SLAC-PUB-9032
BABAR-PROC-01/69
hep-ex/0110053
October, 2001

Search for direct $\mathcal{CP}$ violation in $B \to K\pi, \pi\pi, KK$, Quasi-Two-Body B decays and $B \to K^*\gamma$ with the *BABAR* detector at the PEP-II collider

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Abstract

A sample of 23 million $B\overline{B}$ events collected with the *BABAR* detector at the PEP-II collider is used in a search for direct $\mathcal{CP}$ violation in charmless two-body B decays, quasi two-body B decays, and the radiative penguin decays $B \to K^*\gamma$. No evidence for direct $\mathcal{CP}$ violation is found in the considered modes and 90 % confidence level limits are reported. We also present a limit on the branching fraction of the decay $B^0 \to \gamma\gamma$.

Contributed to the Proceedings of the International Europhysics Conference On High-Energy Physics (HEP 2001),
7/12/2001—7/18/2001, Budapest, Hungary

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Work supported in part by Department of Energy contract DE-AC03-76SF00515.

1 Introduction

Rare B meson decays are interesting in searches for direct $\mathcal{CP}$ violation because they have significant penguin amplitudes. In the Standard Model substantial $\mathcal{CP}$ violation in B decays could arise from the interference of penguin and tree amplitudes [1] and would manifest itself in an asymmetry of B decay rates:

$$\mathcal{A}_{\mathcal{CP}} = \frac{\Gamma(\overline{\mathrm{B}} \to \overline{f}) - \Gamma(\mathrm{B} \to f)}{\Gamma(\overline{\mathrm{B}} \to \overline{f}) + \Gamma(\mathrm{B} \to f)}. \quad (1)$$

In general the weak phase difference between the $\mathrm{b} \to \mathrm{u}$ tree amplitude and the $\mathrm{b} \to \mathrm{s}$ or $\mathrm{b} \to \mathrm{d}$ penguin amplitude is γ or $\gamma + \beta = \pi - \alpha$. Therefore $\mathcal{A}_{\mathcal{CP}}$ can be used to constrain the CKM angles α and γ in the phase convention given in [2, 3]. For pure penguin decays like $\mathrm{B} \to \mathrm{K}^*\gamma$ $\mathcal{A}_{\mathcal{CP}}$ is negligible in the Standard Model. Extensions of the Standard Model could introduce new virtual high-mass fermions and bosons in the loop thus providing additional amplitudes with different phases. Depending on the model parameters, $\mathcal{A}_{\mathcal{CP}}$ may be as large as 20 % [4].

2 Data Sample

The data sample used in these analyses was collected with the *BABAR* detector [5] at the PEP-II $\mathrm{e^+e^-}$ collider [6] at SLAC. It corresponds to an integrated luminosity of $20.7\,\mathrm{fb}^{-1}$ taken on the $\Upsilon(4\mathrm{S})$ resonance ("on-resonance") and $2.6\,\mathrm{fb}^{-1}$ taken at a center-of-mass energy 40 MeV below the $\Upsilon(4\mathrm{S})$ resonance ("off-resonance"), which are used for continuum background studies. The on-resonance sample corresponds to 22.6 million $\mathrm{B\overline{B}}$ pairs. The collider is operated with asymmetric beam energies, producing a boost ($\beta\gamma = 0.56$) of the $\Upsilon(4\mathrm{S})$ along the collision axis (z). The boost increases the momentum range of two-body B decay products from a narrow distribution centered near 2.6 GeV to a broad distribution extending from 1.7 GeV to 4.3 GeV.

The *BABAR* detector is a spectrometer of charged and neutral particles and is described in detail in Ref. [5]. Charged particle (track) momenta are measured in a tracking system consisting of a 5-layer, double-sided, silicon vertex detector (SVT) and a 40-layer drift chamber (DCH) filled with a gas mixture of helium (80 %) and isobutane (20 %), both operating within a 1.5 T solenoidal magnet. Photons are detected in an electro-magnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. Charged hadron identification is based on the Čerenkov angle θ_c measured by a unique, internally reflecting Čerenkov ring imaging detector (DIRC).

