

Measurements of Branching Fractions, Polarizations, and Direct CP -Violation Asymmetries in $B \rightarrow \rho K^*$ and $B \rightarrow f_0(980)K^*$ Decays

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We report searches for B -meson decays to the charmless final states ρK^* and $f_0(980)K^*$ with a sample of 232×10^6 $B\bar{B}$ pairs collected with the $BABAR$ detector at the PEP-II e^+e^- collider. We measure in units of 10^{-6} the following branching fractions, where the first error quoted is statistical and the second systematic, or upper limits are given at the 90% confidence level: $\mathcal{B}(B^+ \rightarrow \rho^0 K^{*+}) < 6.1$, $\mathcal{B}(B^+ \rightarrow \rho^+ K^{*0}) = 9.6 \pm 1.7 \pm 1.5$, $\mathcal{B}(B^0 \rightarrow \rho^- K^{*+}) < 12.0$, $\mathcal{B}(B^0 \rightarrow \rho^0 K^{*0}) = 5.6 \pm 0.9 \pm 1.3$, $\mathcal{B}(B^+ \rightarrow f_0(980)K^{*+}) = 5.2 \pm 1.2 \pm 0.5$, and $\mathcal{B}(B^0 \rightarrow f_0(980)K^{*0}) < 4.3$. For the significant modes, we also measure the fraction of longitudinal polarization and the charge asymmetry: $f_L(B^+ \rightarrow \rho^+ K^{*0}) = 0.52 \pm 0.10 \pm 0.04$, $f_L(B^0 \rightarrow \rho^0 K^{*0}) = 0.57 \pm 0.09 \pm 0.08$, $\mathcal{A}_{CP}(B^+ \rightarrow \rho^+ K^{*0}) = -0.01 \pm 0.16 \pm 0.02$, $\mathcal{A}_{CP}(B^0 \rightarrow \rho^0 K^{*0}) = 0.09 \pm 0.19 \pm 0.02$, and $\mathcal{A}_{CP}(B^+ \rightarrow f_0(980)K^{*+}) = -0.34 \pm 0.21 \pm 0.03$.

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The study of B -meson decays to charmless hadronic final states plays an important role in understanding CP violation. The charmless decays $B \rightarrow \rho K^*$ proceed through dominant penguin loops and Cabibbo-suppressed tree processes ($B^+ \rightarrow \rho^+ K^{*0}$ is pure penguin) to two vector particles (VV). A large longitudinal polarization fraction f_L [of order $(1 - 4m_V^2/m_B^2) \sim 0.9$] is predicted for both tree- and penguin-dominated VV decays [1]. However, recent measurements of the pure penguin VV decays $B \rightarrow \phi K^*$ indicate $f_L \sim 0.5$ [2]. Several attempts to understand this small value of f_L within or beyond the standard model (SM) have been made [3]. Further information about $SU(3)$ -related decays may provide some insight into this polarization puzzle. Characterization of the four $B \rightarrow \rho K^*$ modes can also be used within the SM framework to help constrain the angles α and γ of the unitarity triangle [4].

We report measurements of branching fractions, longitudinal polarizations, and direct CP -violating asymmetries for the $B \rightarrow \rho K^*$ decay modes, with explicit consideration of nonresonant backgrounds. We also measure branching fractions and direct CP -violating asymmetries for the $B \rightarrow f_0(980)K^*$ modes that share the same final states. Some modes were previously measured [5–7]. Charge-conjugate modes are implied throughout.

This analysis is based on a data sample of 232×10^6 $B\bar{B}$ pairs, corresponding to an integrated luminosity of 210 fb^{-1} , collected with the $BABAR$ detector [8] at the Stanford Linear Accelerator Center (SLAC) PEP-II asymmetric-energy e^+e^- collider operating at a center-of-mass (c.m.) energy $\sqrt{s} = 10.58 \text{ GeV}$, corresponding to the $Y(4S)$ resonance mass.

