Amplitude Analysis of the $B^{\pm} \rightarrow \varphi K^{*}(892)^{\pm}$ Decay

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We perform an amplitude analysis of $B^{\pm} \rightarrow \varphi(1020)K^{*}(892)^{\pm}$ decay with a sample of about 384×10^6 $B\bar{B}$ pairs recorded with the *BABAR* detector. Overall, twelve parameters are measured, including the fractions of longitudinal f_L and parity-odd transverse $f_{\perp}$ amplitudes, branching fraction, strong phases, and six parameters sensitive to CP violation. We use the dependence on the $K\pi$ invariant mass of the interference between the $J^P = 1^-$ and 0^+ $K\pi$ components to resolve the discrete ambiguity in the determination of the strong and weak phases. Our measurements of $f_L = 0.49 \pm 0.05 \pm 0.03$,

$f_\perp = 0.21 \pm 0.05 \pm 0.02$, and the strong phases point to the presence of a substantial helicity-plus amplitude from a presently unknown source.

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The polarization anomaly in vector-vector charmless hadronic B-meson decays [1–7] motivates a revision in our understanding of the effective flavor-changing $b \rightarrow s$ quark transition in B-meson decays. Explanations of this anomaly led to development of models either with physics beyond the standard model [8] or new strong and weak dynamics [9,10].

A vector-vector B-meson decay, such as $B \rightarrow \varphi K^*$, is characterized by three complex helicity amplitudes $A_{1\lambda}$ which correspond to helicity states $\lambda = -1, 0, +1$ of the vector mesons. The A_{10} amplitude is expected to dominate [11] due to the $(V - A)$ nature of the weak interactions and helicity conservation in the strong interactions. Experimental results suggest that A_{1+1} and A_{1-1} comprise about 50% of the total decay amplitude in $B \rightarrow \varphi K^*$ [1,2]. Recently, the *BABAR* experiment extended the study of the $B^0 \rightarrow \varphi K^{*0}$ decay to resolve the discrete ambiguity between the A_{1+1} and A_{1-1} amplitudes [5].

We now investigate the polarization puzzle with a full amplitude analysis of the $B^\pm \rightarrow \varphi K^*(892)^\pm$ decay. Within the standard model, the leading contributions to the neutral- and charged-B-meson decays to $\varphi K^*(892)$ are expected to be the same. However, independent measurements of both decay modes provide important constraints on new contributions. In this Letter, we report 12 independent parameters for the three B^+ and three B^- decay amplitudes, six of which are presented for the first time. Moreover, we use the dependence on the $K\pi$ invariant mass of the interference between the $J^P = 1^-$ and 0^+ $(K\pi)^\pm$ components [5,12,13] to resolve the discrete ambiguity between the A_{1+1} and A_{1-1} helicity amplitudes.

We use a sample of $(383.6 \pm 4.2) \times 10^6$ $\Upsilon(4S) \rightarrow B\bar{B}$ events collected with the *BABAR* detector [14] at the PEP-II e^+e^- asymmetric-energy storage rings. The e^+e^- center-of-mass energy $\sqrt{s}$ is equal to 10.58 GeV. Momenta of charged particles are measured in a tracking system consisting of a silicon vertex tracker with five double-sided layers and a 40-layer drift chamber, both within the 1.5-T magnetic field of a solenoid. Identification of charged particles is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter.

The $B^\pm \rightarrow \varphi(1020)K^{*\pm} \rightarrow (K^+K^-)(K\pi)^\pm$ candidates are analyzed with two $(K\pi)^\pm$ final states, $K^0_S\pi^\pm$ and $K^\pm\pi^0$. The neutral pseudoscalar mesons are reconstructed in the final states $K^0_S \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$. We define the helicity angle θ_i as the angle between the direction of the K or K^+ meson from $K^* \rightarrow K\pi$ (θ_1) or $\varphi \rightarrow K^+K^-$ (θ_2) and the direction opposite the B in the K^* or φ rest frame, and Φ as the angle between the decay planes of the two systems [5]. The differential decay width has four complex amplitudes $A_{J\lambda}$ which describe two spin states of the $K\pi$ system ($J = 1$ or 0) and the three helicity states of the $J = 1$ state ($\lambda = 0$ or ± 1):

