Bound on the Ratio of Decay Amplitudes for $\overline{B}^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^{*0}$

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We have measured the time-dependent decay rate for the process $B \to J/\psi K^{*0}(892)$ in a sample of about 88×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory at SLAC. In this sample we study flavor-tagged events in which one neutral B meson is reconstructed in the $J/\psi K^{*0}$ or $J/\psi \overline{K}^{*0}$ final state. We measure the coefficients of the cosine and sine terms in the time-dependent asymmetries for $J/\psi K^{*0}$ and $J/\psi \overline{K}^{*0}$, find them to be consistent with the standard model expectations, and set upper limits at 90% confidence level (C.L.) on the decay amplitude ratios $|A(\overline{B}^0 \to J/\psi K^{*0})|/|A(B^0 \to J/\psi K^{*0})| < 0.26$ and $|A(B^0 \to J/\psi \overline{K}^{*0})|/|A(\overline{B}^0 \to J/\psi \overline{K}^{*0})| < 0.32$. For a single ratio of wrong-flavor to favored amplitudes for B^0 and $\overline{B}^0$ combined, we obtain an upper limit of 0.25 at 90% C.L.

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The standard model of electroweak interactions describes CP violation in weak interactions of quarks by the presence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, the CP asymmetries in the proper-time distributions of neutral B decays to $J/\psi K_S^0$ and $J/\psi K_L^0$ are directly related to the CP-violation parameter $\sin 2\beta$ [2]. The time-dependent CP asymmetries for $J/\psi K_S^0$ and $J/\psi K_L^0$ are of opposite sign and, to a very good approximation, equal in magnitude [3]. The decay $B^0 \to J/\psi K_S^0$ ($B^0 \to J/\psi K_L^0$) proceeds through the CKM-favored, color-suppressed decay $B^0 \to J/\psi K^0$ [4] followed by $K^0 \to K_S^0$ ($K^0 \to K_L^0$). The so-called wrong-flavor B^0 decay amplitude to the opposite strangeness final state $B^0 \to J/\psi \overline{K}^0$ is expected to be negligible in the standard model [3]. Interference between a wrong-flavor amplitude and the favored amplitude can alter the relation between the CP asymmetries, A_{CP}, for the $J/\psi K_S^0$ and $J/\psi K_L^0$ final states. In general, a difference between $A_{CP}(J/\psi K_S^0)$ and $-A_{CP}(J/\psi K_L^0)$ of more than a few times 10^{-3} requires a wrong-flavor amplitude [3]. A limit on the CP-odd part of the phase difference between the wrong-flavor amplitude and the favored amplitude can be derived from the measured values of $\sin 2\beta$ from B decays to the $J/\psi K_S^0$ and $J/\psi K_L^0$ final states. No test of the modulus of the wrong-flavor amplitude currently exists.

The decay mode $B^0 \to J/\psi K^{*0}$ proceeds via the same quark transition as $B^0 \to J/\psi K^0$. The matrix elements, and therefore the ratio of wrong-flavor to favored amplitudes, are expected to be similar for $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^0$ [3]. In this Letter we present a measurement of the ratio of wrong-flavor to favored amplitude for the decay $B^0 \to J/\psi K^{*0}$, from the time-dependent asymmetry, where we use $K^{*0} \to K^+\pi^-$ to identify the strangeness of the final state. The data sample consists of about 88×10^6 $B\overline{B}$ pairs produced in e^+e^- interactions at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 82 fb^{-1}, collected with the *BABAR* detector [5] at the PEP-II asymmetric-energy collider at SLAC.

Charged particles are detected, and their momenta measured, by a combination of a vertex tracker consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter. Further charged particle identification is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring imaging Cherenkov detector covering the central region. Muons are identified by their penetration through the iron plates of a magnet flux return.

The analysis method is similar to that of other time-dependent mixing measurements performed at *BABAR* [6]. We use a sample of events ($B_{J/\psi K\pi}$) in which one neutral B meson is reconstructed in the state $J/\psi K^{*0}$ or $J/\psi \overline{K}^{*0}$. The J/ψ meson is reconstructed through its decay to e^+e^- or $\mu^+\mu^-$, and the K^{*0} ($\overline{K}^{*0}$) meson through its decay to $K^+\pi^-$ ($K^-\pi^+$). We examine each event in this sample for evidence that the other B meson decayed either as a B^0 or $\overline{B}^0$ (flavor tag).

