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Vector-Tensor and Vector-Vector Decay Amplitude Analysis of $B^0 \to \phi K^{*0}$

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We perform an amplitude analysis of the decays $B^0 \to \phi K_2^*(1430)^0$, $\phi K^*(892)^0$, and $\phi(K\pi)^0_{S-\text{wave}}$ with a sample of about 384 million $B\overline{B}$ pairs recorded with the *BABAR* detector. The fractions of longitudinal polarization f_L of the vector-tensor and vector-vector decay modes are measured to be $0.853^{+0.061}_{-0.069} \pm 0.036$ and $0.506 \pm 0.040 \pm 0.015$, respectively. Overall, twelve parameters are measured for the vector-vector decay and seven parameters for the vector-tensor decay, including the branching fractions and parameters sensitive to *CP*-violation.

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The interest in the polarization and *CP*-asymmetry measurements in $B \to \phi K^*$ decays is motivated by their potential sensitivity to physics beyond the standard model in the $b \to s$ transition, shown in Fig. 1 (a) [1–3]. The large fraction of transverse polarization in the $B \to \phi K^*(892)$ decay measured by *BABAR* [4] and by Belle [5] indicates a significant departure from the naive expectation of predominant longitudinal polarization. This suggests other contributions to the decay amplitude, previously neglected, either within or beyond the standard model [6]. We now extend our investigation of the polarization puzzle with an amplitude analysis of the vector-tensor $B^0 \to \phi K_2^*(1430)^0$ decay. We also measure vector-vector $B^0 \to \phi K^*(892)^0$ and vector-scalar $B^0 \to \phi(K\pi)_0^{*0}$ decay amplitudes, where $(K\pi)_0^{*0}$ is the $J^P = 0^+$ $K\pi$ component.

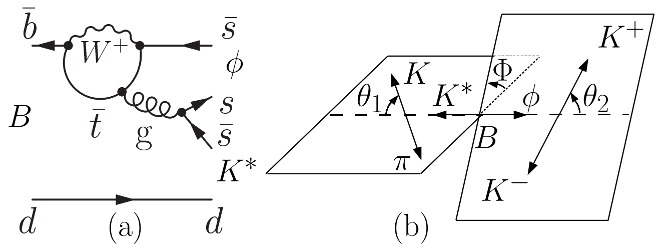

FIG. 1: (a) Feynman diagram describing the $B^0 \to \phi K^{*0}$ decay; (b) definition of decay angles given in the rest frames of the decaying parents.

The angular distribution of the $B \to \phi K^*$ decay can be expressed as a function of $\mathcal{H}_i = \cos\theta_i$ and Φ shown in Fig. 1 (b). Here θ_i is the angle between the direction of the K meson from the $K^* \to K\pi$ (θ_1) or $\phi \to K\overline{K}$ (θ_2) and the direction opposite the B in the K^* or ϕ rest frame, and Φ is the angle between the decay planes of the two systems. The differential decay width has seven complex amplitudes $A_{J\lambda}$ corresponding to the spin of the $K\pi$ system J and the helicity $\lambda = 0$ or ± 1:

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

where Y_J^λ are the spherical harmonics with $J = 2$ for $K_2^*(1430)$, $J = 1$ for $K^*(892)$, and $J = 0$ for $(K\pi)_0^*$. We can re-parameterize the amplitudes with the index J suppressed as A_0 and $A_{\pm1} = (A_\parallel \pm A_\perp)/\sqrt{2}$.

We analyze $\overset{(-)}{B}{}^0 \to \phi \overset{(-)}{K}{}^{*0} \to (K^+K^-)(K^\pm\pi^\mp)$ candidates using data collected with the *BABAR* detector [7] at the PEP-II e^+e^- collider. A sample of 383.6 ± 4.2 million $\Upsilon(4S) \to B\overline{B}$ events was recorded at the center-of-mass (CM) energy $\sqrt{s} = 10.58$ GeV. Charged-particle momenta 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. Charged-particle identification is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector.

We use two kinematic variables: $\Delta E = (E_i E_B - \mathbf{p}_i \cdot \mathbf{p}_B - s/2)/\sqrt{s}$ and $m_{\rm ES} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}$, where $(E_i, \mathbf{p}_i)$ is the e^+e^- beam four-momentum, and $(E_B, \mathbf{p}_B)$ is the four-momentum of the B candidate. We require $|\Delta E| < 0.1$ GeV and $m_{\rm ES} > 5.25$ GeV. The requirements on the invariant masses are $0.99 < m_{K\overline{K}} < 1.05$ GeV and $0.75 < m_{K\pi} < 1.05$ GeV (lower $m_{K\pi}$ range) or $1.13 < m_{K\pi} < 1.53$ GeV (higher $m_{K\pi}$ range).

