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POLARIZATION PUZZLE IN $B \to \phi K^*$ AND OTHER $B \to VV$ AT *BABAR*

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With a sample of about 227 million $B\overline{B}$ pairs recorded with the *BABAR* detector we perform a full angular analysis of the decay $B^0 \to \phi K^{*0}(892)$. Ten measurements include polarization, phases, and five *CP* asymmetries. We also observe the decay $B^0 \to \phi K^{*0}(1430)$. Polarization measurements are performed with the $B \to \rho K^*(892)$, $B \to \rho\rho$, and $B \to \rho\omega$ decay modes, and limits are set on the $B \to \omega K^*(892)$ decay rates. These measurements help to understand the puzzle of large fraction of transverse polarization observed in $B \to \phi K^*$ decays and allow for new ways to study *CP* violation and potential new amplitude contributions.

1 Introduction

The decay $B \to \phi K^*(892)$ is expected to have contributions from $b \to s$ loop penguin transitions while the tree-level transition is suppressed in the Standard Model. Angular correlation measurements and asymmetries are particularly sensitive to amplitudes arising outside the Standard Model [1]. The first evidence for this decay was provided by the CLEO [2] and *BABAR* [3] experiments. The large fraction of transverse polarization observed by *BABAR* [4] and confirmed by BELLE [5] was a surprise and enabled a full angular analysis described by ten parameters for contributing amplitudes and their phases.

Similarly, the decays $B \to \rho K^*(892)$ and $B \to \omega K^*(892)$ are expected to have contributions from $b \to s$ loop transitions with some tree contributions. Polarization measurements in these channels may help in understanding the $B \to \phi K^*$ polarization puzzle. The decays $B \to \rho\rho$ and $\omega\rho$ are expected to proceed through the tree-level $b \to u$ transition and through CKM-suppressed $b \to d$ penguin transitions. These are particularly interesting modes for the CKM angle α studies and have the advantage of a larger decay rate and smaller uncertainty in penguin pollution compared to $B \to \pi\pi$. The *BABAR* [4,6] and the BELLE [7] experiments reported observation of the $B \to \rho K^*$ and $\rho\rho$ decays.

The angular distribution of the $B \to VV$ decay products are expressed as a function of $\cos\theta_i$ and Φ, where θ_i is the helicity angle of a ϕ, K^*, ρ, or ω, and Φ is the angle between the two resonance decay planes. The differential decay width has three complex amplitudes A_λ corresponding to the vector meson helicity $\lambda = 0$ or ± 1 [1,8]. The last two can be expressed in terms of $A_{||} = (A_{+1} + A_{-1})/\sqrt{2}$ and $A_\perp = (A_{+1} - A_{-1})/\sqrt{2}$.

In this paper we present the latest results from *BABAR* in a number of charmless $B \to VV$ decays. We measure the branching fraction, the polarization parameters $f_L = |A_0|^2/\Sigma|A_\lambda|^2$, $f_\perp = |A_\perp|^2/\Sigma|A_\lambda|^2$, and the relative phases $\phi_{||} = \arg(A_{||}/A_0)$, $\phi_\perp = \arg(A_\perp/A_0)$. We allow for *CP*-violating differences between the $\overline{B}^0$ $(Q = +1)$ and B^0 $(Q = -1)$ decay amplitudes ($\overline{A}_\lambda$ and A_λ), and derive vector triple-product asymmetries [1]:

$$\mathcal{A}_T^{||,0} = \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp A^*_{||,0})}{\Sigma|A_\lambda|^2} + \frac{\mathrm{Im}(\overline{A}_\perp \overline{A}^*_{||,0})}{\Sigma|\overline{A}_\lambda|^2}\right)$$

The B flavor sign Q can be determined in the self-tagging final state, then we have ten independent measured quantities:

$$n^Q_{\rm sig} = n_{\rm sig}\,(1 + Q\,\mathcal{A}_{CP})/2;$$
$$f_L^Q = f_L\,(1 + Q\,\mathcal{A}^0_{CP});$$
$$f_\perp^Q = f_\perp\,(1 + Q\,\mathcal{A}^\perp_{CP});$$
$$\phi^Q_{||} = \phi_{||} + Q\,\Delta\phi_{||};$$
$$\phi^Q_\perp = \phi_\perp + \frac{\pi}{2} + Q\,(\Delta\phi_\perp + \frac{\pi}{2}).$$