3 Event Selection

Hadronic events are selected based on track multiplicity and event topology. Backgrounds from non hadronic events are reduced by requiring the ratio of the Fox-Wolfram moments H_2/H_0 [7] to be less than 0.95 and the sphericity [8] of the event to be greater than 0.01 (charmless two-body decays [9]) or by requiring $|\cos\theta_T^*| < 0.8$ ($\mathrm{K}^*\gamma$ decays), where θ_T^* denotes the angle between the thrust vector of the event excluding the B daughter candidates and the high energy photon candidate in the center-of-mass frame. Candidate tracks are required to originate from the interaction point, and to have at least 12 DCH hits and a minimum transverse momentum of 0.1 GeV. Looser criteria are applied to tracks forming K^0_S candidates to allow for displaced decay vertices. Kaon tracks are distinguished from pion and proton tracks via a likelihood ratio that includes, for momenta below 0.7 GeV $\mathrm{d}E/\mathrm{d}x$ information from the SVT and DCH, and for higher momenta Čerenkov angle and number of photons as measured by the DIRC.

Pairs of tracks with opposite charge from a common vertex are combined to form K^0_S, ϕ, K^{*0} and ρ^0 candidates. Pairs of charged tracks are further combined with a π^0 or η candidate to select ω or η' candidates. The required mass ranges for ϕ, ω, η' and η candidates are as follows (in GeV): $0.99 < m_{K^+K^-} < 1.05$, $0.735 < m_{\pi^+\pi^-\pi^0} < 0.83$, $0.93 < m_{\eta\pi^+\pi^-} < 0.99$, $0.9 < m_{\rho^0\gamma} < 1.0$, $0.49 < m_{\gamma\gamma} < 0.6$.

K^0_S candidates should have a mass within 3.5σ of the nominal mass, where σ is typically 4.3 MeV for two-body B decays, and a proper lifetime significance of at least 5 for the two-body-analysis. Similar cuts are applied in the $K^*\gamma$ and the quasi-two-body-analyses [10].

The ρ mass is required to be in the interval $[0.5, 0.995]$ GeV. The K^* reconstruction is completed by requiring the invariant mass of the $K\pi$ pairs to be within ± 100 MeV of the nominal K^{*0}/K^{*+} mass, except for $K^+\pi^0$ and $K^0_S\pi^+$ pairs for the quasi-two-body analysis where ± 150 MeV are required.

$J/\psi \to \mu^+\mu^-$ candidates are constructed from two identified muons each with polar angle in the range $[0.3, 2.7]$ rad and with invariant mass $3.06\,\mathrm{GeV} < m_{\mu^+\mu^-} < 3.14\,\mathrm{GeV}$ [11]. The absolute cosine of the helicity angle of the J/ψ decay is required to be less than 0.9. $J/\psi \to e^+e^-$ candidates are constructed from two identified electrons each with polar angle in the range $[0.41, 2.409]$ rad and with invariant mass $2.95\,\mathrm{GeV} < m_{\mu^+\mu^-} < 3.14\,\mathrm{GeV}$. The absolute cosine of the helicity angle of the J/ψ decay is required to be less than 0.8.

The $K^*\gamma$ analysis selects high energy photon candidates in the EMC in the energy range $1.5\,\mathrm{GeV} < E_\gamma < 4.5\,\mathrm{GeV}$ in the laboratory frame and $2.3\,\mathrm{GeV} < E^*_\gamma < 2.85\,\mathrm{GeV}$ in the center-of-mass frame. The candidate must be isolated by 25 cm from any other photon candidate or track and have a lateral energy profile consistent with a photon shower. Photons from $\pi^0(\eta)$ are vetoed by requiring that the invariant mass of the combination with any other photon of energy greater than 50(250) MeV not lie within the range $115(508)\,\mathrm{MeV} < m_{\gamma\gamma} < 155(588)\,\mathrm{MeV}$. Similar requirements are imposed on the high energetic photons in the $B^0 \to \gamma\gamma$ analysis [12].

