Branching Fractions and CP Asymmetries in $B^0 \to K^+K^-K^0_S$ and $B^+ \to K^+K^0_SK^0_S$

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We measure the branching fractions and CP asymmetries in the decays $B^0 \to K^+K^-K^0_S$ and $B^+ \to K^+K^0_SK^0_S$ using a sample of approximately 122×10^6 $B\overline{B}$ pairs collected by the *BABAR* detector. From a time-dependent analysis of the $K^+K^-K^0_S$ sample that excludes ϕK^0_S, the values of the CP-violation parameters are $S = -0.56 \pm 0.25 \pm 0.04$ and $C = -0.10 \pm 0.19 \pm 0.10$, where the first uncertainty is statistical and the second is systematic. We confirm that the final state is nearly purely CP even and extract the standard model parameter $\sin 2\beta = 0.57 \pm 0.26 \pm 0.04^{+0.17}_{-0}$ where the last error is due to uncertainty on the CP content. We present the first measurement of the CP-violating charge asymmetry $\mathcal{A}_{CP}(B^+ \to K^+ K^0_S K^0_S) = -0.04 \pm 0.11 \pm 0.02$. The branching fractions are $\mathcal{B}(B^0 \to K^+ K^- K^0) = (23.8 \pm 2.0 \pm 1.6) \times 10^{-6}$ and $\mathcal{B}(B^+ \to K^+ K^0_S K^0_S) = (10.7 \pm 1.2 \pm 1.0) \times 10^{-6}$.

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In the standard model (SM) of particle physics, the decays $B^0 \to K^+ K^- K^0_S$ and $B^+ \to K^+ K^0_S K^0_S$ [1] are dominated by $b \to s\bar{s}s$ gluonic penguin diagrams [2]. CP violation in such decays arises from the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing mechanism [3]. Neglecting CKM-suppressed contributions, the expectation for the CP-asymmetry parameters in $B^0 \to K^+ K^- K^0_S$ decays is the same as in $B^0 \to J/\psi K^0_S$ decays, where CP violation has been observed [4,5]. The decay rates for $B^+ \to K^+ K^0_S K^0_S$ and $B^- \to K^- K^0_S K^0_S$ are expected to be equal. However, contributions from physics beyond the SM could invalidate these predictions [6]. Since $b \to s\bar{s}s$ decays involve one-loop transitions, they are especially sensitive to additional contributions. Present results in decays of neutral B mesons are inconclusive due to large statistical errors. Belle measures the CP asymmetry parameter in ϕK^0_S decays of $\sin 2\beta = -0.96 \pm 0.50^{+0.09}_{-0.11}$ [7] which is 3.5 standard deviations from the SM expectation of $\sin 2\beta = 0.731 \pm 0.056$ [4,5]. A *BABAR* measurement of $\sin 2\beta = 0.47 \pm 0.34^{+0.08}_{-0.06}$ [8] is consistent with the SM and disagrees with Belle by 2.3 standard deviations.

A more accurate CP measurement can be made using all the decays to $K^+ K^- K^0_S$ that do not contain a ϕ meson. This sample is several times larger than the sample of ϕK^0_S [9,10]. As Belle noted [10], the CP content of the final state can be extracted using an isospin analysis. In decays that exclude ϕK^0_S, Belle measures $\sin 2\beta = 0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0}$ [7], consistent with the SM expectation. In this Letter we present measurements of CP asymmetry and CP content in $K^+ K^- K^0_S$ decays, and the first measurement of the charge asymmetry rate in $B^+ \to K^+ K^0_S K^0_S$ decays.

This analysis is based on about 122×10^6 $B\bar{B}$ pairs collected with the *BABAR* detector [11] at the PEP-II asymmetric-energy e^+e^- storage rings at SLAC, operating on the $\Upsilon(4S)$ resonance. We reconstruct B mesons from $K^0_S \to \pi^+\pi^-$ and $K^\pm$ candidates. Charged kaons are distinguished from pions and protons using energy-loss (dE/dx) information in the tracking system and from the Cherenkov angle and number of photons measured by the detector of internally reflected Cherenkov light. We accept $K^0_S \to \pi^+\pi^-$ candidates that have a two-pion invariant mass within 12 MeV/c^2 of the nominal K^0_S mass [12], a decay length greater than 3 standard deviations, and a cosine of the angle between the line connecting the B and K^0_S decay vertices and the K^0_S momentum greater than 0.999. The three daughters in the B decay are fitted constraining their paths to a common vertex, and the K^0_S mass to the nominal value.