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Experimental technique

We use data collected with the *BABAR* detector [9] at the PEP-II asymmetric-energy e^+e^- collider operated at the center-of-mass energy of the $\Upsilon(4S)$ resonance ($\sqrt{s}=10.58$ GeV). We fully reconstruct vector-vector B meson decays involving ϕ, ρ, ω, and K^* resonances. We identify B meson candidates using two variables: $m_{\rm ES}=[(s/2+\mathbf{p}_i\cdot\mathbf{p}_B)^2/E_i^2-\mathbf{p}_B^2]^{1/2}$ and $\Delta E=(E_iE_B-\mathbf{p}_i{\cdot}\mathbf{p}_B-s/2)/\sqrt{s}$, where $(E_i,\mathbf{p}_i)$ is the initial state four-momentum, and $(E_B,\mathbf{p}_B)$ is the four-momentum of the reconstructed B candidate. To reject the dominant quark-antiquark continuum background we apply event-shape requirements.

We use an unbinned maximum-likelihood (ML) fit to extract signal parameters. There are several event categories j: signal, continuum $q\overline{q}$, combinatoric $B\overline{B}$ background, and specific B-decay background modes. The likelihood for each candidate i is defined as $\mathcal{L}_i=\sum_{j,k}n_j^k\,\mathcal{P}_j^k(\vec{x}_i;\vec{\alpha};\vec{\beta})$, where each of the $\mathcal{P}_j^k(\vec{x}_i;\vec{\alpha};\vec{\beta})$ is the probability density function for input variables. The n_j^k is the number of events with the B flavor k in the category j. The event yields n_j, asymmetries $\mathcal{A}_j$, and the signal polarization parameters $\vec{\alpha}$ are obtained by maximizing $\mathcal{L}=\exp(-\sum n_j^k)\prod\mathcal{L}_i$.

In Fig. 1 examples of fit input variables and ML fit projections are shown, where data distributions are shown with the signal enhanced with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded.

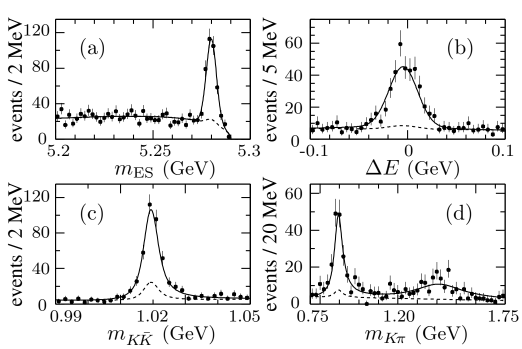

Figure 1. Projections onto the variables $m_{\rm ES}$ (a), ΔE (b), $m_{K\overline{K}}$ (c), and $m_{K\pi}$ (d) for the signal $B^0\to\phi K^{*0}(892)$ and $\phi K^{*0}(1430)$ candidates combined.

Results

The results of our maximum likelihood fit to the sample of $B^0\to\phi K^{*0}(892)$ candidates are summarized in Table 1. We observe, with more than 5σ significance, non-zero contributions from all of the three amplitudes A_0, $A_\perp$, and $A_{||}$ ($f_L+f_\perp+f_{||}=1$). We find 3σ evidence for non-zero final-state-interaction phases ($\phi_{||}$ and $\phi_\perp$ differ from π or zero). We also observe $B^0\to\phi K^{*0}(1430)$ decays.

In Table 2 we show results for all $B\to VV$ modes with the dominant $b\to s$ penguin contribution expected. Naive SU(3) decomposition of the relative penguin and tree dia-

Table 1. Summary of the $B^0\to\phi K^{*0}(892)$ fit results. We show results for the ten primary signal fit parameters and the derived branching fraction $\mathcal{B}$ and triple-product asymmetries $\mathcal{A}_T^{||}$ and $\mathcal{A}_T^0$.

