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Observation and Polarization Measurements of $B^+ \rightarrow \phi K_1^+$ and $B^0 \rightarrow \phi K_2^{*0}$


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With the full \textit{BABAR} data sample of \(465 \times 10^6\) \(B \bar{B}\) pairs, we observe the decays \(B^\pm \rightarrow \varphi K_s(1270)^\pm\) and \(B^\pm \rightarrow \varphi K_s^*(1430)^\pm\). We measure the branching fractions \((6.1 \pm 1.6 \pm 1.1) \times 10^{-6}\) and \((8.4 \pm 1.8 \pm 1.0) \times 10^{-6}\) and the fractions of longitudinal polarization \(0.46^{+0.12+0.06}_{-0.13-0.07}\) and \(0.80^{+0.09}_{-0.10} \pm 0.03\), respectively. We also report on the \(B^\pm \rightarrow \varphi K^*_0(1430)^\pm\) decay branching fraction of \((7.0 \pm 1.3 \pm 0.9) \times 10^{-6}\) and several parameters sensitive to CP violation and interference in the above three decays. Upper limits are placed on the \(B^\pm\) decay rates to final states with \(\varphi\) and \(K_s(1400)^\pm\), \(K^*(1410)^\pm\), \(K_2(1770)^\pm\), or \(K_2(1820)^\pm\). Understanding the observed polarization pattern requires amplitude contributions from an uncertain source.

Measurements of polarization in rare vector-vector \(B\) meson decay, such as \(B \rightarrow \varphi K^*\) [1,2], have revealed an unexpectedly large fraction of transverse polarization and suggested contributions to the decay amplitude which were previously neglected. Decays to other excited spin-1 kaons \(K_J^{(*)}\) can also take place. The differential width for a \(B \rightarrow \varphi K_J^{(*)}\) decay has three complex amplitudes \(A_{\lambda J}\), which describe the three helicity states \(\lambda = 0, \pm 1\), except when \(J = 0\). The expected hierarchy of the \(A_{\lambda J}\) amplitudes \(|A_{\lambda J}|^2 \gg |A_{\lambda J}|^2 \gg |A_{\lambda J}|^2\) is sensitive to the (V-A) structure of the weak interactions with the left-handed fermion couplings [3–5], and therefore is sensitive to physics beyond the standard model. For example, tensor or scalar interactions would violate \(|A_{\lambda J}|^2 \gg |A_{\lambda J}|^2\) and the right-handed fermion couplings would violate \(|A_{\lambda J}|^2 \gg |A_{\lambda J}|^2\) [3]. Strong interaction effects could change these predictions as well, but they were originally expected to be small [3].

However, all previous studies have been limited to the two-body \(K_J \rightarrow K\pi\) decays, thus considering only the spin-parity \(K_J\) states with \(P = (-1)^J\). In this Letter we report the measurement with the three-body final states \(K_J^{(*)} \rightarrow K\pi\pi\) which include \(P = (-1)^{J+1}\) mesons such as \(K_1\) and \(K_2\). We complement these measurements with the two-body \(K_J^*\) final states in the \(B^\pm\) decays and report polarization in the \(\varphi K_1(1270)^\pm\) and \(\varphi K_2^*(1430)^\pm\) final states which have not been seen before. We also search for other final states with \(\varphi\) and \(K_0^0(1430)^\pm\), \(K_1(1400)^\pm\), \(K^*(1410)^\pm\), \(K_2(1770)^\pm\), or \(K_2(1820)^\pm\).

We use data collected with the \(BABAR\) detector [6] at the PEP-II \(e^+e^-\) collider. A sample of \((465 \pm 5) \times 10^6\) \(\Upsilon(4S) \rightarrow B\bar{B}\) events was recorded at the \(e^+e^-\) center-of-mass energy \(\sqrt{s} = 10.58\text{ GeV}\). 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.