In the characterization of the B candidates we use two kinematic variables. The energy difference $\Delta E = E_B - \sqrt{s}/2$ is reconstructed from the energy of the B candidate E_B and the total energy $\sqrt{s}$ in the e^+e^- center-of-mass (c.m.) frame. The ΔE resolution for signal events is 18 MeV. We also use the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 - \vec{p}_B^{\,2}}$, where $(\vec{p}_i, E_i)$ is the four-momentum of the initial e^+e^- system and $\vec{p}_B$ is the momentum of the B candidate, both measured in the laboratory frame. The $m_{\rm ES}$ resolution for signal events is 2.6 MeV/c^2. We retain candidates with $|\Delta E| < 200$ MeV and $5.2 < m_{\rm ES} < 5.3$ GeV/c^2.

The background is dominated by random combinations of tracks created in $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events. We suppress this background by utilizing the difference in the topology in the c.m. frame between jetlike $q\bar{q}$ events and spherical signal events. The topology is described using angle θ_T between the thrust axis of the B candidate and the thrust axis of the charged and neutral particles in the rest of the event (ROE) [11]. Other quantities that characterize the event topology are two sums over the ROE: $\sum |\vec{p}_i^{\,*}|$ and $\sum |\vec{p}_i^{\,*}| \cos^2\theta_i$, where θ_i is the angle between the momentum $\vec{p}_i^{\,*}$ and the thrust axis of the B candidate. Additional separation is achieved using the angle θ_B between the B-momentum direction and the beam axis. After requiring $|\cos\theta_T| < 0.9$, these four event shape variables are combined into a Fisher discriminant $\mathcal{F}$ [13].

The remaining background originates from B decays where a neutral or charged pion is missed during reconstruction (peaking B background). We use Monte Carlo (MC) events to model the signal and the peaking background, and data sidebands to model continuum background.

We suppress background from B decays that proceed through a $b \to c$ transition leading to the $K^+ K^- K^0_S$ ($K^+ K^0_S K^0_S$) final state by applying invariant mass cuts to remove $D^0 \to KK$, $D^+ \to K^+ K^0_S$, $J/\psi \to KK$, and $\chi_{c0} \to KK(K^0_S K^0_S)$ decays. Finally, B decays into final states with pions are eliminated by requiring the pion misidentification rate to be less than 2%.

The time-dependent CP asymmetry is obtained by measuring the proper time difference Δt between a fully reconstructed neutral B meson (B_{CP}) decaying into $K^+K^-K^0_S$, and the partially reconstructed recoil B meson ($B_{\rm tag}$). Decay products of the recoil side are used to determine the $B_{\rm tag}$ meson's flavor (flavor tag) and to classify the event into five mutually exclusive tagging categories [4]. If the fraction of events in category c is ϵ_c and the mistag probability is w_c, the overall quality of the tagging, $\sum_c \epsilon_c(1-2w_c)^2$, is $(28.0 \pm 0.4)\%$.

The time difference Δt is extracted from the measurement of the separation Δz between the B_{CP} and $B_{\rm tag}$ vertices, along the boost axis (z) of the $B\overline{B}$ system. The vertex position of the B_{CP} meson is reconstructed primarily from kaon tracks, and its MC-estimated resolution ranges between 40 and 80 μm, depending on the opening angle and direction of the kaon pair. The final Δt resolution is dominated by the uncertainty on the $B_{\rm tag}$ vertex which allows the Δt (Δz) precision with rms of 1.1 ps (180 μm). We retain events that have $|\Delta t| < 20$ ps and whose estimated uncertainty $\sigma_{\Delta t}$ is less than 2.5 ps. The Δt resolution function is parametrized as a sum of two Gaussian distributions whose widths are given by a scale factor times the event-by-event uncertainty $\sigma_{\Delta t}$. A third Gaussian distribution, with a fixed large width, accounts for a small fraction of outlying events [4].