Fit parameter	Fit result
$n_{\rm sig}$ (events)	$201\pm20\pm6$
f_L	$0.52\pm0.05\pm0.02$
$f_\perp$	$0.22\pm0.05\pm0.02$
$\phi_{\vert\vert}$ (rad)	$2.34^{+0.23}_{-0.20}\pm0.05$
$\phi_\perp$ (rad)	$2.47\pm0.25\pm0.05$
$\mathcal{A}_{CP}$	$-0.01\pm0.09\pm0.02$
$\mathcal{A}_{CP}^0$	$-0.06\pm0.10\pm0.01$
$\mathcal{A}_{CP}^\perp$	$-0.10\pm0.24\pm0.05$
$\Delta\phi_{\vert\vert}$ (rad)	$0.27^{+0.20}_{-0.23}\pm0.05$
$\Delta\phi_\perp$ (rad)	$0.36\pm0.25\pm0.05$
$\mathcal{B}$	$(9.2\pm0.9\pm0.5)\times10^{-6}$
$\mathcal{A}_T^{\vert\vert}$	$-0.02\pm0.04\pm0.01$
$\mathcal{A}_T^0$	$+0.11\pm0.05\pm0.01$

Table 2. The *BABAR* measurements of the branching fractions ($\mathcal{B}$) and polarizations (f_L) of the $B \to VV$ decays with the dominant $b \to s$ penguin contribution. Relative coefficients in front of the penguin, color-allowed and color-suppressed tree amplitudes contributing to each decay mode are shown with α_P, α_T, and α_C. Naive SU(3) decomposition is used for illustration. The last column indicates the number of $B\overline{B}$ pairs used in each analysis. New preliminary results this year are indicated by "new", while references are given to the published results. The last error in the $\rho^+ K^{*0}$ channel has non-resonant decay rate uncertainty separated.

B decay	α_P	α_T	α_C	$\mathcal{B}(10^{-6})$	f_L	$N_{B\bar{B}}(10^6)$
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.9 \pm 0.5$	$0.52 \pm 0.05 \pm 0.02$	227 (new)
ϕK^{*+}	$\sqrt{2}$	0	0	$12.7\ ^{+2.2}_{-2.0} \pm 1.1$	$0.46 \pm 0.12 \pm 0.03$	89 (publ. [4])
$\rho^0 K^{*0}$	1	0	-1	–	–	–
$\rho^0 K^{*+}$	-1	-1	-1	$10.6\ ^{+3.0}_{-2.6} \pm 2.4$	$0.96^{+0.04}_{-0.15} \pm 0.04$	89 (publ. [4])
$\rho^+ K^{*0}$	$\sqrt{2}$	0	0	$17.0 \pm 2.9 \pm 2.0^{+0.0}_{-1.9}$	$0.79 \pm 0.08 \pm 0.04 \pm 0.02$	89 (new)
$\rho^- K^{*+}$	$-\sqrt{2}$	$-\sqrt{2}$	0	< 24 (90% C.L.)	–	123 (new)
ωK^{*0}	1	0	1	< 6.1 (90% C.L.)	–	89 (new)
ωK^{*+}	1	1	1	< 7.4 (90% C.L.)	–	89 (new)

Table 3. The *BABAR* measurements of the branching fractions ($\mathcal{B}$) and polarizations (f_L) of the $B \to VV$ decays with the $b \to u$ tree and $b \to d$ penguin contributions. Relative coefficients in front of the color-allowed tree, color-suppressed tree, and penguin amplitudes are shown with α_T, α_C, and α_P.