We search for \(B^\pm \rightarrow \varphi K_J^{(*)}\) decays using three final states of the \(K_J^{(*)}\) decay: \(K_0^0\pi^\pm\), \(K^\pm\pi^0\), and \(K^\pm\pi^+\pi^-\), where \(K_0^0 \rightarrow \pi^+\pi^-\) and \(\pi^0 \rightarrow \gamma\gamma\). We define the two helicity angles \(\theta_1\) as the angle between the direction of the \(K\) or \(K^+\) meson from \(K_1^* \rightarrow K\pi\ (\theta_1)\) or \(\varphi \rightarrow K^+K^-\ (\theta_2)\) and the direction opposite to the \(B\) in the \(K^*\) or \(\varphi\) rest frame. The normal to the three-body decay plane for \(K_J^{(*)} \rightarrow K\pi\pi\) is chosen as the analyzer of the \(K_J^{(*)}\) polarization instead of the direction of the \(K\) from \(K_J^{(*)}\) in the two-body decays. We define \(\mathcal{H}_I = \cos\theta_I\).

We identify \(B\) meson candidates using two kinematic variables: \(m_{ES} = (s/4 - p_B^2)^{1/2}\) and \(\Delta E = \sqrt{s}/2 - E_B\), where \((E_B, p_B)\) is the four-momentum of the \(B\) candidate in the \(e^+e^-\) center-of-mass frame. We require \(m_{ES} > 5.25\text{ GeV}\) and \(|\Delta E| < 0.1\text{ GeV}\) (or 0.08 GeV for \(K_J^{(*)} \rightarrow K^\pm\pi^\pm\pi^-\)). We also require the invariant masses to satisfy \(1.1 < m_{K\pi} < 1.6\text{ GeV}\), \(1.1 < m_{K\pi\pi} < 2.1\text{ GeV}\), and \(0.99 < m_{K^+K^-} < 1.05\text{ GeV}\). To reject the dominant \(e^+e^-\rightarrow\) light quark-antiquark background, we use the angle \(\theta_T\) between the thrust axis of the \(B\)-candidate decay products and that of the rest of the event requiring \(|\cos\theta_T| < 0.8\), and a Fisher discriminant \(\mathcal{F}\) which combines event-shape parameters [7].

To reduce combinatorial background in the mode \(K_J^{(*)} \rightarrow K^\pm\pi^0\), we require \(\mathcal{H}_1 < 0.6\). When more than one candidate is reconstructed (7.6% of events with \(K_0^0\pi^\pm\), 2.9% with \(K^\pm\pi^0\), and 14.6% with \(K^\pm\pi^+\pi^-\)), we select the one whose \(\chi^2\) of the charged-track vertex fit combined with \(\chi^2\) of the invariant mass consistency of the \(K_0^0\) or \(\pi^0\) 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] to extract the event yields \(n_j\) and the probability density function (PDF) parameters, denoted by \(\zeta\) and \(\xi\), to be described below. The index \(j\) represents the event categories, which include continuum background and several \(B\)-decay modes. In the \(B^\pm \rightarrow \varphi K_J^{(*)}\rightarrow (K^+K^-)(K\pi)\) topology, the following event categories are considered: \(\varphi K_1^0(1430)^\pm\), \(\varphi (K\pi)_0^\pm\), and \(f_0(K\pi)_0^\pm\), where the \(J^P = 0^+\) \((K\pi)_0^\pm\) contribution includes both a nonresonant
component and the $K_0^*(1430)^\pm$ resonance [8]. In the $B^\pm \to \phi K_1^0 (\pm) \to (K^{+}\pi^-)(K\pi\pi\pi)$ topology, we consider $\phi K_1(1270)^\pm$, $\phi K_2(1400)^\pm$, $\phi K_3^+ (1410)^\pm$, $\phi K_2^0 (1420)^\pm$, a nonresonant $\phi K^+\pi^+\pi^-$, and $f_0 K_1(1400)^\pm$ contributions. In the latter topology, the mode $\phi K_2(1770)^\pm$ is also considered in place of $\phi K_2^0 (1420)^\pm$. In all cases, the modes with a $f_0$ model can account for a possible broad non-$\phi$ ($K^+\pi^-\pi^+$) contribution under the $\phi$.