The angular distribution of the ρK^* decay products, after integrating over the angle between the decay planes of the vector mesons, for which the acceptance is uniform, is proportional to

$$\frac{1}{4}(1 - f_L)\sin^2\theta_{K^*}\sin^2\theta_\rho + f_L\cos^2\theta_{K^*}\cos^2\theta_\rho, \quad (1)$$

where θ_{K^*} and θ_ρ are the helicity angles of K^* and ρ , defined between the $K(\pi^+)$ momentum and the direction opposite to B in the $K^*(\rho)$ rest frame [9]. We also measure the time-integrated direct CP -violating asymmetry $\mathcal{A}_{CP} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where the superscript on

the total width Γ indicates the sign of the b -quark charge in the B meson.

We fully reconstruct charged and neutral decay products including the intermediate states ρ^0 or $f_0(980) \rightarrow \pi^+\pi^-$, $\rho^+ \rightarrow \pi^+\pi^0$, $K^{*0} \rightarrow K^+\pi^-$, $K^{*+} \rightarrow K^+\pi^0$, $K^{*+} \rightarrow K_S^0\pi^+$ (only in $\rho^0 K^{*+}$), $\pi^0 \rightarrow \gamma\gamma$, and $K_S^0 \rightarrow \pi^+\pi^-$. We assume the $f_0(980)$ measured line shape [10] and a branching ratio of 100% for $f_0(980) \rightarrow \pi^+\pi^-$. Table I lists the selection requirements on the invariant mass and helicity angle of B -daughter resonances.

The tracks from the B -meson candidate are required to originate from the interaction point. Looser criteria are applied to tracks forming K_S^0 candidates, for which we require $|m_{\pi^+\pi^-} - m_{K_S^0}| < 12 \text{ MeV}$, a measured proper decay time greater than 5 times its uncertainty, and the cosine of the angle between the reconstructed flight and momentum directions to exceed 0.995. Charged particle identification provides discrimination between kaons and pions and is also used to reject electrons and protons. We reconstruct π^0 mesons from pairs of photons, each with a minimum energy of 30 ($\rho^0 K^{*+}$) or 50 MeV ($\rho^+ K^{*0}$ and $\rho^- K^{*+}$). The invariant mass of π^0 candidates is required to be within 15 ($\rho^0 K^{*+}$) or 25 MeV ($\rho^+ K^{*0}$ and $\rho^- K^{*+}$) of the nominal mass [11].

B -meson candidates are characterized kinematically by the energy difference $\Delta E = E_B^* - \sqrt{s}/2$ and the energy-substituted mass $m_{ES} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}$, where (E_i, \mathbf{p}_i) and (E_B, \mathbf{p}_B) are the four-momenta of the $Y(4S)$ and B candidates, respectively, and the asterisk denotes the $Y(4S)$ frame. Our signal lies in the region $|\Delta E| \leq 0.1 \text{ GeV}$ and $5.27 \leq m_{ES} \leq 5.29 \text{ GeV}$. Sidebands in m_{ES} and ΔE are used to characterize the continuum background. The average number of signal B candidates per selected data event ranges from 1.05 to 1.27, depending on the final state. A single candidate per event is chosen as the one with the smallest B vertex-fit χ^2 ($\rho^+ K^{*0}$ and $\rho^0 K^{*0}$), the smallest value of χ^2 constructed from deviations of reconstructed π^0 masses from the expected value ($\rho^- K^{*+}$), or randomly ($\rho^0 K^{*+}$). Monte Carlo (MC) simulation shows that up to 38% (23%) of longitudinally (transversely) polarized signal events are misreconstructed with one or more tracks originating from the other B in the event.

TABLE I. Selection requirements on the invariant mass (in GeV) and helicity angle of B -daughter resonances.