The pseudoscalar to vector-vector decay $B^0 \to J/\psi K^{*0}(892)$ is described by three amplitudes, A_0, $A_\parallel$, and $A_\perp$, for the longitudinal, parallel, and perpendicular transverse polarization [7], respectively, of the vector mesons. In the selection of $B^0 \to J/\psi K^{*0}(892)$ there is a small contribution from $B^0 \to J/\psi K_0^*(1430)$, whose decay amplitude is denoted with A_s. The favored decay amplitudes $A_\lambda(B^0 \to J/\psi K^+\pi^-) = a_\lambda e^{i\delta_\lambda^a} e^{+i\phi^a}$ are described by the magnitudes a_λ, weak phase ϕ^a, and strong phases δ_λ^a, where $\lambda = 0, \parallel, \perp, s$. The amplitudes for the wrong-flavor decays are given by $A_\lambda(\overline{B}^0 \to J/\psi K^+\pi^-) = b_\lambda e^{i\delta_\lambda^b} e^{+i\phi^b}$. The corresponding decay amplitudes for the charge-conjugate final state $J/\psi K^-\pi^+$ are obtained by replacing ϕ^a with $-\bar{\phi}^a$, b_λ with $\bar{b}_\lambda$, δ_λ^b with $\bar{\delta}_\lambda^b$, and ϕ^b with $-\bar{\phi}^b$. We assume $a_\lambda = \bar{a}_\lambda$.

The proper-time distributions of B meson decays to $J/\psi K^+\pi^-$ ($J/\psi K^-\pi^+$), having either a B^0 or $\overline{B}^0$ tag, can be expressed in terms of the B^0-$\overline{B}^0$ oscillation amplitude and the amplitudes describing $\overline{B}^0$ and B^0 decays to this final state [8]. The angular-integrated decay rate f_+ (f_-) to the final state $J/\psi K^+\pi^-$ when the tagging meson is a B^0($\overline{B}^0$) is given by

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

where $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay times of the reconstructed B meson ($B_{\rm rec}$) and the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency. The corresponding decay rates $\overline{\mathrm{f}}_+$ and $\overline{\mathrm{f}}_-$ for the charge-conjugate final state $J/\psi K^-\pi^+$ are obtained by replacing C with $-\overline{C}$ and S with $-\overline{S}$.

The C and S coefficients are related to the wrong-flavor and favored amplitudes by

$$C = \frac{a^2 - b^2}{a^2 + b^2}, \qquad \text{and} \qquad S = \frac{2\sum_{\lambda} \eta a_\lambda b_\lambda \sin(\phi + \delta_\lambda)}{a^2 + b^2}, \tag{2}$$

with $a^2 \equiv a_0^2 + a_\parallel^2 + a_\perp^2 + a_s^2$, $b^2 \equiv b_0^2 + b_\parallel^2 + b_\perp^2 + b_s^2$, and $\eta = +1(-1)$ for $\lambda = 0, \parallel, s(\perp)$. The strong and weak phase differences are given by $\delta_\lambda = \delta_\lambda^b - \delta_\lambda^a$ and $\phi = \arg(q/p) + (\phi_b - \phi_a)$, respectively, where (q/p) contains the weak phase of B^0-$\overline{B}^0$ oscillations. The $\overline{C}$ and $\overline{S}$ coefficients are given by the same expressions, replacing $b_{(\lambda)}$ with $\bar{b}_{(\lambda)}$, δ_λ with $\bar{\delta}_\lambda$, and ϕ with $-\bar{\phi}$.

In the $B \to J/\psi K^{*0}$ selection, a J/ψ candidate must consist of two identified lepton tracks [5] that form a good vertex. The lepton-pair invariant mass must be in the range 3.06–3.14 GeV/c^2 for muons and 2.95–3.14 GeV/c^2 for electrons. This corresponds to a $\pm 3\sigma$ interval for muons, and, for electrons, accommodates the remaining radiative tail after bremsstrahlung correction [6]. We form $K^+\pi^-$ candidate pairs, where the track that is most consistent with being a kaon is assigned to be the kaon candidate. The $K^+\pi^-$ pair must have an invariant mass within 100 MeV/c^2 of the nominal $K^{*0}(892)$ mass [9]. In the selected mass window the $K_0^*(1430)$ contributes $(7.3 \pm 1.6)\%$ of the $K^+\pi^-$ events.