To reject the dominant $e^+e^- \to$ quark-antiquark background, we use variables calculated in the CM frame. We require $|\cos\theta_T| < 0.8$, where θ_T is the angle between the B-candidate thrust axis and that of the rest of the event. We construct a Fisher discriminant, $\mathcal{F}$, that combines 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 [8].

We remove signal candidates that have decay products with invariant mass within 12 MeV of the nominal mass values for $D_s^\pm$ or $D^\pm \to \phi\pi^\pm$. In about 5% of events more than one candidate is reconstructed and we select the one whose four-track vertex has the lowest χ^2. We define the flavor sign Q to be the charge of the pion.

We use an unbinned, extended maximum-likelihood fit [4] to extract the event yields n_j, flavor asymme-

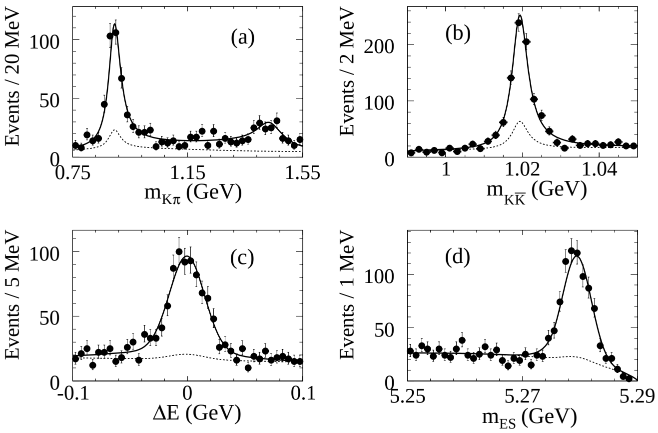

FIG. 2: Projections onto the variables $m_{K\pi}$ (a), $m_{K\overline{K}}$ (b), ΔE (c), and $m_{\rm ES}$ (d) for the signal $B^0 \to \phi(K\pi)$ candidates. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dashed) lines show the signal-plus-background (background) PDF projections.

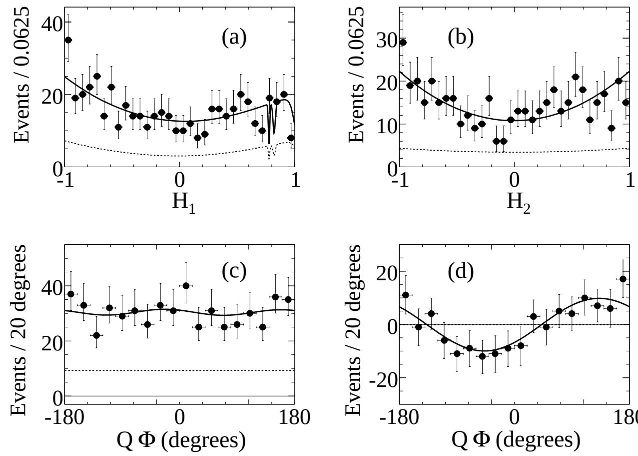

FIG. 3: Projections onto the variables $\mathcal{H}_1$ (a), $\mathcal{H}_2$ (b), $Q\,\Phi$ (c), and the differences between the $Q\,\Phi$ projections for events with $\mathcal{H}_1\,\mathcal{H}_2 > 0$ and with $\mathcal{H}_1\,\mathcal{H}_2 < 0$ (d) for the signal $B^0 \to \phi K^*(892)^0$ candidates following the solid (dashed) line definitions in Fig. 2. The $D^{\pm}_{(s)}$-meson veto causes the sharp acceptance dips seen in (a).

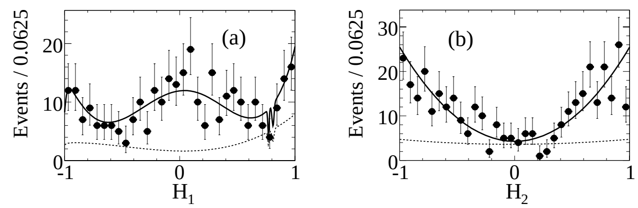

FIG. 4: Same as Fig. 3 (a,b), but for the signal $B^0 \to \phi K_2^*(1430)^0$ and $\phi(K\pi)_0^{*0}$ candidates combined.