$$\frac{d^3\Gamma}{d\mathcal{H}_1 d\mathcal{H}_2 d\Phi} \propto \Big|\sum A_{J\lambda} Y_J^\lambda(\mathcal{H}_1, \Phi) Y_1^{-\lambda}(-\mathcal{H}_2, 0)\Big|^2, \tag{1}$$

where $\mathcal{H}_i = \cos\theta_i$ and Y_J^λ are the spherical harmonics with $J = 1$ for $K^*(892)$ and $J = 0$ for $(K\pi)^*_0$. We reparametrize the amplitudes as $A_{1\pm1} = (A_{1\parallel} \pm A_{1\perp})/\sqrt{2}$, where $A_{1\parallel}$ and $A_{1\perp}$ are parity-even and parity-odd amplitudes, respectively.

We identify B meson candidates using two kinematic variables: $m_{\mathrm{ES}} = [(s/2 + \mathbf{p}_\Upsilon \cdot \mathbf{p}_B)^2/E^2_\Upsilon - \mathbf{p}^2_B]^{1/2}$ and $\Delta E = (E_\Upsilon E_B - \mathbf{p}_\Upsilon \cdot \mathbf{p}_B - s/2)/\sqrt{s}$, where $(E_B, \mathbf{p}_B)$ is the four-momentum of the B candidate, and $(E_\Upsilon, \mathbf{p}_\Upsilon)$ is the e^+e^- initial state four-momentum, both in the laboratory frame. We require $m_{\mathrm{ES}} > 5.25$ GeV and $|\Delta E| < 100$ MeV. The ΔE resolution is 34 and 20 MeV for the subchannels with and without π^0, respectively. The requirements on the invariant masses are $0.75 < m_{K\pi} < 1.05$ GeV, $0.99 < m_{K\bar{K}} < 1.05$ GeV, $|m_{\pi\pi} - m_{K^0}| < 12$ MeV, and $120 < m_{\gamma\gamma} < 150$ MeV for the $K^{*\pm}$, φ, K^0_S, and π^0, respectively. For the K^0_S candidates, we also require the cosine of the angle between the flight direction from the interaction point and momentum direction to be greater than 0.995 and the measured proper decay time greater than 5 times its uncertainty.

To reject the dominant $e^+e^- \rightarrow$ quark-antiquark background, we use the angle θ_T between the B-candidate thrust axis and that of the rest of the event, and a Fisher discriminant $\mathcal{F}$ [15]. Both variables are calculated in the center-of-mass frame. The discriminant combines the polar angles of the B-momentum vector and the B-candidate thrust axis with respect to the beam axis, and two moments of the energy flow around the B-candidate thrust axis [15].

To reduce combinatorial background with low-momentum π^0 candidates, we require $\mathcal{H}_1 < 0.6$. When more than one candidate is reconstructed, which happens in 7% of events with K^0_S and 17% with π^0, we select the one whose χ^2 of the charged-track vertex fit combined with χ^2 of the invariant mass consistency of the K^0_S or π^0 candidate is the lowest. We define the b-quark flavor sign Q to be opposite to the charge of the B meson candidate.

We use an unbinned, extended maximum-likelihood fit [1,5] to extract the event yields n^k_j and the parameters of the probability density function (PDF) $\mathcal{P}^k_j$. The index j represents three event categories used in our data model: the signal $B^\pm \rightarrow \varphi(K\pi)^\pm$ $(j = 1)$, a possible background from $B^{\pm} \to f_0(980)K^{*\pm}$ ($j = 2$), and combinatorial background ($j = 3$). The superscript k corresponds to the value of $Q = \pm$ and allows for a CP violating difference between the B^+ and B^- decay amplitudes (A and $\bar{A}$). In the signal category, the yield and asymmetry of the $B^{\pm} \to \varphi K^*(892)^{\pm}$ mode, n_{sig} and $\mathcal{A}_{CP}$, and those of the $B^{\pm} \to \varphi(K\pi)_0^{*\pm}$ mode are parametrized by applying the fraction of $\varphi K^*(892)^{\pm}$ yield, μ^k, to n_1^k. Hence, $n_{\text{sig}} = n_1^+ \times \mu^+ + n_1^- \times \mu^-$, $\mathcal{A}_{CP} = (n_1^+ \times \mu^+ - n_1^- \times \mu^-)/n_{\text{sig}}$, and the $\varphi(K\pi)_0^{*\pm}$ yield is $n_1^+ \times (1 - \mu^+) + n_1^- \times (1 - \mu^-)$.