Mode	$m_{\pi\pi}$	$m_{K\pi}$	$\cos\theta_\rho$	$\cos\theta_{K^*}$
$\rho^0 K_{K^+\pi^0}^{*+}$	(0.52, 1.10)	(0.75, 1.05)	(-0.95, 0.95)	(-0.5, 1.0)
$\rho^0 K_{K^0\pi^+}^{*+}$	(0.52, 1.10)	(0.75, 1.05)	(-0.95, 0.95)	(-0.9, 1.0)
$\rho^+ K^{*0}$	(0.40, 1.15)	(0.77, 1.02)	(-0.66, 0.95)	(-0.95, 1.0)
$\rho^- K_{K^+\pi^0}^{*+}$	(0.40, 1.15)	(0.77, 1.02)	(-0.80, 0.98)	(-0.80, 0.98)
$\rho^0 K^{*0}$	(0.52, 1.15)	(0.77, 1.02)	(-0.95, 0.95)	(-0.95, 1.0)

To reject the dominant $q\bar{q}$ continuum background, we require $|\cos\theta_T| < 0.8$, where θ_T is the c.m. frame angle between the thrust axes of the B candidate and that formed from the other tracks and neutral clusters in the event. We also use as discriminant variables the polar angles of the B -momentum vector and the B -candidate thrust axis with respect to the beam axis and the two Legendre moments L_0 and L_2 of the energy flow around the B -candidate thrust axis in the c.m. frame [12]. These variables are combined in a Fisher discriminant \mathcal{F} ($\rho^0 K^{*+}$) or a neural network (NN) (other modes). Finally, we suppress background from B decays to charmed states by removing signal candidates that have decay products consistent with $D^0 \rightarrow K^- \pi^+ (\pi^0)$ and $D^- \rightarrow K^+ \pi^- \pi^-$ decays.

We use an extended (not extended in the $\rho^+ K^{*0}$ mode) unbinned maximum-likelihood (ML) fit to extract signal yields, asymmetries, and angular polarizations simultaneously. We define the likelihood \mathcal{L}_i for each event candidate i as the sum of $n_j \mathcal{P}_j(\vec{x}_i; \vec{\alpha})$ over hypotheses j (signal, $q\bar{q}$ background, and several $B\bar{B}$ backgrounds discussed below), where the $\mathcal{P}_j(\vec{x}_i; \vec{\alpha})$ are the probability density functions (PDFs) for the measured variables \vec{x}_i , and n_j are the yields for the different hypotheses. The quantities $\vec{\alpha}$ represent parameters in the expected distributions of the measured variables for each hypothesis. They are extracted from MC simulation and (m_{ES} , ΔE) sideband data. They are fixed in the fit except for some shape parameters of the continuum ΔE and m_{ES} distributions. The extended likelihood function for a sample of N candidates is $\mathcal{L} = \exp(-\sum n_j) \prod_{i=1}^N \mathcal{L}_i$.

The fit input variables \vec{x}_i are m_{ES} , ΔE , NN or \mathcal{F} , invariant masses of the candidates ρ [$f_0(980)$] and K^* , and helicity angles θ_ρ and θ_{K^*} . We study large control samples of $B \rightarrow D\pi$ decays of similar topology to verify the simulated resolutions in ΔE and m_{ES} , adjusting the PDFs to account for any difference found.

Since almost all correlations among the fit input variables are found to be small, we take each \mathcal{P}_j to be the product of the PDFs for the separate variables with the following exceptions where we explicitly account for correlations: the correlation between the two helicity angles in signal, the correlation due to misreconstructed events in signal, and the correlation between mass and helicity in backgrounds. The effect of neglecting other correlations is evaluated by fitting ensembles of simulated experiments in

which we embed the expected numbers of signal and charmless B -background events, randomly extracted from fully simulated MC samples.

