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CP-violating asymmetries in $\eta' K$ and direct CP violation searches with BABAR in charmless hadronic B meson decays

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Abstract. We present preliminary results of the measurement of branching fractions and CP violating asymmetries in B meson decays to $\eta' K$ and ϕK^*. We update also the results of the direct CP violation searches with BABAR in charmless hadronic B meson decays.

Keywords. CP violation; B decays.

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1. Introduction

The decay $B^0 \to \eta' K^0$ is a Cabibbo–Kobayashi–Maskawa (CKM) suppressed process expected to be dominated by penguin $b \to s$ transitions with small contributions from tree and electroweak amplitudes [1]. The observed branching fraction is larger than initially expected [2]. Several conjectures were advanced for its explanation, including flavour singlet [3], charm enhanced [4] and constructively interfering internal penguin diagrams [5]. We present here the measurement of branching fractions and time-dependent CP violating asymmetries in the B meson decay $B \to \eta' K$ with K charged or neutral.

Direct CP violation can be detected as a partial-rate asymmetry defined as

$$\mathcal{A}(f) \equiv \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)}, \tag{1}$$

where B is either a B^0 or B^+ meson, f is a final state which is able to specify the flavor of the parent B meson, and $\bar{B}$ and $\bar{f}$ are their conjugates.

Rare B decays have significant contribution from penguin amplitudes. Interference of different decay amplitudes could enhance direct CP violation when amplitudes have comparable magnitudes and different weak and strong phases. Direct CP asymmetry can be enhanced by new particles, such as charged Higgs bosons or supersymmetric particles, contributing to penguin amplitudes.

The $B \to \phi K^*$ decays proceed through pure penguin diagrams and are particularly interesting in the search for new physics.

2. Data sample and candidate selection

The data used in these measurements were collected in 1999–2002 with the BABAR detector at the PEP II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. An integrated luminosity of 81.9 fb^{-1}, corresponding to a sample of 88.9 million of $B\bar{B}$ pairs was recorded at the $\Upsilon(4S)$ resonance. The BABAR detector is described elsewhere [6]. B candidates are characterized kinematically by two observables. First is the difference ΔE between the B candidate energy and the beam energy in the center-of-mass frame. The second variable is the energy substituted-mass, $m_{\mathrm{ES}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_B)^2}$, where E^*_{beam} and p^*_B are the beam energy and B candidate momentum in the center-of-mass frame. For further data analysis we select events in the region: $|\Delta E| \leq 0.2$ GeV and $5.2 \leq m_{\mathrm{ES}} \leq 5.29\ \mathrm{GeV/c^2}$. We combine $\eta \to \gamma\gamma$ candidates with two charged tracks to form $\eta' \to \eta\pi^+\pi^-$ and ρ^0 candidates with a photon to form $\eta' \to \rho^0\gamma$ candidates. B candidates are formed by combining the η' candidate with a charged track or $K^0_S \to \pi^+\pi^-$. The decay $B \to \phi K^*$ has been reconstructed from the intermediate states $\phi \to K^+K^-$, $K^{*0} \to K^+\pi^-$, $K^{*0} \to K^0\pi^0$, $K^{*+} \to K^+\pi^0$ and $K^{*+} \to K^0\pi^+$. We select B resonance daughter candidates with requirements on their invariant masses similar to those of our previous analysis [7]. We reject continuum background using the angle θ_{T} between the thrust axis of the B candidate and all the remaining tracks (charged and neutral) in the event (ROE). We require $|\cos\theta_{\mathrm{T}}| < 0.9$ in $B \to \eta' K$ and $|\cos\theta_{\mathrm{T}}| < 0.8$ in $B \to \phi K^*$. We also use a Fisher discriminant $\mathcal{F}$ combining four variables: the angles with respect to the beam axis in the $\Upsilon(4S)$ rest frame of the beam momentum and B thrust axis, and the zeroth and second Legendre moments of the ROE tracks and neutrals around the B thrust axis. For charged B decays, the B primary track must have an associated DIRC Cherenkov angle between -5σ and $+2\sigma$ of the value expected for a kaon.