B decay	α_T	α_C	α_P	$\mathcal{B}$ (10^{-6})	f_L	$N_{B\bar{B}}(10^6)$
$\rho^-\rho^+$	$\sqrt{2}$	0	$\sqrt{2}$	$30 \pm 4 \pm 5$	$0.99 \pm 0.03^{+0.04}_{-0.03}$	89 (publ. [6])
$\rho^0\rho^+$	1	1	0	$23\ ^{+6}_{-5} \pm 6$	$0.97^{+0.03}_{-0.07} \pm 0.04$	89 (publ. [4])
$\rho^0\rho^0$	0	1	-1	< 1.1 (90% C.L.)	–	227 (new)
$\omega\rho^+$	-1	-1	2	$12.6\ ^{+3.7}_{-3.3} \pm 1.8$	$0.88^{+0.12}_{-0.15} \pm 0.03$	89 (new)
$\omega\rho^0$	0	0	$-\sqrt{2}$	< 3.3 (90% C.L.)	–	89 (new)
$\phi\phi$	0	0	0	< 1.5 (90% C.L.)	–	89 (new)

grams is shown. Transverse polarization fraction in both $B \to \phi K^*(892)$ charge modes are close to 50%, while this effect is less pronounced in the $B \to \rho K^*(892)$ modes. At the same time, polarization measurements in the tree-dominated modes presented in Table 3 favor longitudinal polarization dominance.

For B decays to light charmless particles we expect the hierarchy of decay amplitudes to be $|A_0| \gg |A_{+1}| \gg |A_{-1}|$ under the assumption of either loop or tree diagram contribution [10]. Our measurements with the decay $B^0 \to \phi K^{*0}(892)$ do not agree with the first inequality but agree with the second one. This suggests other contributions to the decay amplitude, previously neglected, either within or beyond the Standard Model [1,11].

We also observe the decays $B^0 \to \phi K^{*0}(1430)$ which we find to be predominantly longitudinally polarized based on the ϕ helicity angle distribution. The width and the angular distribution of the $K^{*0}(1430)$ resonance structure are not consistent with the pure $K_2^{*0}(1430)$ tensor state at more than 10σ. However, the angular distribution provides evidence of the longitudinally polarized tensor $K_2^{*0}(1430)$ contribution (with statistical significance of 3.2σ) in addition to the scalar $K_0^{*0}(1430)$. If the longitudinal polarization dominance holds for the vector-tensor $B \to \phi K_2^*(1430)$ decays, this will point to the special role of the vector current in the

$B \to \phi K^*(892)$ polarization puzzle.

If one loop diagram dominates the $B \to \phi K^*$ decay amplitude, the direct CP asymmetries $\mathcal{A}_{CP}$, $\mathcal{A}_{CP}^0$, and $\mathcal{A}_{CP}^{\perp}$, and the weak-phase differences $\Delta\phi_{||}$ and $\Delta\phi_{\perp}$, or alternatively $\mathcal{A}_T^0$ and $\mathcal{A}_T^{||}$, are expected to be negligible. These are interesting to look for new amplitude contributions with different weak phases.

The rates of the $B^0 \to \rho^+\rho^-$ and $B^+ \to \rho^0\rho^+$ decays are larger than the corresponding rates of $B \to \pi\pi$ decays [12]. At the same time, the measurements of the $B \to \rho K^*$ branching fractions do not show significant enhancement with respect to $B \to \pi K$ decays [12], both of which are expected to be dominated by $b \to s$ penguin diagrams. We can use flavor SU(3) to relate $b \to s$ and $b \to d$ penguins; the measured branching fractions indicate that the relative penguin contributions in the $B \to \rho\rho$ decays are smaller than in the $B \to \pi\pi$ case.

A more quantitative estimate of penguin contributions in $B \to \rho\rho$ decays can be obtained using isospin relations and measurements of $B \to \rho^0\rho^0$, $\rho^+\rho^-$, and $\rho^+\rho^0$ branching fractions and polarization [6,13]. Since the tree contribution to the $B^0 \to \rho^0\rho^0$ decay is color-suppressed (see Table 3), the decay rate is sensitive to the penguin diagram and its tight experimental limit provides tight constraints on penguin pollution. This makes $B^0 \to \rho^+\rho^-$ an ideal channel for the time-dependent measurement of the CKM angle α. It is interesting to note that $B^0 \to \omega\rho^0$ measurement provides comparable constraint on penguin contribution, but additional assumptions are required.

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