tries $\mathcal{A}_j$, and the probability density function (PDF) parameters, denoted by $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$, to be described below. The data model has five event categories j: $B \to \phi(K\pi)_{J=0,1,2}$, $B \to f_0(980)K^*$, and combinatorial background. The combinatorial background PDF is found to account well for both the dominant quark-antiquark background and the random tracks from the B decays. The likelihood $\mathcal{L}_i$ for each candidate i is defined as $\mathcal{L}_i = \sum_{j,k} n_j^k\, \mathcal{P}_j^k(\mathbf{x_i};\, \boldsymbol{\zeta};\, \boldsymbol{\xi})$, where each of the $\mathcal{P}_j^k$ is the PDF for variables $\mathbf{x_i} = \{\mathcal{H}_1,\, \mathcal{H}_2,\, \Phi,\, m_{K\pi},\, m_{K\overline{K}},\, \Delta E,\, m_{\rm ES},\, \mathcal{F},\, Q\}$. The flavor index k corresponds to the value of Q, that is $\mathcal{P}_j^k \equiv \mathcal{P}_j \times \delta_{kQ}$.

We define $n_j = n_j^+ + n_j^-$ and $\mathcal{A}_j = (n_j^+ - n_j^-)/(n_j^+ + n_j^-)$. The polarization parameters, with the index J suppressed, are defined as $f_L = |A_0|^2/\Sigma|A_\lambda|^2$, $f_\perp = |A_\perp|^2/\Sigma|A_\lambda|^2$, $\phi_\parallel = \arg(A_\parallel/A_0)$, and $\phi_\perp = \arg(A_\perp/A_0)$. We allow for CP-violating differences between the $\overline{B}^0$ ($Q = +1$) and B^0 ($Q = -1$) decay amplitudes ($\overline{A}$ and A) and incorporate them via the replacements $f_L \to f_L \times (1 + \mathcal{A}^0_{CP} \times Q)$, $f_\perp \to f_\perp \times (1 + \mathcal{A}^\perp_{CP} \times Q)$, $\phi_\parallel \to (\phi_\parallel + \Delta\phi_\parallel \times Q)$, and $\phi_\perp \to (\phi_\perp + \pi/2 + (\Delta\phi_\perp + \pi/2) \times Q)$ [2].

The PDF $\mathcal{P}_j(\mathbf{x_i};\, \boldsymbol{\zeta};\, \boldsymbol{\xi})$ for a given candidate i is a joint PDF for the helicity angles, resonance masses, and Q, and the product of the PDFs for each of the remaining variables. The helicity part of the exclusive B decay PDF is the ideal angular distribution from Eq. (1), where the amplitudes $A_{J\lambda}$ are expressed in terms of the polarization parameters $\boldsymbol{\zeta}$, multiplied by an empirically-determined acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2, \Phi) \equiv \mathcal{G}_1(\mathcal{H}_1) \times \mathcal{G}_2(\mathcal{H}_2)$. A relativistic J-spin Breit-Wigner amplitude parameterization is used for the resonance mass [3, 9], except for the $(K\pi)_0^{*0}$ $m_{K\pi}$ amplitude parameterized with the LASS function [10]. The latter includes the $K_0^*(1430)^0$ resonance together with a non-resonant component.

The interference between the $J = 1$ or 2 and the S-wave $(K\pi)$ contributions is modeled with the three terms $2\mathcal{R}{\rm e}(A_{J\lambda}A^*_{00})$ in Eq. (1) with the four-dimensional angular and $m_{K\pi}$ dependence. It has been shown in the decays $B^0 \to J/\psi(K\pi)_0^{*0}$ and $B^+ \to \pi^+(K\pi)_0^{*0}$ [11] that the amplitude behavior is consistent with that observed by LASS except for a constant phase shift. We allow an unconstrained overall shift, again with the index J suppressed, $(\delta_0 + \Delta\delta_0 \times Q)$ between the LASS amplitude phase and either the vector ($J = 1$) or the tensor ($J = 2$) resonance amplitude phase.

The parameters $\boldsymbol{\xi}$ describe the background or the remaining signal PDFs. They are left free to vary in the fit for the combinatorial background or are fixed to the values extracted from Monte Carlo (MC) simulation [12] and calibration B-decay channels for the exclusive B decays. We use a sum of Gaussian functions for the parameterization of the signal PDFs for ΔE, $m_{\rm ES}$, and $\mathcal{F}$. For the combinatorial background, we use polynomials, except for $m_{\rm ES}$ and $\mathcal{F}$ distributions which are parameterized 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.