The extended likelihood is $\mathcal{L} = \exp(-\sum n_j) \prod \mathcal{L}_i$. The likelihood $\mathcal{L}_i$ for each candidate i is defined as $\mathcal{L}_i = \sum_{j,k} n_j^k \mathcal{P}_j^k(\mathbf{x}_i; \mu^k, \boldsymbol{\zeta}, \boldsymbol{\xi})$, where the PDF is formed based on the following set of observables $\mathbf{x}_i = \{\mathcal{H}_1, \mathcal{H}_2, \Phi, m_{K\pi}, m_{K\bar{K}}, \Delta E, m_{\text{ES}}, \mathcal{F}, Q\}$ and the dependence on μ^k and polarization parameters $\boldsymbol{\zeta}$ is relevant only for the signal PDF $\mathcal{P}_1^k$. The remaining PDF parameters $\boldsymbol{\xi}$ are left free to vary in the fit for the combinatorial background and are fixed to the values extracted from Monte Carlo (MC) simulation [16] and calibration $B \to \bar{D}\pi$ decays for event categories $j = 1$ and 2.

The helicity part of the signal PDF is the ideal angular distribution from Eq. (1), multiplied by an empirical acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2, \Phi) \equiv \mathcal{G}_1(\mathcal{H}_1) \times \mathcal{G}_2(\mathcal{H}_2)$. Here, the amplitudes $A_{J\lambda}$ are expressed in terms of the polarization parameters $\boldsymbol{\zeta} \equiv \{f_L, f_\perp, \phi_\parallel, \phi_\perp, \delta_0, \mathcal{A}_{CP}^0, \mathcal{A}_{CP}^\perp, \Delta\phi_\parallel, \Delta\phi_\perp, \Delta\delta_0\}$ defined in Table I. CP violating differences are incorporated via the replacements in Eq. (1) for B^+ decays: $f_L \to f_L \times (1 + \mathcal{A}_{CP}^0 \times Q)$, $f_\perp \to f_\perp \times (1 + \mathcal{A}_{CP}^\perp \times Q)$, $\phi_\parallel \to (\phi_\parallel + \Delta\phi_\parallel \times Q)$, $\phi_\perp \to (\phi_\perp + \pi/2 + (\Delta\phi_\perp + \pi/2) \times Q)$, and $\delta_0 \to (\delta_0 + \Delta\delta_0 \times Q)$.

A relativistic spin-J Breit-Wigner amplitude parametrization is used for the resonance masses [7,17], and the $J^P = 0^+$ $(K\pi)_0^{*\pm}$ $m_{K\pi}$ amplitude is parametrized with the LASS function [12]. The latter includes a nonresonant component with the $K_0^*(1430)^{\pm}$ resonance Breit-Wigner tail. The interference between the $J = 0$ and 1 $(K\pi)^{\pm}$ contributions is modeled with the three terms $2\text{Re}\,(A_{1\lambda}A_{00}^*)$ in Eq. (1) with the four-dimensional angular and $m_{K\pi}$ parametrization and with dependence on μ^k and $\boldsymbol{\zeta}$.