The B-meson candidates are formed from J/ψ and $K^+\pi^-$ candidates with the requirement that the difference $\Delta E = E_B^{\mathrm{cm}} - E_{\mathrm{beam}}^{\mathrm{cm}}$ between their energy and the beam energy in the center-of-mass frame be less than 30 MeV from zero. The beam-energy-substituted mass $m_{\mathrm{ES}} = \sqrt{(E_{\mathrm{beam}}^{\mathrm{cm}})^2 - (p_B^{\mathrm{cm}})^2}$ must be greater than 5.2 GeV/c^2, where p_B^{cm} is the measured B momentum in the center-of-mass frame. We define a signal region with $m_{\mathrm{ES}} > 5.27\ \mathrm{GeV}/c^2$ to determine event yields and purities, and a sideband region with $m_{\mathrm{ES}} < 5.27\ \mathrm{GeV}/c^2$ to study background properties. If several B candidates are found in an event, the one with the smallest $|\Delta E|$ is retained.

A measurement of the asymmetry coefficients C, S, $\overline{C}$, and $\overline{S}$ requires a determination of the experimental Δt resolution and the fraction w of events in which the flavor tag assignment is incorrect. This mistag fraction reduces the amplitudes of the observed asymmetries by a factor $1 - 2w$. Mistag fractions and Δt resolution functions are determined from a sample of neutral B mesons that decay to final states with one charmed meson (B_{Dh}) and consists of the channels $D^{(*)-}h^+$ ($h^+ = \pi^+$, ρ^+, and a_1^+).

The algorithm for B-flavor tagging is explained in Ref. [10]. The total efficiency for assigning a reconstructed B candidate to one of four hierarchical, mutually exclusive tagging categories is $(65.6 \pm 0.5)\%$. Untagged events are excluded from further consideration. The effective tagging efficiency $Q \equiv \sum_i \varepsilon_i (1 - 2w_i)^2$, where ε_i and w_i are the efficiencies and mistag probabilities, for events tagged in category i, is measured to be $(28.1 \pm 0.7)\%$.

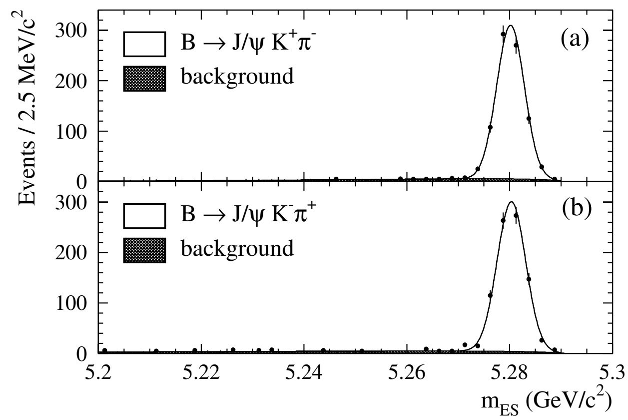

FIG. 1. Distributions of m_{ES} (a) for $J/\psi K^+\pi^-$ candidates and (b) for $J/\psi K^-\pi^+$ candidates satisfying the tagging and vertexing requirements. The fit is described in the text.

The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of the B_{rec} and B_{tag} along the collision (z) axis [6]. We determine the z position of the B_{rec} vertex from its charged tracks. The B_{tag} vertex is determined by fitting tracks not belonging to the B_{rec} candidate to a common vertex, employing constraints from the beam spot location and the B_{rec} momentum [6]. We accept events with a Δt uncertainty of less than 2.5 ps and $|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 95%.

Figure 1 shows the m_{ES} distributions of the $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ candidates that satisfy the tagging and vertexing requirements. The m_{ES} distributions are fit with the sum of a threshold function [11], which accounts for the background from random combinations of tracks in the event, and a Gaussian distribution describing the signal. In Table I we list the event yields and signal purities for the tagged $B \to J/\psi K^+\pi^-$ and $B \to J/\psi K^-\pi^+$ candidates. The fraction of events in the Gaussian component of the m_{ES} fits due to other B decay modes is estimated to be $(1.6 \pm 0.4)\%$ based on simulated events.