3. $B \to \eta' K$ analysis and results

From a $B^0\bar{B}^0$ pair we reconstruct the final state $f = \eta' K^0$ and the other B (B_{tag}). From the z coordinate separation of the two B's vertices we extract the proper decay time difference $\Delta t = t_f - t_{\mathrm{tag}}$. The decay rate distribution $F_+(F_-)$ when $B_{\mathrm{tag}} = B^0(\bar{B}^0)$ is

$$F_\pm(\Delta t) = \frac{\mathrm{e}^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta\omega \pm (1-2\omega)(S_f \sin(\Delta m_d \Delta t) \\ -C_f \cos(\Delta m_d \Delta t)], \quad (2)$$

where τ is the mean B^0 lifetime, Δm_d is the mixing frequency, $\Delta\omega$ and ω are the difference and average respectively of the probabilities that a true $B^0(\bar{B}^0)$ meson is tagged as a $\bar{B}^0(B^0)$. The PDFs used to describe the Δt distributions are each a convolution of the decay time distribution $F(\Delta t)$ and a resolution function $R(\Delta t)$. Tagging efficiency, mistag rate and parameters of the resolution function are measured with a large sample of B decays to flavour eigenstates (B_{flav} sample) [8]. In eq. (2) the parameter C_f measures direct CP violation. If the tree amplitude is negligible and there is no weak phase contribution from new physics, the parameter

Table 1. Results of branching fractions and CP asymmetry parameter measurements.

Mode	Yield	ϵ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}$ (%)	S_f	C_f
$\eta'_{\eta\pi\pi}K^+$	271^{+19}_{-18}	25	17.4	71 ± 5	-0.1 ± 6.8	0.08 ± 0.20	-0.16 ± 0.15
$\eta'_{\rho\gamma}K^+$	514^{+31}_{-30}	24	29.5	82 ± 5	6.3 ± 5.9	-0.07 ± 0.16	-0.14 ± 0.11
$\boldsymbol{\eta' K^+}$				$\mathbf{76.9 \pm 3.5}$	$\mathbf{3.7 \pm 4.5}$	-0.01 ± 0.13	-0.15 ± 0.09
$\eta'_{\eta\pi\pi}K^0$	48 ± 8	24	6.0	38^{+7}_{-6}		0.75 ± 0.51	-0.21 ± 0.35
$\eta'_{\rho\gamma}K^0$	155^{+17}_{-16}	25	10.1	70^{+8}_{-7}		-0.41 ± 0.42	0.24 ± 0.27
$\boldsymbol{\eta' K^0}$				$\mathbf{55.4 \pm 5.2}$		$\mathbf{0.02 \pm 0.34}$	$\mathbf{0.10 \pm 0.22}$

S_f in eq. (2) is equal to $\sin 2\beta$. A deviation of S_f from the value of $\sin 2\beta$ measured in charmonium channels could be due to weak phase contribution from new physics [9].

The yields and decay time evolution are obtained with extended unbinned maximum likelihood (ML) fits. The input observables are: Δt, ΔE, m_{ES}, $m_{\eta'}$ and $\mathcal{F}$. PDFs for signal events are determind with MC signal events while background PDFs are obtained from data sidebands ($m_{\mathrm{ES}} < 5.27$ GeV/c^2, $|\Delta E| > 0.1$ GeV).

In the charged modes we have also measured direct CP violation (see eq. (1)) as charge asymmetry $\mathcal{A}$ in the B^- and B^+ rates.

For the time evolution we combine the two decay modes in a single fit with 28 free parameters: S_f, C_f, yields for signal, continuum and $B\overline{B}$ background (3), and background PDFs (23) (Δt, m_{ES}, ΔE, $m_{\eta'}$, $\mathcal{F}$). We show in table 1 the final results: signal yield, detection efficiency ϵ, daughter branching fraction product, measured branching fraction, charge asymmetry, S_f, and C_f for each decay mode, and the combined result for each mode, with statistical error. The S_f and C_f values for $B^+ \to \eta' K^+$ are included as a control; they are consistent with zero, as expected.

In figure 1 we show projections of m_{ES} and ΔE made by selecting events with signal likelihood (computed without the variable plotted) exceeding a cut optimized to select the more signal-like events.