The signal PDF for a given candidate i is a joint PDF for the helicity angles and resonance mass as discussed above, and the product of the PDFs for each of the remaining variables. The combinatorial background PDF is the product of the PDFs for independent variables and is found to describe well both the dominant quark-antiquark background and the background from random combinations of B tracks. The signal and background PDFs are illustrated in Figs. 1 and 2. For illustration, the signal fraction is enhanced with a requirement on the signal-to-background probability ratio, calculated with the plotted variable excluded, that is at least 50% efficient for signal $B^{\pm} \to \varphi(K\pi)^{\pm}$ events. We use a sum of Gaussian functions for the parametrization of the signal PDFs for ΔE, m_{ES}, and $\mathcal{F}$. For the combinatorial background, we use polynomials,

TABLE I. Summary of results for the $B^{\pm} \to \varphi K^*(892)^{\pm}$ decay. The 12 primary results are presented for the two decay subchannels along with the combined results, where the branching fraction $\mathcal{B}$ is computed using the number of signal events n_{sig} and the total selection efficiency ε, which includes the daughter branching fractions [7] and the reconstruction efficiency $\varepsilon_{\text{reco}}$ obtained from MC simulation. The definition of the six CP violating parameters allows for differences between the B^+ and B^- decay amplitudes A and $\bar{A}$ with superscript $Q = -$ and $+$, respectively. The systematic uncertainties are quoted last and are not included for the intermediate primary results in each subchannel. The dominant fit correlation coefficients ($\mathcal{C}$) are presented, where we show correlations of δ_0 with $\phi_\parallel/\phi_\perp$ and of $\Delta\delta_0$ with $\Delta\phi_\parallel/\Delta\phi_\perp$.

Parameter	Definition	$K^*(892)^{\pm} \to K_S^0\pi^{\pm}$	$K^*(892)^{\pm} \to K^{\pm}\pi^0$	Combined	$\mathcal{C}$
$\mathcal{B}$	$\Gamma/\Gamma_{\text{total}}$	$(10.5 \pm 1.4) \times 10^{-6}$	$(11.6 \pm 1.5) \times 10^{-6}$	$(11.2 \pm 1.0 \pm 0.9) \times 10^{-6}$	
f_L	$\lvert A_{10}\rvert^2/\Sigma\lvert A_{1\lambda}\rvert^2$	0.51 ± 0.07	$0.46^{+0.10}_{-0.09}$	$0.49 \pm 0.05 \pm 0.03$	$\}-58\%$
$f_\perp$	$\lvert A_{1\perp}\rvert^2/\Sigma\lvert A_{1\lambda}\rvert^2$	$0.22^{+0.07}_{-0.06}$	$0.21^{+0.09}_{-0.08}$	$0.21 \pm 0.05 \pm 0.02$	
$\phi_\parallel - \pi$	$\arg\,(A_{1\parallel}/A_{10}) - \pi$	$-0.75^{+0.28}_{-0.24}$	-0.77 ± 0.35	$-0.67 \pm 0.20 \pm 0.07$	$\}+56\%$
$\phi_\perp - \pi$	$\arg\,(A_{1\perp}/A_{10}) - \pi$	-0.15 ± 0.24	$-0.89^{+0.40}_{-0.46}$	$-0.45 \pm 0.20 \pm 0.03$	
$\delta_0 - \pi$	$\arg\,(A_{00}/A_{10}) - \pi$	-0.25 ± 0.24	$+0.11 \pm 0.31$	$-0.07 \pm 0.18 \pm 0.06$	$+37\%/+36\%$
$\mathcal{A}_{CP}$	$(\Gamma^+ - \Gamma^-)/(\Gamma^+ + \Gamma^-)$	-0.09 ± 0.13	$+0.07 \pm 0.13$	$0.00 \pm 0.09 \pm 0.04$	
$\mathcal{A}_{CP}^0$	$(f_L^+ - f_L^-)/(f_L^+ + f_L^-)$	$+0.24 \pm 0.15$	$+0.09 \pm 0.20$	$+0.17 \pm 0.11 \pm 0.02$	$\}-50\%$
$\mathcal{A}_{CP}^\perp$	$(f_\perp^+ - f_\perp^-)/(f_\perp^+ + f_\perp^-)$	$+0.12 \pm 0.31$	$+0.41^{+0.54}_{-0.40}$	$+0.22 \pm 0.24 \pm 0.08$	
$\Delta\phi_\parallel$	$(\phi_\parallel^+ - \phi_\parallel^-)/2$	$+0.02 \pm 0.28$	$+0.22 \pm 0.35$	$+0.07 \pm 0.20 \pm 0.05$	$\}-57\%$
$\Delta\phi_\perp$	$(\phi_\perp^+ - \phi_\perp^- - \pi)/2$	$+0.18 \pm 0.24$	$+0.48^{+0.46}_{-0.40}$	$+0.19 \pm 0.20 \pm 0.07$	
$\Delta\delta_0$	$(\delta_0^+ - \delta_0^-)/2$	$+0.13 \pm 0.24$	$+0.34 \pm 0.31$	$+0.20 \pm 0.18 \pm 0.03$	$+37\%/+37\%$
n_{sig}		$102 \pm 13 \pm 6$	$117^{+15}_{-16} \pm 7$		
ε		$(2.53 \pm 0.13)\%$	$(2.59 \pm 0.17)\%$		
$\varepsilon_{\text{reco}}$		$(22.3 \pm 1.2)\%$	$(16.0 \pm 1.0)\%$		