Parameters describing the tagging performance and the Δt resolution function are extracted from approximately 30 000 B^0 decays into $D^{(*)-}X^+$ ($X^+ = \pi^+, \rho^+, a_1^+$) flavor eigenstates ($B_{\rm flav}$ sample).

The decay rate f_+ (f_-) when the flavor of the tagging meson is a B^0 ($\overline{B}^0$) is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \quad (1)$$

where τ_{B^0} is the mean B^0 lifetime and Δm_d is the B^0–$\overline{B}^0$ oscillation frequency. The parameters C and S describe the magnitude of CP violation in the decay and the interference between decay and mixing, respectively. In the SM, we expect $C = 0$ because there can be no direct CP violation when there is only one decay mechanism. If we exclude ϕK^0_S events by applying a K^+K^- invariant mass cut of 15 MeV$/c^2$ around the nominal ϕ mass [12], and assume that the remaining B_{CP} candidates are CP even, as our analysis below indicates, we expect $S = -\sin 2\beta = -0.731 \pm 0.056$ [4,5].

Direct CP violation in $B^+ \to K^+K^0_SK^0_S$ decays is measured as an asymmetry in the decay rates

$$\mathcal{A}_{CP} = \frac{\Gamma_{K^-K^0_SK^0_S} - \Gamma_{K^+K^0_SK^0_S}}{\Gamma_{K^-K^0_SK^0_S} + \Gamma_{K^+K^0_SK^0_S}}. \quad (2)$$

The SM expectation for $\mathcal{A}_{CP}$ is zero.

Branching fractions and CP asymmetries are extracted in unbinned extended maximum likelihood fits to the different samples. The likelihood function $\mathcal{L}$, with event yields N_i and probability density functions (PDFs) $\mathcal{P}_{i,j}$, is

$$\mathcal{L} = \exp\left(-\sum_i N_i\right)\prod_{j=1}\left[\sum_i N_i \mathcal{P}_{i,j}\right], \quad (3)$$

where j runs over events and i over event yields. We have a total of 6144 events in the $K^+K^0_SK^0_S$ mode, and 13 864 (12 862) in the $K^+K^-K^0_S$ mode with ϕK^0_S included (excluded).

In the measurement of the branching fractions $\mathcal{B}$, the total PDF is formed as $\mathcal{P}(m_{\rm ES})\mathcal{P}(\Delta E)\mathcal{P}(\mathcal{F})$. Event yields for signal, continuum, and peaking B background are varied in the fit. In the extraction of the charge asymmetry $\mathcal{A}_{CP}$ in $K^+K^0_SK^0_S$ decays, the yields are split by the charge, which brings the total number of varied parameters to six. To extract the branching fractions, we assign a weight for each event to belong to the signal decay, $\mathcal{W}_j = (\sum_i V_{s,i}\mathcal{P}_{i,j})/(\sum_i N_i \mathcal{P}_{i,j})$, where $V_{s,i}$ is the signal row of the covariance matrix obtained from the fit [14]. The branching fraction is calculated as $\mathcal{B} = \frac{1}{N_{B\overline{B}}}\sum_j \mathcal{W}_j/\varepsilon_j$, where $N_{B\overline{B}}$ is the total number of $B\overline{B}$ pairs. Since the efficiency ε_j varies across the phase space, ε_j is computed in small phase-space bins using simulated events. The method is cross-checked with a simple counting analysis. Distributions of $m_{\rm ES}$ are shown in Fig. 1, and the fit results are given in Table I.

In the time-dependent CP fit, $K^+K^-K^0_S$ events that exclude ϕK^0_S decays are fit simultaneously with the $B_{\rm flav}$ sample. The PDFs are formed as $\mathcal{P}(m_{\rm ES})\mathcal{P}(\Delta E)\mathcal{P}(\mathcal{F})\mathcal{P}_c(\Delta t; \sigma_{\Delta t})$ for B_{CP} events and $\mathcal{P}(m_{\rm ES})\mathcal{P}_c(\Delta t; \sigma_{\Delta t})$ in the $B_{\rm flav}$ sample. The Δt resolution and tagging parameters are allowed to be different for each tagging category c. Fit parameters that are common to both samples are the signal fractions in tagging categories ϵ_c, the average mistag fraction w_c, the difference between B^0 and $\overline{B}^0$ mistag rates Δw_c, and the Δt resolution functions for signal and background events. We also vary the $K^+K^-K^0_S$ signal yield and background yields in

