Polarization Puzzle in $B \rightarrow \phi K^*$ and Other $B \rightarrow VV$ 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 $B^0 \rightarrow \phi K^{*0}(892)$. Ten measurements include polarization, phases, and five CP asymmetries. We also observe the decay $B^0 \rightarrow \phi K^{*0}(1430)$. Polarization measurements are performed with the $B \rightarrow pK^*(892)$, $B \rightarrow pp$, and $B \rightarrow \rho \omega$ decay modes, and limits are set on the $B \rightarrow \omega K^*(892)$ decay rates. These measurements help to understand the puzzle of large fraction of transverse polarization observed in $B \rightarrow \phi K^*$ decays and allow for new ways to study CP violation and potential new amplitude contributions.

1 Introduction

The decay $B \rightarrow \phi K^*(892)$ is expected to have contributions from $b \rightarrow s$ 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. The first evidence for this decay was provided by the CLEO and BABAR experiments. The large fraction of transverse polarization observed by BABAR and confirmed by BELLE was a surprise and enabled a full angular analysis described by ten parameters for contributing amplitudes and their phases.

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

The angular distribution of the $B \rightarrow VV$ decay products are expressed as a function of $\cos \theta_i$ and $\Phi$, where $\theta_i$ is the helicity angle of a $\phi$, $K^*$, $\rho$, or $\omega$, and $\Phi$ is the angle between the two resonance decay planes. The differential decay width has three complex amplitudes $A_{\lambda}$ corresponding to the vector meson helicity $\lambda = 0$ or $\pm 1$. The last two can be expressed in terms of $A_{\parallel} = (A_{+1} + A_{-1})/\sqrt{2}$ and $A_{\perp} = (A_{+1} - A_{-1})/\sqrt{2}$.

In this paper we present the latest results from BABAR in a number of charmless $B \rightarrow VV$ 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 $\phi_{\parallel} = \arg(A_{\parallel}/A_0)$, $\phi_{\perp} = \arg(A_{\perp}/A_0)$. We allow for $CP$-violating differences between the $B^0$ $(Q = +1)$ and $B^0$ $(Q = -1)$ decay amplitudes $(A_{\lambda} = A_{\lambda}^*)$, and derive vector triple-product asymmetries.

$$ A^{\parallel,\perp}_{T} = \frac{1}{2} \left( \frac{\text{Im}(A_{\parallel} A_{\parallel}^*)}{\Sigma |A_{\lambda}|^2} + \frac{\text{Im}(A_{\perp} A_{\perp}^*)}{\Sigma |A_{\lambda}|^2} \right) $$

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

$$ n_{\text{sig}}^Q = n_{\text{sig}} (1 + Q A_{CP})/2; $$
$$ f_L^Q = f_L (1 + Q A_{CP}^L); $$
$$ f_{\perp}^Q = f_{\perp} (1 + Q A_{CP}^\perp); $$
$$ \phi_{\parallel}^Q = \phi_{\parallel} + Q \Delta \phi_{\parallel}; $$
$$ \phi_{\perp}^Q = \phi_{\perp} + \frac{\pi}{2} + Q (\Delta \phi_{\perp} + \frac{\pi}{2}). $$
Experimental technique

We use data collected with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider operated at the center-of-mass energy of the $Y(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). We fully reconstruct vector-vector $B$ meson decays involving $\phi$, $\rho$, $\omega$, and $K^*$ resonances. We identify $B$ meson candidates using two variables: $m_{ES} = \sqrt{[(s/2 + p_t \cdot p_B)^2 / E_t^2 - p_B^2]^{1/2}}$ and $\Delta E = (E_i E_B - p_i \cdot p_B - s/2)/\sqrt{s}$, where $(E_i, p_i)$ is the initial state four-momentum, and $(E_B, p_B)$ 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 $q\bar{q}$, combinatoric $BB$ background, and specific $B$-decay background modes. The likelihood for each candidate $i$ is defined as $L_i = \sum_{j,k} n_{ik}^j P_j^k(\vec{x}_i; \vec{\alpha}; \vec{\beta})$, where each of the $P_j^k(\vec{x}_i; \vec{\alpha}; \vec{\beta})$ is the probability density function for input variables. The $n_{ik}^j$ is the number of events with the $B$ flavor $k$ in the category $j$. The event yields $n_j$, asymmetries $A_j$, and the signal polarization parameters $\vec{\alpha}$ are obtained by maximizing $L = \exp(-\sum n_{ik}^j) \prod L_i$.