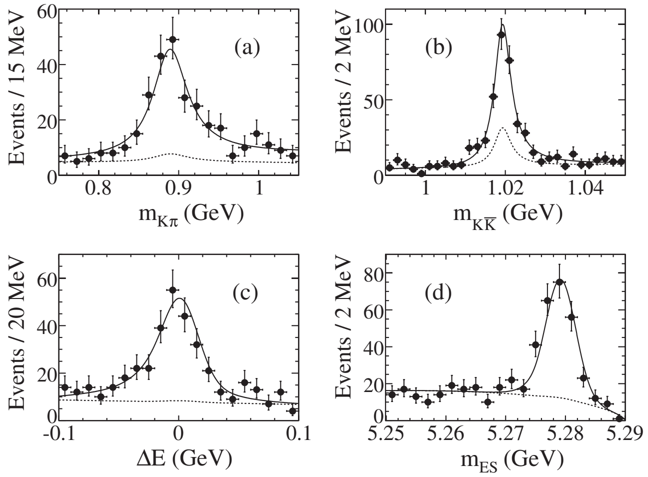

FIG. 1. Projections onto the variables (a) $m_{K\pi}$, (b) $m_{K\bar{K}}$, (c) ΔE, and (d) $m_{\rm ES}$ for the signal $B^{\pm} \to \varphi(K\pi)^{\pm}$ candidates with a requirement discussed in the text. The solid (dashed) lines show the signal-plus-background (background) PDF projections.

except for $m_{\rm ES}$ and $\mathcal{F}$ distributions which are parametrized by an empirical phase-space function and by Gaussian functions, respectively. Resonance production occurs in the background and is taken into account in the PDF.

We observe a nonzero $B^{\pm} \to \varphi K^{*}(892)^{\pm}$ yield with significance, including systematic uncertainties, of more than 10σ. The significance is defined as the square root of the change in $2\ln\mathcal{L}$ when the yield is constrained to zero in the likelihood $\mathcal{L}$. In Table I, results of the fit are presented, where the combined results are obtained from the simultaneous fit to the two decay subchannels.

