f) decays (points with error bars) enhanced in signal decays using additional requirements on probability ratios. Solid curves represent the PDF projections for the sum of signal and background components, while the dotted curves show the contribution from background only.

459 ± 29 events in the remaining 139×10^6 $B\bar{B}$ events, which is consistent with the signal yield obtained in the first part of the sample.

For the $K^0_S K^+$ mode, we compute an upper limit on the signal yield as the value of n_0 for which $\int_0^{n_0} \mathcal{L}_{\max} dn / \int_0^{\infty} \mathcal{L}_{\max} dn = 0.9$, where $\mathcal{L}_{\max}$ is the likelihood as a function of n, maximized with respect to the remaining free parameters. The corresponding branching-fraction upper limit is calculated by increasing n_0 and reducing the efficiency by their respective systematic uncertainties.

We compare data and PDFs in the high-statistics $K^0_S\pi^+$ mode using the event-weighting technique described in Ref. [24]. For the plots in Figs. 1(a) and 1(b), we perform a fit 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 PDF shapes for $m_{\rm ES}$ and ΔE. In Figs. 1(c)–1(f), we show projections of the $K^0_S K^+$ and $K^0_S K^0_S$ data obtained by selecting on probability ratios calculated from the signal and background PDFs (except the variable being plotted). The solid curves in each plot show the fit result after correcting for the efficiency of this additional selection.

Systematic uncertainties on the signal yields are 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 parametrizations for $m_{\rm ES}$ ($^{+13}_{-15}$ events for $K^0_S\pi^+$, $^{+1.3}_{-1.7}$ events for $K^0_S K^+$) and ΔE ($^{+16}_{-5}$ events for $K^0_S\pi^+$, $^{+2.8}_{-0.7}$ events for $K^0_S K^+$), while for the neutral mode it is due to uncertainty in the background $m_{\rm ES}$ shape (± 0.7 events) and the potential fit bias (± 1.4 events). The systematic uncertainties on efficiency estimates are dominated by the selection on $\cos\theta^*_S$ (2.5%) and the uncertainty (1.2% per K^0_S) in K^0_S reconstruction efficiencies evaluated in a large inclusive sample of K^0_S mesons reconstructed in data. We use the uncertainty on the background asymmetries to set the systematic uncertainty on $\mathcal{A}_{CP}$ due to potential bias [12]. We find $\mathcal{A}_{CP}(K^0_S\pi) = -0.005 \pm 0.010$ and $\mathcal{A}_{CP}(K^0_S K) = -0.002 \pm 0.011$, consistent with no bias.

In summary, we find evidence for the decays $B^+ \to \bar{K}^0 K^+$ and $B^0 \to K^0 \bar{K}^0$ with branching fractions on the order of 10^{-6} and significances of 3.5σ and 4.5σ, respectively, including systematic uncertainties. These results represent evidence for the $b \to dg$ penguin-decay process. The branching fractions are consistent with recent theoretical estimates [5], implying that soft rescattering effects may not play an important role in these decays. We also measure the branching fraction $\mathcal{B}(B^+ \to K^0_S\pi^+) = (26.0 \pm 1.3 \pm 1.0) \times 10^{-6}$ and the CP-violating charge asymmetry $\mathcal{A}_{CP}(K^0_S\pi^+) = -0.09 \pm 0.05 \pm 0.01$, which are both consistent with previous measurements by other experiments [23,25].

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