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.

Results

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

In Table II 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-

| Fit parameter | Fit result |
|---------------|------------|
| $n_{\text{sig}}$ (events) | $201 \pm 20 \pm 6$ |
| $f_L$ | $0.52 \pm 0.05 \pm 0.02$ |
| $f_\perp$ | $0.22 \pm 0.05 \pm 0.02$ |
| $\phi_\parallel$ (rad) | $2.34^{+0.23}_{-0.25} \pm 0.05$ |
| $\phi_\perp$ (rad) | $2.47 \pm 0.25 \pm 0.05$ |
| $A_{\text{CP}}$ | $-0.01 \pm 0.09 \pm 0.02$ |
| $A_{\text{CP}}^0$ | $-0.06 \pm 0.10 \pm 0.01$ |
| $A_{\text{CP}}^\parallel$ | $-0.10 \pm 0.24 \pm 0.05$ |
| $\Delta \phi_\parallel$ (rad) | $0.27^{+0.29}_{-0.23} \pm 0.05$ |
| $\Delta \phi_\perp$ (rad) | $0.36 \pm 0.25 \pm 0.05$ |
| $B$ | $(9.2 \pm 0.9 \pm 0.5) \times 10^{-6}$ |
| $A_T^0$ | $-0.02 \pm 0.04 \pm 0.01$ |
| $A_T^\parallel$ | $+0.11 \pm 0.05 \pm 0.01$ |

Table I. 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 $B$ and triple-product asymmetries $A_T^0$ and $A_T^\parallel$. 

Figure 1. Projections onto the variables $m_{ES}$ (a), $\Delta E$ (b), $m_{KK}$ (c), and $m_{K\pi}$ (d) for the signal $B^0 \to \phi K^{*0}(892)$ and $\phi K^{*0}(1430)$ candidates combined.
Table 2. The BABAR measurements of the branching fractions (B) and polarizations (f_L) of the B → VV decays with the dominant b → 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 \( \alpha_P, \alpha_T, \) and \( \alpha_C \). Naive SU(3) decomposition is used for illustration. The last column indicates the number of \( BB \) 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 | \( \alpha_P \) | \( \alpha_T \) | \( \alpha_C \) | \( B(10^{-6}) \) | \( f_L \) | \( N_{BB}(10^6) \) |
|---------|---------------|---------------|---------------|----------------|-------------|----------------|
| \( \phi K^{*0} \) | \( \sqrt{2} \) | 0 | 0 | 9.2 ± 0.9 ± 0.5 | 0.52 ± 0.05 ± 0.02 | 227 (new) |
| \( \phi K^{*+} \) | \( \sqrt{2} \) | 0 | 0 | 12.7 ± 2.2 ± 1.1 | 0.46 ± 0.12 ± 0.03 | 89 (publ.) |
| \( \rho^0 K^{*0} \) | 1 | 0 | -1 | – | – | – |
| \( \rho^0 K^{*+} \) | -1 | -1 | -1 | 10.6 ± 3.0 ± 2.4 | 0.96 ± 0.04 ± 0.04 | 89 (publ.) |
| \( \rho^+ K^{*0} \) | \( \sqrt{2} \) | 0 | 0 | 17.0 ± 2.9 ± 2.0 ± 0.9 | 0.79 ± 0.08 ± 0.04 ± 0.02 | 89 (new) |
| \( \rho^- K^{*+} \) | -\( \sqrt{2} \) | -\( \sqrt{2} \) | 0 | < 24 (90% C.L.) | – | 123 (new) |
| \( \omega K^{*0} \) | 1 | 0 | 1 | < 6.1 (90% C.L.) | – | 89 (new) |
| \( \omega K^{*+} \) | 1 | 1 | 1 | < 7.4 (90% C.L.) | – | 89 (new) |