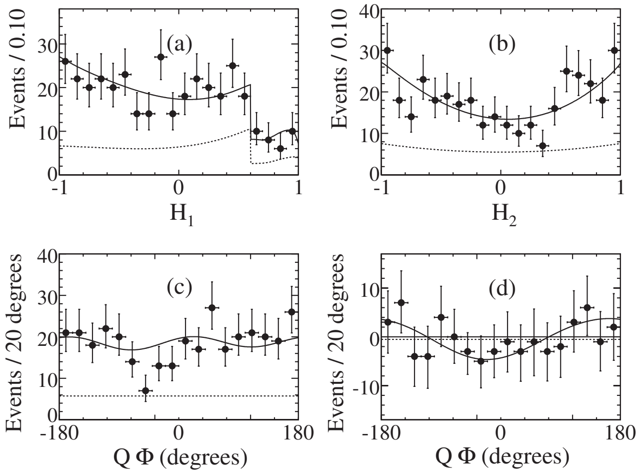

FIG. 2. Projections onto the variables (a) $\mathcal{H}_1$, (b) $\mathcal{H}_2$, (c) $Q\Phi$, and (d) the differences between the $Q\Phi$ projections for events with $\mathcal{H}_1\mathcal{H}_2 > 0$ and with $\mathcal{H}_1\mathcal{H}_2 < 0$ for the signal $B^{\pm} \to \varphi(K\pi)^{\pm}$ candidates following the solid (dashed) line definitions in Fig. 1. The step in the $\mathcal{H}_1$ PDF distributions is due to the selection requirement $\mathcal{H}_1 < 0.6$ in the $B^{\pm} \to \varphi(K^{\pm}\pi^{0})$ channel.

We repeat the fit by varying the fixed parameters in $\boldsymbol{\xi}$ within their uncertainties and obtain the associated systematic uncertainties. We allow for a flavor-dependent acceptance function and reconstruction efficiency in the study of asymmetries. The biases from the finite resolution of the angle measurements, the dilution due to the presence of fake combinations, or other imperfections in the signal PDF model are estimated with MC simulation and generated samples.

The $B^{\pm} \to f_0 K^{*\pm}$ category accounts for final states with K^+K^- from either f_0, a_0, or any other broad K^+K^- contribution under the φ. Its yield is consistent with zero. The $m_{K\bar{K}}$ PDF shape in this category is varied from the resonant to phase space. We assign an additional systematic uncertainty due to yield variation in the $B^{\pm} \to f_0 K^{*\pm}$ category when we fix its branching fraction to the value observed in the neutral B-decay analysis [5]. Additional systematic uncertainty originates from other potential B backgrounds, which we estimate can contribute at most a few events to the signal component. The systematic uncertainties in efficiencies are dominated by those in particle identification, track finding, and K_S^0 and π^0 selection. Other systematic effects arise from event-selection criteria, B-decay daughter branching fractions, and the number of B mesons.

The yield of the $\varphi(K\pi)_0^{*\pm}$ contribution is 57^{+14}_{-13} events with a statistical significance of 7.9σ, combining the $|A_{00}|^2$ term and the interference terms $2{\rm Re}\,(A_{1\lambda}A_{00}^{*})$, which confirms the significant S-wave $K\pi$ contribution observed in the neutral B-decay mode [5]. The dependence of the interference on the $K\pi$ invariant mass [5,12,13] allows us to reject the other solution near $(2\pi - \phi_{\parallel}, \pi - \phi_{\perp})$ relative to that in Table I with significance of 6.3σ, including systematic uncertainties.

The $(V - A)$ structure of the weak interactions, helicity conservation in strong interactions, and the s-quark spin flip suppression in the penguin decay diagram suggest $|A_{10}| \gg |A_{1+1}| \gg |A_{1-1}|$ [11]. This expectation disagrees with our observed value of f_L. We obtain the solution $\phi_{\parallel} \simeq \phi_{\perp}$ without discrete ambiguities, which is consistent with the approximate decay amplitude hierarchy $|A_{10}| \simeq |A_{1+1}| \gg |A_{1-1}|$.

We find that $\phi_{\perp}$ and $\phi_{\parallel}$ deviate from either π or zero by more than 3.1σ and 2.4σ, respectively, including systematic uncertainties. This indicates the presence of final-state interactions not accounted for in naïve factorization. Our measurements of the six CP violating parameters are consistent with zero and exclude a significant part of the physical region. We find no evidence of CP violation in this decay.

In summary, we have performed a full amplitude analysis and searched for CP violation in the angular distribution of the $B^{\pm} \to \varphi K^{*\pm}$ decay. Our results are summarized in Table I and supersede our prior measurements in Ref. [1]. These results find substantial A_{1+1} amplitude in the $B^{\pm} \rightarrow \varphi K^{*\pm}$ decay and point to physics outside the standard model or new dynamics [8–10].

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