We use MC-simulated events to study backgrounds from other B decays. Charmless B backgrounds are grouped into up to 11 classes with similar topologies depending on the mode. Yields for decays with poorly known branching fractions are varied in the fit with those remaining kept fixed to their measured values. One to four additional classes account for neutral and charged B decays to final states with charm. Up to 6 classes account for misreconstructed events in signal. We also introduce components for nonresonant backgrounds such as $\pi\pi K^*$, $\rho K\pi$, $f_0(980)K\pi$, and $f_0(1370)K\pi$, which differ from signal only in resonance mass and helicity distributions. The magnitudes of these components are determined by extrapolating from fits performed on a wider mass range reaching to higher-mass values and are fixed in the fit. Figure 1 shows the sPlots [13] for the invariant mass of $K\pi$ and $\pi\pi$ in the $\rho^+ K^{*0}$ and $\rho^0 K^{*0}$ modes, respectively. The data events are weighted by their probability to be signal, calculated from the signal and backgrounds PDFs of the ΔE , m_{ES} , and NN variables.

The results of the ML fits are summarized in Table II. For the branching fractions, we assume equal production rates of $B^+ B^-$ and $B^0 \bar{B}^0$. The significance S of a signal is defined by $\Delta \ln \mathcal{L} = S^2/2$, where $\Delta \ln \mathcal{L}$ represents the change in likelihood from the maximal value when the

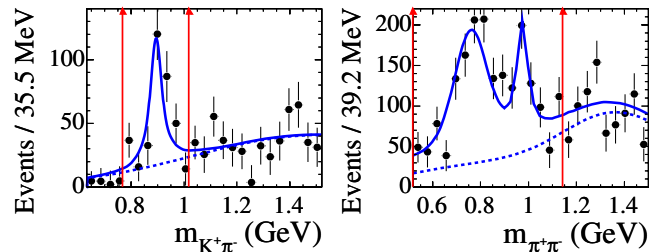


FIG. 1 (color online). sPlots [13] for the invariant mass of $K\pi$ in $\rho^+ K^{*0}$ (left) and $\pi\pi$ in $\rho^0/f_0(980)K^{*0}$ (right) up to the higher-mass regions. The points with error bars show the data, and the solid (dashed) lines show the projected PDFs of the signal and nonresonant background [nonresonant background only: $\rho K\pi$ in $\rho^+ K^{*0}$; the sum of $f_0(1370)K^*$, $\pi\pi K^*$, and $\pi\pi K\pi$ in $\rho^0 K^{*0}$]. The arrows show the nominal fit regions.

TABLE II. Summary of results for the measured B -decay modes: signal yield n_{sig} and its statistical uncertainty, reconstruction efficiency ε , daughter branching fraction product $\prod \mathcal{B}_i$, significance S (systematic uncertainties included), measured branching fraction \mathcal{B} (90% C.L. upper limit in parentheses), measured longitudinal polarization f_L (for the modes with nonsignificant signals, the numbers in brackets are not quoted as measurements), and charge asymmetry \mathcal{A}_{CP} .