TABLE I. Number of events, N_{tag}, and signal purity, P, in the signal region for the $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ samples and for the B_{Dh} sample. Errors are statistical only.

Sample	N_{tag}	$P(\%)$
$J/\psi K^+\pi^-$ sample	860	95.5 ± 0.7
$J/\psi K^-\pi^+$ sample	856	96.5 ± 0.6
B_{Dh} sample	25 375	84.9 ± 0.2

We determine the C, S, $\overline{C}$, and $\overline{S}$ coefficients with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the tagged $B_{J/\psi K\pi}$ and B_{Dh} samples. In this fit the Δt distributions of the $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ samples are described by Eq. (1). The Δt distributions of the B_{Dh} sample are described by the same equation with $C = 1$ and $S = 0$. The observed amplitudes for the time-dependent asymmetries in the $B_{J/\psi K\pi}$ sample and for flavor oscillation in the B_{Dh} sample are reduced by the same factor, $1 - 2w$, due to flavor mistags. Events are assigned signal and background probabilities based on the m_{ES} distributions. The Δt distributions for the signal are convolved with a common resolution function, modeled by the sum of three Gaussians [6]. Backgrounds are incorporated by means of an empirical description of their Δt spectra, obtained from the m_{ES}-sideband region, containing prompt and nonprompt components convolved with a resolution function [6] distinct from that of the signal.

There are 48 free parameters in the fit. The fit parameters that describe the signal Δt distributions are C, S, $\overline{C}$, and $\overline{S}$ (4), the average mistag fraction w, the difference Δw between B^0 and $\overline{B}^0$ mistag fractions, and the linear dependence of the mistag fraction on the Δt error for each tagging category (12), parameters for the signal Δt resolution (8), and parameters to account for differences in reconstruction and tagging efficiencies for B^0 and $\overline{B}^0$ mesons (5). The $B_{J/\psi K\pi}$ and B_{Dh} background Δt distributions are described by parameters for the background time dependence (8), Δt resolution (3), and mistag fractions (8). We fix τ_{B^0} at 1.542 ps and Δm_d at 0.489 ps^{-1} [9]. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the large B_{Dh} sample. Background parameters are determined from events with $m_{ES} < 5.27$ GeV$/c^2$.

The fit to the $B_{J/\psi K\pi}$ and B_{Dh} samples yields $C = 1.045 \pm 0.058 \pm 0.035$, $S = -0.024 \pm 0.095 \pm 0.041$, $\overline{C} = 0.966 \pm 0.051 \pm 0.035$, and $\overline{S} = 0.004 \pm 0.090 \pm 0.041$, where the first error is statistical and the second error is systematic. Figure 2 shows the Δt distributions and the asymmetries in yields between B^0 tags and $\overline{B}^0$ tags as a function of Δt for the $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ samples, overlaid with the projection of the likelihood fit result.

We estimate common systematic errors for C (S) and $\overline{C}$ ($\overline{S}$). The dominant sources of systematic error are the uncertainties in the level, composition, and time-dependent asymmetry of the background in the selected $B_{J/\psi K\pi}$ sample (0.016 for C, 0.017 for S), uncertainties in the beam spot location and the internal alignment of the vertex detector (0.016 for C, 0.021 for S), and the statistics of the simulated event sample (0.016 for C, 0.015 for S). Another significant contribution to the systematic uncertainty in the cosine coefficients comes from possible differences between the B_{Dh} and $B_{J/\psi K\pi}$ mistag fractions