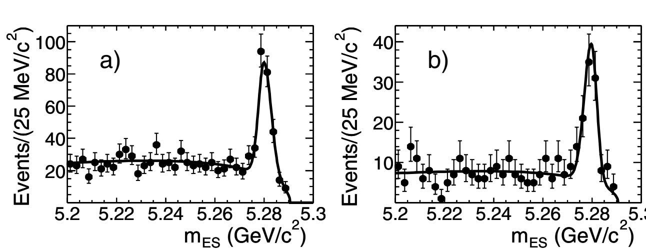

FIG. 1. Projection plots of the $m_{\rm ES}$ variable in the fits for (a) $B^0 \to K^+K^-K^0_S$ and (b) $B^+ \to K^+K^0_SK^0_S$ decays. The points are data and the curves are projections from the likelihood fit. The signal-to-background ratio is enhanced with a cut on the event probability.

TABLE I. Summary of branching-fraction ($\mathcal{B}$), time-dependent (S, C), and direct CP-asymmetry ($\mathcal{A}_{CP}$) results. $N_{\rm sig}$ and ε are the signal yield and the average total efficiency in the branching-fraction fit; $f_{\rm even}$ is the CP-even fraction of the final states. The 90% confidence-level interval for $\mathcal{A}_{CP}$ is $[-0.23, 0.15]$.

Mode	ε (%)	$N_{\rm sig}$	$\mathcal{B}$ (10^{-6})	$f_{\rm even}$	S	C	$\mathcal{A}_{CP}$
$K^+K^-K^0$ (CP)[a]	8.58	201 ± 16	$20.2 \pm 1.9 \pm 1.4$	$0.98 \pm 0.15 \pm 0.04$	$-0.56 \pm 0.25 \pm 0.04$	$-0.10 \pm 0.19 \pm 0.10$	...
$K^+K^-K^0$ (all)	8.78	249 ± 20	$23.8 \pm 2.0 \pm 1.6$	$0.83 \pm 0.12 \pm 0.03$	...	...	...
$K^+K^0_SK^0_S$	9.7	122 ± 14	$10.7 \pm 1.2 \pm 1.0$	...	-0.16 ± 0.35	-0.08 ± 0.22	$-0.04 \pm 0.11 \pm 0.02$

[a] CP excludes ϕK^0_S events.

tag categories, the CP parameters, and the parameters describing the Δt shape of the background. The total number of floated parameters is 38. The largest correlation between S or C with any linear combination of other parameters is 6.6%.

Results of the time-dependent CP asymmetry measurement in $K^+K^-K^0_S$ are given in Table I. Figure 2 shows the Δt distributions of events with B^0 and $\overline{B}^0$ tags, with projections from the likelihood fit superimposed. The fit procedure is verified with the $K^+K^0_SK^0_S$ sample (Table I), where one expects zero asymmetry, and the $J/\psi K^0_S$ sample where the results are consistent with our previous measurement [4].

We evaluate the fraction $f_{\rm even}$ of CP-even final states in $B^0 \to K^+K^-K^0_S$ decays by comparing $K^+K^-K^0$ and $K^+K^0_SK^0_S$ decay rates: $f_{\rm even} = \frac{2\Gamma(B^+\to K^+K^0_SK^0_S)}{\Gamma(B^0\to K^+K^-K^0)}$ [10]. The results listed in Table I are in agreement with Belle's measurements of $0.86 \pm 0.15 \pm 0.05$ and $1.04 \pm 0.19 \pm 0.06$ for the total sample and the CP sample that excludes ϕK^0_S events, respectively [10]. We estimate the fraction of remaining ϕK^0_S events in the CP sample, using a noninterfering Breit-Wigner for the ϕ shape and measured branching fractions, to be $(1.1 \pm 0.4)\%$.