$\pi^0(\eta)$ candidates are formed from pairs of photons with energies of at least 30(100) MeV. The accepted invariant mass range for π^0 candidates is typically $[115, 150]$ MeV.

In all analyses presented here two kinematic variables are used to select B candidates [5]: $\Delta E = E^*_B - \sqrt{s}/2$, and $m_{ES} = \sqrt{s/4 - \mathbf{p}^{*2}_B}$, where E^*_B is the reconstructed energy of the B candidate in the center-of-mass frame, $\mathbf{p}^*_B$ is its momentum vector, and $\sqrt{s}$ is the total center-of-mass energy. In the two-body analysis pion mass is assumed for both tracks in the definition of ΔE whereas the correct mass according to particle identification is used in the other analyses. Therefore the ΔE distribution is peaked near zero for modes with no charged kaons and shifted on average $-45(-91)$ MeV for modes with one (two) charged kaon(s) in the two-body analysis. In the other analyses ΔE peaks near zero for all signal modes for true B candidates. The two-body and charmless quasi-two-body analyses use Fisher discriminants $\mathcal{F}$ [13] built from a nine bin representation of the energy-flow about the B decay axis and in case of the charmless quasi-two-body analysis the $\Upsilon(4S)$ and the B helicity angles. Detailed Monte Carlo (MC) simulation, off-resonance data, and events in on-resonance m_{ES} and ΔE sideband regions are used to study backgrounds. The largest source of background is from random combinations of tracks and neutrals produced in the $e^+e^- \to q\overline{q}$ continuum (where $q = u, d, s$, or c).

4 Signal Extraction

Two different analysis strategies are used to extract signals. A simpler cut-and-count approach where backgrounds are estimated from sideband regions in ΔE and m_{ES} and subtracted from the

Mode	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{\mathcal{CP}}$	$\mathcal{A}_{\mathcal{CP}}$ (90 % C.L.)	note
$\pi^+\pi^-$	$4.1 \pm 1.0 \pm 0.7$			
$K^+\pi^-$	$16.7 \pm 1.6 \pm 1.3$	$-0.19 \pm 0.10 \pm 0.03$	$[-0.35, -0.03]$	
K^+K^-	< 2.5 (90 % C.L.)			
$\pi^+\pi^0$	< 9.6 (90 % C.L.)			
$K^+\pi^0$	$10.8^{+2.1}_{-1.9} \pm 1.0$	$0.00 \pm 0.18 \pm 0.04$	$[-0.30, +0.30]$	
$K^0\pi^+$	$18.2^{+3.3}_{-3.0} \pm 2.0$	$-0.21 \pm 0.18 \pm 0.03$	$[-0.51, +0.09]$	
$\overline{K}^0K^+$	< 2.4 (90 % C.L.)			
$K^0\pi^0$	$8.2^{+3.1}_{-2.7} \pm 1.2$			
$K^0\overline{K}^0$	< 7.3 (90 % C.L.)			preliminary
$J/\psi K^+$		$0.004 \pm 0.029 \pm 0.004$	$[-0.044, +0.052]$	preliminary
$\eta' K^+$		$-0.11 \pm 0.11 \pm 0.02$	$[-0.28, +0.07]$	
$\omega\pi^+$		$-0.01^{+0.29}_{-0.31} \pm 0.03$	$[-0.50, +0.46]$	
ϕK^+		$-0.05 \pm 0.20 \pm 0.03$	$[-0.37, +0.28]$	
ϕK^{*+}		$-0.43^{+0.36}_{-0.30} \pm 0.06$	$[-0.88, +0.18]$	
ϕK^{*0}		$0.00 \pm 0.27 \pm 0.03$	$[-0.43, +0.43]$	
$K^{*0}_{K^+\pi^-}\gamma$	$43.9 \pm 4.1 \pm 2.7$			preliminary
$K^{*0}_{K^0_S\pi^0}\gamma$	$41.0 \pm 17.1 \pm 4.2$			preliminary
$K^{*+}_{K^0_S\pi^+}\gamma$	$31.2 \pm 7.6 \pm 2.1$			preliminary
$K^{*+}_{K^+\pi^0}\gamma$	$55.2 \pm 10.7 \pm 4.2$			preliminary
$K^*\gamma$		$-0.035 \pm 0.076 \pm 0.012$	$[-0.16, +0.09]$	preliminary
$\gamma\gamma$	< 1.7 (90 % C.L.)			