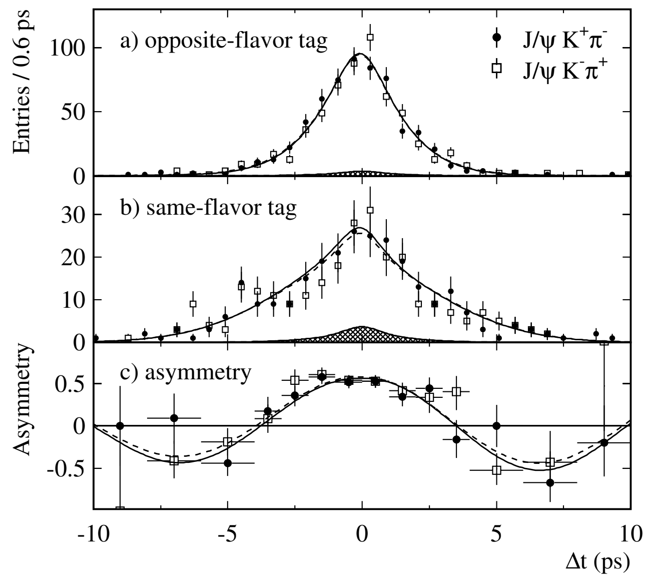

FIG. 2. Number of $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ candidates in the signal region (a) with an opposite-flavor B tag, N_{OF}, (b) with a same-flavor B tag, N_{SF}, and (c) the observed asymmetry $(N_{OF} - N_{SF})/(N_{OF} + N_{SF})$ as functions of Δt. In each figure the solid (dashed) curve represents the fit projection in Δt for $J/\psi K^+\pi^-$ ($J/\psi K^-\pi^+$) candidates. The shaded regions in (a) and (b) represent the background contributions.

(0.012). The uncertainty in the interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ amplitude for the decay modes in the B_{Dh} sample and for certain tagside B decays to hadronic final states [12] contributes to the systematic uncertainty in the sine coefficients (0.019). Finally, there are differences in the angular-integrated efficiency for the $B \to J/\psi K^{*0}(892)$ helicity amplitudes and the $B \to J/\psi K_0^*(1430)$ amplitude (0.007 for C, 0.016 for S). The total systematic errors for the cosine coefficients and sine coefficients are 0.035 and 0.041, respectively. Most systematic errors are determined with data and are expected to decrease with larger sample size.

The large $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ samples allow a number of consistency checks, including separation by data-taking period and tagging category. The results of fits to these subsamples are found to be statistically consistent.

The measured values of the cosine and sine coefficients are consistent with $C = \overline{C} = 1$ and $S = \overline{S} = 0$, as expected for no contributions from the wrong-flavor decays $B^0 \to J/\psi K^-\pi^+$ and $\overline{B}^0 \to J/\psi K^+\pi^-$. We use the measured cosine coefficients C and $\overline{C}$ and assume $|q/p| = 1$ [13] to calculate the wrong-flavor to favored decay rate ratios $\Gamma(\overline{B}^0 \to J/\psi K^+\pi^-)/\Gamma(B^0 \to J/\psi K^+\pi^-) = |b/a|^2 = -0.022 \pm 0.028\,(\text{stat.}) \pm 0.016\,(\text{syst.})$ and $\Gamma(B^0 \to J/\psi K^-\pi^+)/\Gamma(\overline{B}^0 \to J/\psi K^-\pi^+) = |\bar{b}/a|^2 = 0.017 \pm 0.026(\text{stat.}) \pm 0.016(\text{syst.})$, where the negative central value occurs because $C > 1$. From these measurements the wrong-flavor to favored amplitude ratios for $B \to J/\psi K^{*0}(892)$ and $B \to J/\psi \overline{K}^{*0}(892)$ can be calculated. Using the measured fraction of $B \to J/\psi K_0^*(1430)$ events contributing in the $B \to J/\psi K^+\pi^-$ selection, the upper limits for the decay amplitude ratios at 90% confidence level (C.L.) are found to be $|A(\overline{B}^0 \to J/\psi K^{*0})|/|A(B^0 \to J/\psi K^{*0})| < 0.26$ and $|A(B^0 \to J/\psi \overline{K}^{*0})|/|A(\overline{B}^0 \to J/\psi \overline{K}^{*0})| < 0.32$. For the single ratio of wrong-flavor to favored amplitude for B^0 and $\overline{B}^0$ combined, we determine an upper limit of 0.25 at 90% C.L.

In conclusion, we observe no evidence for the wrong-flavor decays $\overline{B}^0 \to J/\psi K^{*0}(892)$ and $B^0 \to J/\psi \overline{K}^{*0}(892)$. Together with theoretical information on the relation between the matrix elements for $B^0 \to J/\psi K^0$ and $B^0 \to J/\psi K^{*0}$ [3], the results presented here can be used to set a limit on the difference between $A_{CP}(J/\psi K_S^0)$ and $-A_{CP}(J/\psi K_L^0)$.

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