TABLE I: Fit results for each $m_{K\pi}$ range and signal component: the reconstruction efficiency $\varepsilon_{\rm reco}$ obtained from MC simulation; the total efficiency ε, including the daughter branching fractions [3]; the number of signal events $n_{\rm sig}$; statistical significance ($\mathcal{S}$) of the signal; the branching fraction $\mathcal{B}$; and the flavor asymmetry $\mathcal{A}_{CP}$. The branching fraction $\mathcal{B}(B^0 \to \phi(K\pi)^{*0}_0)$ refers to the coherent sum $|A_{\rm res} + A_{\rm non\text{-}res}|^2$ of resonant and non-resonant $J^P = 0^+$ $K\pi$ components [10] and is quoted for $m_{K\pi} < 1.6$ GeV, while the $\mathcal{B}(B^0 \to \phi K^*_0(1430)^0)$ is derived from it by integrating separately the Breit-Wigner formula of the resonant $|A_{\rm res}|^2$ $K\pi$ component [10] without $m_{K\pi}$ restriction. The systematic errors are quoted last.

Mode	$m_{K\pi}$ (GeV)	$m_{K\pi}$ model	$\varepsilon_{\rm reco}$ (%)	ε (%)	$n_{\rm sig}$ (events)	$\mathcal{S}$ (σ)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
$\phi K^*(892)^0$	0.75 – 1.05	Breit-Wigner [3]	35.0 ± 1.7	11.5 ± 0.6	$406 \pm 29 \pm 15$	21.0	$9.2 \pm 0.7 \pm 0.6$	$-0.03 \pm 0.07 \pm 0.03$
$\phi K^*_2(1430)^0$	1.13 – 1.53	Breit-Wigner [3]	27.1 ± 1.3	4.4 ± 0.2	$133 \pm 19 \pm 7$	9.7	$7.8 \pm 1.1 \pm 0.6$	$-0.12 \pm 0.14 \pm 0.04$
$\phi(K\pi)^{*0}_0$	1.13 – 1.53	LASS [10]	23.4 ± 1.1	7.7 ± 0.3	$147 \pm 23 \pm 7$	9.8	$5.0 \pm 0.8 \pm 0.3$	$+0.17 \pm 0.15 \pm 0.03$
$\phi K^*_0(1430)^0$		Breit-Wigner [10]					$4.6 \pm 0.7 \pm 0.6$	

TABLE II: Summary of polarization results. The dominant fit correlation coefficients ($\mathcal{C}$) are presented for the $\phi K^*(892)^0$ mode where we show correlations of δ_0 with $\phi_\parallel/\phi_\perp$ and of $\Delta\delta_0$ with $\Delta\phi_\parallel/\Delta\phi_\perp$. For the $\phi K^*_2(1430)^0$ mode the dominant values of $\mathcal{C}$ are 32% for $(\delta_0, \phi_\parallel)$ and 26% for $(\phi_\parallel, \phi_\perp)$.

	$B^0 \to \phi K^*_2(1430)^0$	$B^0 \to \phi K^*(892)^0$	$\mathcal{C}$
f_L	$0.853^{+0.061}_{-0.069} \pm 0.036$	$0.506 \pm 0.040 \pm 0.015$	}-53%
$f_\perp$	$0.045^{+0.049}_{-0.040} \pm 0.013$	$0.227 \pm 0.038 \pm 0.013$	
$\phi_\parallel$	$2.90 \pm 0.39 \pm 0.06$	$2.31 \pm 0.14 \pm 0.08$	} 61%
$\phi_\perp$	$5.72^{+0.55}_{-0.87} \pm 0.11$	$2.24 \pm 0.15 \pm 0.09$	
δ_0	$3.54^{+0.12}_{-0.14} \pm 0.06$	$2.78 \pm 0.17 \pm 0.09$	37%/27%
$\mathcal{A}^0_{CP}$	–	$-0.03 \pm 0.08 \pm 0.02$	}-51%
$\mathcal{A}^\perp_{CP}$	–	$-0.03 \pm 0.16 \pm 0.05$	
$\Delta\phi_\parallel$	–	$+0.24 \pm 0.14 \pm 0.08$	} 61%
$\Delta\phi_\perp$	–	$+0.19 \pm 0.15 \pm 0.08$	
$\Delta\delta_0$	–	$+0.21 \pm 0.17 \pm 0.08$	37%/27%

We observe a non-zero yield with more than 9σ significance, including systematic uncertainties, in each of the three $B^0 \to \phi K^{*0}$ decay modes. 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 Figs. 2–4 we show projections onto the variables. In Tables I and II the n_j, $\mathcal{A}_j$, and $\boldsymbol{\zeta} \equiv \{f_L,\ f_\perp,\ \phi_\parallel,\ \phi_\perp,\ \delta_0,\ \mathcal{A}^0_{CP},\ \mathcal{A}^\perp_{CP},\ \Delta\phi_\parallel,\ \Delta\phi_\perp,\ \Delta\delta_0\}$ parameters of the $B^0 \to \phi K^*(892)^0$ decay or the $\phi K^*_2(1430)^0$ and $\phi(K\pi)^{*0}_0$ decays are obtained from the fit in the lower or higher $m_{K\pi}$ range, respectively.