The uncertainty in our knowledge of the efficiency is 0.8% per charged track, 2.5% per photon, and 4% per K^0_S. Our estimate of the B production systematic error is 1.1%. The estimate of systematic bias from the fitter itself (0–4%) comes from fits of simulated samples with varying background populations. Published data [10] provide the B daughter product branching fraction uncertainties (3.4%). Selection efficiency uncertainties are 1% for $\cos\theta_{\mathrm{T}}$ and 0.5% for particle identification requirements on primary K^+.

As can be seen in table 1, the branching fractions we find for $B^0 \to \eta' K^0$ are rather different (three standard deviations) as measured with $\eta' \to \eta\pi\pi$ or $\eta' \to \rho\gamma$. Having exhausted other explanations, we attribute this difference to a statistical fluctuation, and include both sub-decay modes in the final measurement.

Using several high-statistics inclusive and B decay samples, we find a systematic uncertainty for $\mathcal{A}$ of 1.1% due to the dependence of reconstruction efficiency on the charge of the high momentum $K^{\pm}$. We find systematic uncertainties for $S_{\eta' K^0_S}$ and $C_{\eta' K^0_S}$ by varying within their errors the fit parameters controlling the PDF shapes. We use the B_{flav} sample to determine the errors associated with the signal

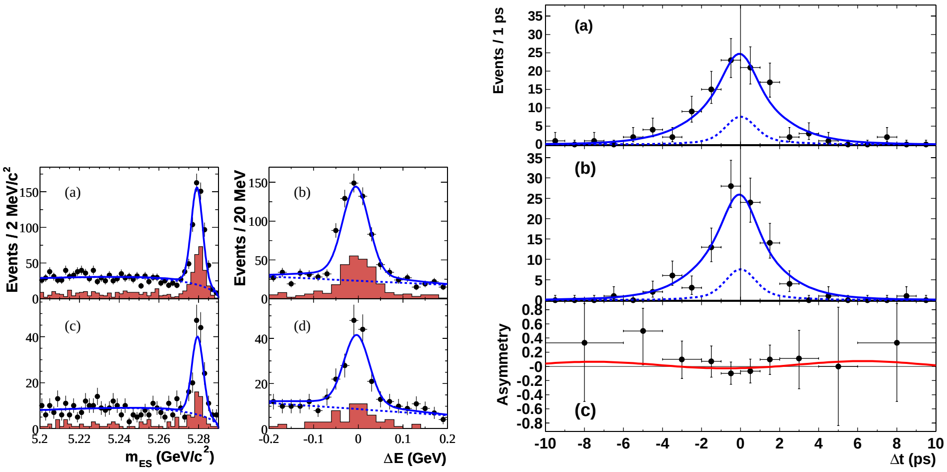

Figure 1. Left: B candidate $m_{\rm ES}$ and ΔE projections for $B^0 \to \eta' K^0_S$. Points with errors represent data, solid curves the full fit functions, the shaded histogram the $\eta'_{\eta\pi\pi}K$ sub-decay mode. Right: Δt projection for $B^0 \to \eta' K^0_S$, data (points with errors), fit function (solid line), and background function (dashed line) for (**a**) B^0 and (**b**) $\bar{B}^0$ tagged events, and (**c**) the asymmetry between B^0 and $\bar{B}^0$ tags.

Δt resolutions, tagging efficiencies, and mistag rates, and published measurements [10] for τ_B and Δm_d. All of these sum to 0.013 (0.014) for $S_{\eta' K^0_S}(C_{\eta' K^0_S})$. The contributions from the $m_{\rm ES}$, ΔE, $m_{\eta'}$, and $\mathcal{F}$ PDFs are 0.025 and 0.014 respectively. We take systematic uncertainties due to SVT alignment (0.01), beam spot (0.01), boost and z scale (negligible) from previous determinations of these effects [8]. The measured time-dependent asymmetry parameters are $S_{\eta' K^0_S} = 0.02 \pm 0.34 \pm 0.03$ and $C_{\eta' K^0_S} = 0.10 \pm 0.22 \pm 0.03$. Our $S_{\eta' K^0_S}$ measurement is consistent with zero and is about two standard deviations smaller than the value [8,11] in charmonium decay modes and BELLE measurement [12]. A recent calculation obtains an upper bound of 0.3 for the deviation of $S_{\eta' K^0_S}$ from $S_{\psi K^0_S}$ [13].