Mode	n_{sig}	$\varepsilon(\%)$	$\prod \mathcal{B}_i(\%)$	$S(\sigma)$	$\mathcal{B}(10^{-6})$	f_L	\mathcal{A}_{CP}
$\rho^0 K^{*+}$				2.5	$3.6_{-1.6}^{+1.7} \pm 0.8$ (6.1)	$[0.9 \pm 0.2]$	...
$\rightarrow \rho^0 K_{K^+ \pi^0}^{*+}$	19_{-15}^{+16}	7.9	32.9	1.3	$3.2_{-2.4}^{+2.7} \pm 0.9$	$[0.8_{-0.5}^{+0.3}]$	...
$\rightarrow \rho^0 K_{K_S^0 \pi^+}^{*+}$	32_{-17}^{+19}	15.8	22.9	2.1	$3.8_{-2.1}^{+2.2} \pm 0.9$	$[1.0 \pm 0.3]$	...
$\rho^+ K^{*0}$	194 ± 29	13.5	66.7	7.1	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	$-0.01 \pm 0.16 \pm 0.02$
$\rho^- K_{K^+ \pi^0}^{*+}$	60_{-22}^{+25}	15.2	32.5	1.6	$5.4_{-3.4}^{+3.8} \pm 1.6$ (12.0)	$[-0.18_{-1.74}^{+0.52}]$	...
$\rho^0 K^{*0}$	185 ± 30	22.9	66.7	5.3	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	$0.09 \pm 0.19 \pm 0.02$
$f_0(980)K^{*+}$				5.0	$5.2 \pm 1.2 \pm 0.5$	...	$-0.34 \pm 0.21 \pm 0.03$
$\rightarrow f_0(980)K_{K^+ \pi^0}^{*+}$	40_{-12}^{+13}	8.5	32.9	3.8	$6.2_{-1.9}^{+2.1} \pm 0.7$	...	$-0.50 \pm 0.29 \pm 0.03$
$\rightarrow f_0(980)K_{K_S^0 \pi^+}^{*+}$	37_{-12}^{+14}	16.6	22.9	3.2	$4.2_{-1.4}^{+1.5} \pm 0.5$	...	$-0.13 \pm 0.30 \pm 0.01$
$f_0(980)K^{*0}$	83 ± 19	21.7	66.7	3.5	$2.6 \pm 0.6 \pm 0.9$ (4.3)	...	$-0.17 \pm 0.28 \pm 0.02$

number of signal events is set to zero, corrected for the systematic error defined below. We find significant signals for $\rho^+ K^{*0}$, $\rho^0 K^{*0}$, and $f_0(980)K^{*+}$, and some evidence for $f_0(980)K^{*0}$. For the modes with significance smaller than 5 standard deviations, we also measure the 90% confidence level (C.L.) upper limit, taking into account the systematic uncertainty. Figure 2 shows projections of the fits onto m_{ES} .

A source of systematic error is related to the determination of the PDFs and is due to the limited statistics of the Monte Carlo simulation and to the uncertainty on the PDF shapes. We obtain variations in the yields ranging from 1% to 18%, depending on the mode. The systematic error due to the nonresonant background extrapolation and interference with signal is in the range 6%–21%. Event yields for B -background modes fixed in the fit are varied by their respective uncertainties. This results in a systematic uncertainty of 2%–12%. We evaluate and correct for possible fit biases with MC experiments. We assign a systematic uncertainty of 1%–7% for this.

The reconstruction efficiency depends on the decay polarization. For the $\rho^0 K^{*+}$ mode, we calculate the efficiency using the measured polarization (combined for the two $\rho^0 K^{*+}$ modes) and assign a systematic uncertainty corresponding to the total polarization measurement error (9% and 20% for each mode, respectively). For the other modes, we exploit the correlation between \mathcal{B} and f_L and obtain the values of \mathcal{B} from fits where \mathcal{B} and f_L are free parameters. Figure 3 shows the behavior of $-2 \ln \mathcal{L}(f_L, \mathcal{B})$ for the modes with significant signal.

Additional reconstruction efficiency uncertainties arise from tracking (3%–5%), particle identification (1%–2%), vertex probability (2%), track multiplicity (1%), and thrust angle (1%). K_S^0 and π^0 reconstruction contribute 2.3% and 3% uncertainty, respectively. Other minor systematic effects are from uncertainty in daughter branching fractions,

MC sample statistics, and the number of B mesons. The absolute systematic uncertainty in f_L takes into account PDF shape variations (5%–10%), B and nonresonant backgrounds (4%–8%), and efficiency dependence on the polarization (1%–2%). The absolute uncertainty in the charge asymmetry due to track charge bias is less than