Table 3. The BABAR measurements of the branching fractions (B) and polarizations (f_L) of the B → VV decays with the b → u tree and b → d penguin contributions. Relative coefficients in front of the color-allowed tree, color-suppressed tree, and penguin amplitudes are shown with \( \alpha_T, \alpha_C, \) and \( \alpha_P \).

| B decay | \( \alpha_T \) | \( \alpha_C \) | \( \alpha_P \) | \( B(10^{-6}) \) | \( f_L \) | \( N_{BB}(10^6) \) |
|---------|---------------|---------------|---------------|----------------|-------------|----------------|
| \( \rho^0 \rho^+ \) | \( \sqrt{2} \) | 0 | \( \sqrt{2} \) | 30 ± 4 ± 5 | 0.99 ± 0.03 ± 0.04 | 89 (publ.) |
| \( \rho^0 \rho^0 \) | 1 | 1 | 0 | 23 ± 6 | 0.97 ± 0.03 ± 0.04 | 89 (publ.) |
| \( \rho^- \rho^+ \) | 0 | 1 | -1 | < 1.1 (90% C.L.) | – | 227 (new) |
| \( \omega \rho^+ \) | -1 | -1 | 2 | 12.6 ± 3.7 ± 1.8 | 0.88 ± 0.12 ± 0.03 | 89 (new) |
| \( \omega \rho^0 \) | 0 | 0 | -\( \sqrt{2} \) | < 3.3 (90% C.L.) | – | 89 (new) |
| \( \phi \rho \) | 0 | 0 | 0 | < 1.5 (90% C.L.) | – | 89 (new) |

grams is shown. Transverse polarization fraction in both \( B \rightarrow \phi K^{*}(892) \) charge modes are close to 50%, while this effect is less pronounced in the \( B \rightarrow \rho K^{*}(892) \) 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. Our measurements with the decay \( B^0 \rightarrow \phi K^{*0}(892) \) 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. We also observe the decays \( B^0 \rightarrow \phi K^{*0}(1430) \) which we find to be predominantly longitudinally polarized based on the \( \phi \) helicity angle distribution. The width and the angular distribution of the \( K^{*0}(1430) \) resonance structure are not consistent with the pure \( K^0_2(1430) \) tensor state at more than 10\( \sigma \). However, the angular distribution provides evidence of the longitudinally polarized tensor \( K^0_2(1430) \) contribution (with statistical significance of 3.2\( \sigma \)) in addition to the scalar \( K^0_0(1430) \). If the longitudinal polarization dominance holds for the vector-tensor \( B \rightarrow \phi K^*_2(1430) \) decays, this will point to the special role of the vector current in the
$B \rightarrow \phi K^*(892)$ polarization puzzle.

If one loop diagram dominates the $B \rightarrow \phi K^*$ decay amplitude, the direct CP asymmetries $A_{CP}^0$, $A_{CP}^3$, and $A_{CP}^\perp$, and the weak-phase differences $\Delta \phi_\parallel$ and $\Delta \phi_\perp$, or alternatively $A_{CP}^{0\parallel}$ and $A_{CP}^{0\perp}$, are expected to be negligible. These are interesting to look for new amplitude contributions with different weak phases.

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

A more quantitative estimate of penguin contributions in $B \rightarrow \rho \rho$ decays can be obtained using isospin relations and measurements of $B \rightarrow \rho^0 \rho^0$, $\rho^+ \rho^-$, and $\rho^+ \rho^0$ branching fractions and polarization. Since the tree contribution to the $B^0 \rightarrow \rho^0 \rho^0$ decay is color-suppressed (see Table 9, the decay rate is sensitive to the penguin diagram and its tight experimental limit provides tight constraints on penguin pollution. This makes $B^0 \rightarrow \rho^+ \rho^-$ an ideal channel for the time-dependent measurement of the CKM angle $\alpha$. It is interesting to note that $B^0 \rightarrow \omega \rho^0$ measurement provides comparable constraint on penguin contribution, but additional assumptions are required.

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