Measurement of the Ratio of Decay Amplitudes for $\bar{B}^0 \to J/\psi K^{*0}$ 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 million $\Upsilon(4S) \to B \bar{B}$ 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 $J/\psi K^{0}\bar{s}$ final state. We measure the coefficients of the cosine and sine terms in the time-dependent asymmetries for $J/\psi K^{*0}$ and $J/\psi K^{0}\bar{s}$, find them to be consistent with the Standard Model expectations, and set upper limits at 90% C.L. on the decay amplitude ratios $|A(B^0 \to J/\psi K^{*0})|/|A(B^0 \to J/\psi K^{0}\bar{s})| < 0.26$ and $|A(B^0 \to J/\psi K^{0}\bar{s})|/|A(B^0 \to J/\psi K^{*0})| < 0.32$. For a single ratio of wrong-flavor to favored amplitudes for $B^0$ and $\bar{B}^0$ 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 $\mathbb{U}$. In this framework, the CP asymmetries in the proper-time distributions of neutral $B$ decays to $J/\psi K^{0}_S$ and $J/\psi K^{0}_L$ are directly related to the CP-violation parameter $\sin 2\beta$ [2]. The time-dependent CP asymmetries for $J/\psi K^{0}_S$ and $J/\psi K^{0}_L$ are of opposite sign and, to a very good approximation, equal in magnitude [2]. The decay $B^0 \to J/\psi K^{0}_S$ ($B^0 \to J/\psi K^{0}_L$) proceeds through the CKM-favored, color-suppressed decay $B^0 \to J/\psi K^0$ [2] followed by $K^0 \to K^{0}_S$ ($K^{0}_L \to K^{0}_S$). The so-called wrong-flavor $B^0$ decay amplitude to the opposite strangeness final state $B^0 \to J/\psi K^{0}\bar{s}$ 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 measured values of $\sin 2\beta$ and $\sin 2\beta$ [2], and therefore the ratio of wrong-flavor to favored amplitudes can alter the relation between $\sin 2\beta$ and $\sin 2\beta$ [2]. The time-dependent $\sin 2\beta$ and $\sin 2\beta$ are directly related to the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 82 fb$^{-1}$, collected with the BABAR detector [3] 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.
tagging $B$ meson ($B_{\text{tag}}$), $\tau_{B^0}$ is the $B^0$ lifetime, and $\Delta m_d$ is the $B^0$-$\bar{B}^0$ oscillation frequency. The corresponding decay rates $\bar{f}_+$ and $\bar{f}_-$ for the charge-conjugate final state $J/\psi K^-\pi^+$ are obtained by replacing $C$ with $-\bar{C}$ and $S$ with $-\bar{S}$.

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

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

with $a^2 = a_0^2 + a_1^2 + a_2^2$, $b^2 = b_0^2 + b_1^2 + b_2^2$, and $\eta = +1 (-1)$ for $\lambda = 0, \parallel, s$. The strong and weak phase differences are given by $\delta_\lambda = \delta_0^\lambda - \delta_1^\lambda$ and $\phi = \arg(q/p) + (\phi_0 - \phi_a)$, respectively, where $(q/p)$ contains the weak phase of $B^0$-$\bar{B}^0$ oscillations. The $C$ and $S$ coefficients are given by the same expressions, replacing $b_\lambda$ with $\bar{b}_\lambda$, $\delta_\lambda$ with $\bar{\delta}_\lambda$, and $\phi$ with $-\bar{\phi}$.

In the $B \rightarrow J/\psi K^{*0}$ selection, a $J/\psi$ candidate must consist of two identified lepton tracks $\mathcal{C}$ 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 $\mathcal{C}$. 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 $\mathcal{C}$. 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 $J/\psi$ and $K^+\pi^-$ candidates with the requirement that the difference $\Delta E = E_{\text{ES}}^m - E_{\text{beam}}^m$ 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 $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^m)^2 - (p_B^m)^2} \geq 8$ must be greater than $5.2$ GeV/$c^2$, where $p_B^m$ is the measured $B$ momentum in the center-of-mass frame. We define a signal region with $m_{\text{ES}} > 5.27$ GeV/$c^2$ to determine event yields and purities, and a sideband region with $m_{\text{ES}} < 5.27$ 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 $C$, $S$, $\bar{C}$, and $\bar{S}$ requires a determination of the experimental $\Delta t$ 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 $\Delta t$ resolution functions are determined from a sample of neutral $B$ mesons that decay to final states with one charmed meson ($B_{\text{dh}}$), and consists of the channels $D^{(*)}-h^+ (h^+ = \pi^+, \rho^+, \gamma)$.

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

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

![Figure 1: Distributions of $m_{\text{ES}}$ 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.](image-url)

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

We determine the $C$, $S$, $\bar{C}$, and $\bar{S}$ coefficients with a simultaneous unbinned maximum likelihood fit to the $\Delta t$ distributions of the tagged $B_{J/\psi K^+}$ and $B_{\text{dh}}$ samples. In this fit the $\Delta t$ distributions of the $J/\psi K^+\pi^-$ and $J/\psi K^-\pi^+$ samples are described by Eq. $[\text{I}]$. The $\Delta t$ distributions of the $B_{\text{dh}}$ sample are described by the same equation with $C = 1$ and $S = 0$. The observed amplitudes for the time-dependent asymmetries in the $B_{J/\psi K^+}$ sample and for flavor oscillation in the $B_{\text{dh}}$ sample are reduced by the same factor, $1 - 2w$, due to flat-
Table I: Number of events, \( N_{\text{tag}} \), 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          | \( N_{\text{tag}} \) | \( P(\%) \) |
|-----------------|-----------------------|-------------|
| \( J/\psi K^+\pi^- \) sample | 860                  | 95.5 \( \pm \) 0.7 |
| \( J/\psi K^-\pi^+ \) sample  | 856                  | 96.5 \( \pm \) 0.6 |
| \( B_{Dh} \) sample          | 25375                | 84.9 \( \pm \) 0.2 |

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, \( \Omega_{OF} \), b) with a same-flavor \( B \) tag, \( \Omega_{SF} \), and c) the observed asymmetry \( (\Omega_{SF} - \Omega_{OF})/(\Omega_{OF} + \Omega_{SF}) \) as functions of \( \Delta t \). In each figure the solid (dashed) curves represent the fit projection in \( \Delta t \) for \( J/\psi K^+\pi^- \) (\( J/\psi K^-\pi^+ \)) candidates. The shaded regions in (a) and (b) represent the background contributions.
measurements the wrong-flavor to favored amplitude ratios for $B \to J/\psi K^{*0}(892)$ and $B \to J/\psi K^{*0}(1430)$ 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 $|A(B^0 \to J/\psi K^{*0})|/|A(B^0 \to J/\psi K^{-})| < 0.26$ and $|A(B^0 \to J/\psi K^{*0})|/|A(B^0 \to J/\psi K^{*0})| < 0.32$. For the single ratio of wrong-flavor to favored amplitude for $B^0$ and $\bar{B}^0$ combined, we determine an upper limit of 0.25 at 90% C.L.

In conclusion, we observe no evidence for the wrong-flavor decays $B^0 \to J/\psi K^{*0}(892)$ and $B^0 \to J/\psi K^{*0}(1430)$. Together with theoretical information on the relation between the matrix elements for $B^0 \to J/\psi K^0$ and $B^0 \to J/\psi K^{*0}$, the results presented here can be used to set a limit on the difference between $A_{CP}(J/\psi K^0_S)$ and $-A_{CP}(J/\psi K^0_L)$.

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