We find $\mathcal{A} = 0.037 \pm 0.045 \pm 0.011$. The 90% CL limit interval is $[-0.04, +0.11]$. The measured branching fractions are $\mathcal{B}(B^+ \to \eta' K^+) = (76.9 \pm 3.5 \pm 4.4) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^0) = (55.4 \pm 5.2 \pm 4.0) \times 10^{-6}$.

4. $B \to \phi K^*$ analysis and results

The decay $B \to \phi K^*$ is expected to proceed through pure penguin diagrams. The asymmetry $\mathcal{A}$ expected from the standard model [14] is at the level of about 1%. New particles in loops coming from non-standard model physics could provide additional amplitudes with different phases. Depending on the model, $\mathcal{A}$ can be 30% or larger [15]. In $B \to \phi K^*$ decay modes the B flavor is tagged by the charge of the kaon from the $K^{*0} \to K^+\pi^-$. The ML fit input variables are ΔE, $m_{\rm ES}$, $\mathcal{F}$ Fisher discriminant, invariant masses of K^* and ϕ resonances, and the ϕ and K^* helicity angles. We have measured the branching fractions

Table 2. Signal yield, branching fraction, charge asymmetry and 90% confidence level interval in rare charmless hadronic B decays.

Final state	$\mathcal{B}$ (10^{-6})	$\mathcal{A}$ (%)	90% CL interval
$\eta' K^+$	$76.9 \pm 3.5 \pm 4.4$	$0.037 \pm 0.045 \pm 0.011$	$[-0.04, +0.11]$
ϕK^{*0}	$11.1^{+1.3}_{-1.2} \pm 1.1$	$+0.04 \pm 0.12 \pm 0.02$	$[-0.16, +0.23]$
ϕK^{*+}	$12.1^{+2.1}_{-1.9} \pm 1.5$	$+0.16 \pm 0.17 \pm 0.04$	$[-0.13, +0.13]$
$\pi^+\pi^0$	$5.5^{+1.0}_{-0.9} \pm 0.6$	$-0.03^{+0.18}_{-0.17} \pm 0.02$	$[-0.32, +0.27]$
$K^+\pi^0$	$12.8^{+1.2}_{-1.1} \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$	$[-0.24, +0.06]$
$K^0\pi^0$	$10.4 \pm 1.5 \pm 0.8$	$0.03 \pm 0.36 \pm 0.09$	$[-0.58, +0.64]$
$K^+\pi^-$	$17.9 \pm 0.9 \pm 0.6$	$-0.102 \pm 0.050 \pm 0.016$	$[-0.188, -0.016]$
$K^0\pi^+$	$17.5 \pm 1.8 \pm 1.3$	$-0.17 \pm 0.10 \pm 0.02$	
$K^+\phi$		$-0.05 \pm 0.20 \pm 0.03$	
ρK		$0.19 \pm 0.14 \pm 0.11$	
$\rho\pi$		$-0.22 \pm 0.08 \pm 0.07$	

$\mathcal{B}(B^0 \to \phi K^{*0})= (11.1^{+1.3}_{-1.2}\pm1.1)\times10^{-6}$ and $\mathcal{B}(B \to \phi K^{*+})= (12.1^{+2.1}_{-1.9}\pm1.5)\times10^{-6}$. Direct CP violation has been searched for the three self-tagging K^* modes and the following charge asymmetries have been measured: $\mathcal{A}(\phi K^{*0}) = +0.04 \pm 0.12 \pm 0.02$ and $\mathcal{A}(\phi K^{*+}) = +0.16 \pm 0.17 \pm 0.04$. The 90% CL limit intervals are $[-0.16, +0.23]$ and $[-0.13, +0.13]$ respectively.

5. BABAR results on direct CP violation searches in charmless hadronic B decays

We show in table 2 branching fractions and direct CP violation asymmetry $\mathcal{A}$ in rare charmless hadronic B decays recently measured by BABAR. All these measurements are limited by statistical uncertainties. There is no evidence of direct CP violation in the considered B decay modes.

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