Table 1: Branching ratios and $\mathcal{CP}$ violating charge asymmetries in rare two-body and quasi-two-body B decays.

signal region gives the number of signal events by counting the remaining events in the signal region ($B^0 \to \gamma\gamma$). Alternatively unbinned extended maximum Likelihood fits are performed and signal as well as background yields and the asymmetry parameters are determined by the fits. The kinematic variables used in the likelihoods are: $m_{\rm ES}$ (all analyses); ΔE (all analyses but $K^*\gamma$); $\mathcal{F}$ and $\theta_{\rm c}$ (two-body and charmless quasi-two-body); $p_{\rm K}$ ($J/\psi K^+$); $m_{\eta',\omega,\phi,K^*,\eta}$ and helicity angles for ω and ϕ (charmless quasi two-body). The shape and the fixed parameters for the probability density functions (PDF) are extracted from signal and background distributions from MC simulation, on-resonance ΔE-$m_{\rm ES}$ sidebands, and off-resonance data. The MC resolutions are adjusted by comparisons of data and simulation in abundant calibration channels with similar kinematics and topology, such as $B \to D\pi, D\rho$ with $D \to K\pi, K\pi\pi$. The Čerenkov angle residual parameterizations are determined from samples of $D^0 \to K^-\pi^+$ originating from D^* decays.

5 Results

In table 1 the results for branching ratios and charge asymmetries are summarized[1]. Given errors denote statistical and systematic uncertainties, respectively.

[1]For the $K^0\overline{K}^0$ mode we assume the Standard Model prediction that $B^0 \to K^0_S K^0_S$ proceeds through the $K^0\overline{K}^0$ intermediate state and use $\mathcal{B}(K^0\overline{K}^0 \to K^0_S K^0_S) = 0.5$

90 % C.L. upper limits for the branching ratios are given in cases where no signal is observed or the significance of the signal is less than 4σ.

Systematic uncertainties arise from: imperfect knowledge of the PDF shapes, uncertainties in the detection efficiencies, and potential charge bias in track reconstruction and particle identification. For most of the measurements, the PDF shapes contribute the largest systematic error. These uncertainties are often dominated by the statistical error on the used control sample. Due to the high statistics in the $J/\psi K^+$ mode greater care is taken of possible systematic effects. The fake asymmetry due to the different probability of interaction of K^+ and K^- in the detector material before the DCH is estimated to be -0.0039. We correct $\mathcal{A}_{\mathcal{CP}}$ in this mode by this number and add 100 % of its magnitude to the systematic error.

6 Conclusions

We have measured branching fractions for the rare charmless decays $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B^+ \to K^+\pi^0$, $B^+ \to K^0\pi^+$, and $B^0 \to K^0\pi^0$, and set upper limits on $B^0 \to K^+K^-$, $B^+ \to \pi^+\pi^0$, $B^+ \to \overline{K}^0K^+$, and a preliminary upper limit on $B^0 \to K^0\overline{K}^0$. We also report preliminary branching ratios for the radiative penguin decays $B^{0(+)} \to K^{*0(+)}\gamma$ and set an upper limit on $B^0 \to \gamma\gamma$.

We found no evidence for direct $\mathcal{CP}$ violation in the considered modes and 90 % confidence level limits are reported.

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