The non-resonant K^+K^- contribution under the ϕ is accounted for with the $B^0 \to f_0 K^{*0}$ category. Its yield is consistent with zero in the higher $m_{K\pi}$ range and is 89 ± 18 events in the lower $m_{K\pi}$ range. The uncertainties due to $m_{K\overline{K}}$ interference are estimated with the samples generated according to the observed K^+K^- intensity and with various interference phases analogous to δ_0 in $K\pi$. These are the dominant systematic errors for the $\boldsymbol{\zeta}$ parameters of the $B^0 \to \phi K^*(892)^0$ decay.

We vary those parameters in $\boldsymbol{\xi}$ not used to model combinatoric background within their uncertainties and derive the associated systematic errors. We allow for the flavor-dependent acceptance function and the reconstruction efficiency in the study of asymmetries. The biases from the finite resolution of the angle measurement, the dilution due to the presence of fake combinations, or other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainty originates from B background, where we estimate that only a few events can fake the signal. The systematic errors in efficiencies are dominated by those in particle identification and track finding. Other systematic effects arise from event-selection criteria, ϕ and K^{*0} branching fractions, and number of B mesons.

In the lower $m_{K\pi}$ range the yield of the $\phi(K\pi)^{*0}_0$ contribution is 60^{+17}_{-14} events with the statistical significance of 7.9σ, including the interference term. This allows us to reject the other solution near $(2\pi - \phi_\parallel, \pi - \phi_\perp)$ relative to that in Table II for the $B^0 \to \phi K^*(892)^0$ decay with significance of 5.4σ, including systematic uncertainties. We also resolve this ambiguity with statistical significance of more than 4σ with the $\overline{B}^0$ or B^0 decays independently. Because of the low significance of our measured $f_\parallel = (1 - f_L - f_\perp)$ (2.9σ) and $f_\perp$ (1.6σ) in the $B^0 \to \phi K^*_2(1430)^0$ decay we have insufficient information to constrain $\phi_\parallel$ and $\phi_\perp$ at higher significance and to measure five asymmetries, and so we fix these asymmetry parameters to zero in the fit in the higher $m_{K\pi}$ range.

The $(V - A)$ structure of the weak interactions and the s-quark spin flip suppression in the diagram in Fig. 1 (a) suggest $|A_0| \gg |A_{+1}| \gg |A_{-1}|$ [1, 6]. This expectation is consistent with our measurements in the vector-tensor $B^0 \to \phi K_2^*(1430)^0$ decay, but disagrees with our observed vector-vector polarization. In the $B^0 \to \phi K^*(892)^0$ decay we obtain the solution $\phi_\parallel \simeq \phi_\perp$ without discrete ambiguities. Combined with the approximate solution $f_L \simeq 1/2$ and $f_\perp \simeq (1-f_L)/2$, this results in the approximate decay amplitude hierarchy $|A_0| \simeq |A_{+1}| \gg |A_{-1}|$ (and $|\overline{A}_0| \simeq |\overline{A}_{-1}| \gg |\overline{A}_{+1}|$).

We find more than 5σ (4σ) deviation, including systematic uncertainties, of $\phi_\perp(\phi_\parallel)$ from either π or zero in the $B^0 \to \phi K^*(892)^0$ decay, indicating the presence of final-state interactions (FSI) not accounted for in naive factorization. The effect of FSI is evident in the phase shift of the cosine distribution in Fig. 3 (d). Our measurement of eight *CP*-violating parameters rule out a significant part of the physical region. Significant non-zero *CP*-violating parameters would indicate the presence of new amplitudes. The $\Delta\phi_\perp$ and $\Delta\phi_\parallel$ are particularly interesting due to cancellation of hadronic uncertainties, while the *CP*-violating $\Delta\delta_0$ parameter represents potential differences of weak phases among decay modes.

In summary, we have performed an amplitude analysis and searched for *CP*-violation in the angular distribution with the $B^0 \to \phi K^{*0}$ decays with the tensor, vector, and scalar K^{*0}. Our results are summarized in Tables I and II and supersede corresponding measurements in Ref. [4]. Our vector-tensor results are in agreement with quark spin flip suppression and A_0 amplitude dominance, whereas the vector-vector mode contains substantial A_{+1} amplitude from a presently unknown source either within or beyond the standard model [6].

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