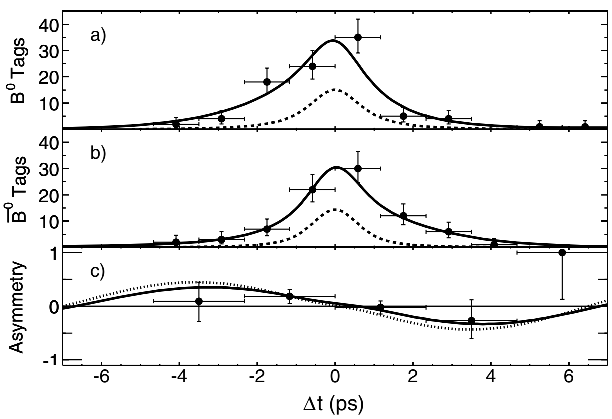

FIG. 2. (a),(b) The Δt distributions of B^0- and $\overline{B}^0$-tagged $K^+K^-K^0_S$ events. The solid lines refer to the fit for all events; the dashed lines correspond to the background. (c) The raw asymmetry, where the solid line is obtained from the fit and the dotted line is the SM expectation for the measured CP content. The signal-to-background ratio is enhanced with a cut on the event probability.

As a consistency check, we examine the distribution of the cosine of the helicity angle θ_H, which is defined as the angle between the K^+ and B^0 directions in the K^+K^- center-of-mass frame [15]. The distribution in several K^+K^- invariant mass bins of the CP sample is approximately uniform which is consistent with S-wave decays. However, the existence of interference effects due to CP-odd amplitudes cannot be completely ruled out with the present statistics.

If we account for a small CP-odd fraction in the CP sample, we can extract the SM parameter $\sin 2\beta$. In a fit with $C = 0$ we get $\sin 2\beta = -S/(2f_{\rm even} - 1) = 0.57 \pm 0.26 \pm 0.04^{+0.17}_{-0}$ where the last error is due to uncertainty on the CP content.

Systematic uncertainties in the branching-fraction measurements are given in Table II. We include contributions from the signal reconstruction efficiency and from the modeling of the efficiency variation over the phase space. Other errors come from the fit bias, the counting of $B\overline{B}$ pairs, and the misidentification of kaons. We assume equal production rates of $B^0\overline{B}^0$ and B^+B^-. The systematic uncertainty on $\mathcal{A}_{CP}$ due to charge asymmetry in track finding and identification is 0.02.

The systematic errors on the time-dependent CP-asymmetry parameters are given in Table III. The errors account for the fit bias, the presence of double CKM-suppressed decays (DCSD) in $B_{\rm tag}$ [16], uncertainty in the beam spot and detector alignment, and the asymmetry in the tagging efficiency for signal and background events. Other smaller effects come from Δt resolution, PDF parametrization of yield variables, and uncertainty on the B^0 lifetime and mixing frequency. In the fit we use $\tau_{B^0} = 1.537 \pm 0.015$ ps and $\Delta m_d = 0.502 \pm 0.007$ ps^{-1} [12].

TABLE II. Branching-fraction systematic uncertainties (%).

Source	$K^+K^-K^0_S$	$K^+K^0_SK^0_S$
Efficiency	5.6	8.6
PDF parametrization	2.7	2.5
Noncharm $B\overline{B}$ background	2.2	2.9
Charm $B\overline{B}$ background	1.2	1.0
Other	1.7	1.6
Total	6.9	9.6

TABLE III. Systematic uncertainties in CP parameters.

Source	S	C
Fit bias	0.024	0.026
DCSD	0.018	0.053
Detector effects	0.013	0.012
Tag asymmetries	0.010	0.078
Other	0.016	0.012
Total	0.04	0.10

In summary, we have measured branching fractions for charmless decays of B mesons into the three-body final states $B^0 \to K^+K^-K^0$ and $B^+ \to K^+K^0_SK^0_S$. Using two independent approaches, we find that the $K^+K^-K^0_S$ final state is dominated by a CP-even component. The results agree with previous measurements [9,10]. In the first measurement of the charge asymmetry in $B^+ \to K^+K^0_SK^0_S$ decays, we find no evidence for direct CP violation. We measure a time-dependent CP asymmetry in $B^0 \to K^+K^-K^0_S$ decays at the 1.9σ level. The obtained $\sin2\beta$ is consistent with the SM expectation and previous measurements in decays into the $K^+K^-K^0_S$ final state [7,8], but differs from Belle's measurement in ϕK^0_S decays [7] by 2.7 standard deviations.

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§Deceased.

[1] Charge-conjugate states are included unless explicitly stated otherwise.

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