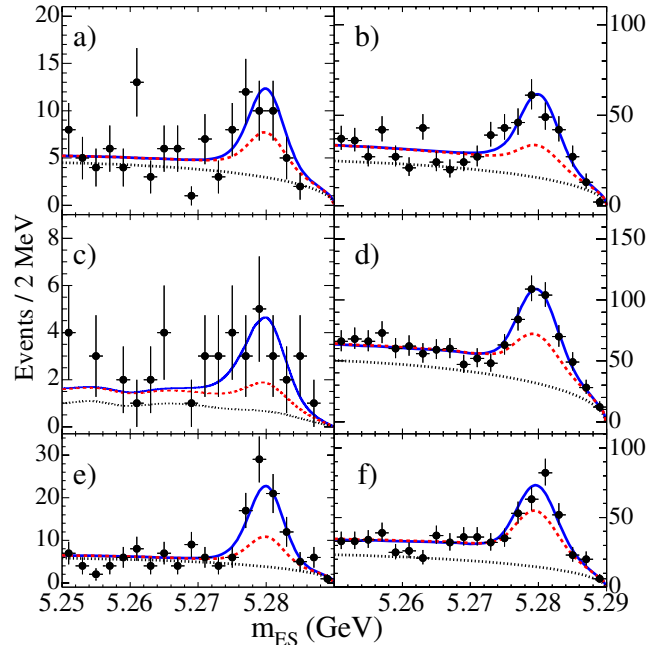


FIG. 2 (color online). Projections of the multidimensional fit onto m_{ES} for events passing a signal-to-total likelihood probability ratio cut with the plotted variable excluded for (a) $\rho^0 K^{*+}$, (b) $\rho^+ K^{*0}$, (c) $\rho^- K^{*+}$, (d) $\rho^0 K^{*0}$, (e) $f_0(980)K^{*+}$, and (f) $f_0(980)K^{*0}$. The points with error bars show the data; the solid, dashed, and dotted lines show the total, background, and continuum PDF projections, respectively.

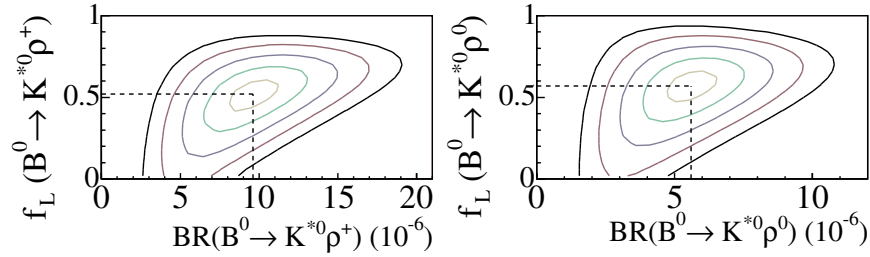


FIG. 3 (color online). Distribution of $-2\ln\mathcal{L}(\mathcal{B}, f_L)$ for $B^+ \rightarrow \rho^+ K^{*0}$ (left) and $B^0 \rightarrow \rho^0 K^{*0}$ (right) decays. The solid dots correspond to the central values and the curves give contours in $\Delta\sqrt{-2\ln\mathcal{L}(\mathcal{B}, f_L)} = 1$ steps.

1%. PDF variations and fixed B -background effects contribute up to 2%.

In summary, we search for $B \rightarrow \rho/f_0(980)K^*$ decays. We measure the significances, the branching fractions or 90% C.L. upper limits, the fractions of longitudinal polarization, and the charge asymmetries, summarized in Table II. Our results agree with and supersede our previous measurement [5], where $\rho^0 K^{*+}$ and $f_0(980)K^{*+}$ were not separated. We measure $B^+ \rightarrow \rho^+ K^{*0}$ with a similar result and precision as in Ref. [6]. For the first time, we observe $B^0 \rightarrow \rho^0 K^{*0}$ and $B^+ \rightarrow f_0(980)K^{*+}$, see evidence for $B^0 \rightarrow f_0(980)K^{*0}$, and search for $B^0 \rightarrow \rho^- K^{*+}$. The measured polarization in the $\rho^+ K^{*0}$ and $\rho^0 K^{*0}$ modes agrees with values measured in ϕK^* decays, which are more precise by a factor of 2.

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