The extended likelihood is $L = \exp(-\sum n_i) \prod L_i$. The likelihood $L_i$ for candidate $i$ is defined as $L_i = \sum_{i=1}^{n_{\text{sig}}} P^i_j(x_i; \xi, \xi)$, where $P^i_j$ is the PDF for variables $x_i = \{H_1, H_2, m_{K\pi\pi}, m_{K^+}, \Delta E, m_{ES}, F, Q\}$. The flavor index $j$ corresponds to the value of $Q$; that is, $P^i_j = P^i_j \times \delta_{kj}$. The $\xi$ parameters describe the background or the remaining signal PDFs, which are left free to vary in the fit for the combinatorial background and are fixed to the values extracted from Monte Carlo (MC) simulation [9] and calibration $B \to D\pi$ decays in other cases.

The signal PDF for a given candidate $i$ is a joint PDF for the helicity angles and resonance mass, and the product of the PDFs for each of the remaining variables. The helicity part of the signal PDF is the ideal angular distribution from Ref. [10], multiplied by an empirical acceptance function $G(H_1, H_2)$. In the $B^\pm \to \phi K_1^0$ or $\phi K_2^0$ parametrization, the additional kinematic parameters for the decays $K_2^\pm \to K^0\pi^+\pi^-$ (such as $r_1, r_2$, and $r_{02}$ in Ref. [10]) are modeled using the sequential two-body decay chains [4]. A relativistic spin-$J$ Breit-Wigner amplitude parametrization is used for the resonance masses [4,11], and the $J^P = 0^+ (K\pi\pi)^0$ amplitude is parametrized with the LASS function [8]. The nonresonant $\phi K^+\pi^+\pi^-$ contribution is modeled through sequential $K^*(892)^\pm \to K\pi\pi$ decay, while the decay $K\rho \to K\pi\pi$ is considered in the systematic uncertainty studies. We use a sum of Gaussian functions for the parametrization of $\Delta E$ and $m_{ES}$, as well as $\Delta E$.

The interference between the $J = 2$ and $0 (K\pi)^\pm$ contributions is modeled with the term $2\text{Re}(A_{20} A_{00}^*)$, with the three-dimensional angular and $m_{K\pi}$ parametrization.

We allow an unconstrained flavor-dependent overall shift $(\delta_0 + \Delta \delta_0 \times Q)$ between the LASS amplitude phase and the tensor resonance amplitude phase. The polarization parameters $\xi$ include the fractions of longitudinal polarization $f_L = |A_{20}|^2/|A_{20}|^2$ in several channels, $\delta_0$, and $\Delta \delta_0$. Similar interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ contributions is allowed in the study of systematic uncertainties but is not included in the nominal fit due to observed dominance of only one mode and therefore unconstrained phase of the interference.

Since the $K_2^*(1430)^0$ meson contributes to all three $K^0\pi^0$, $K^\pm\pi^\mp$, and $K^0\pi^+\pi^-$ final states and $(K\pi)^0$ contributes to two $K\pi$ final states in this analysis, we consider the total $L$ as a product of three likelihoods constructed for each of the three channels. The corresponding yields in different channels are related by the relative efficiency. We

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon_{\text{rec}}$ (%)</th>
<th>$\varepsilon$ (%)</th>
<th>$n_{\text{sig}}$ (events)</th>
<th>$\mathcal{S}$ ($\sigma$)</th>
<th>$f_L$</th>
<th>$B$ ($10^{-6}$)</th>
<th>$\mathcal{A}_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K_1(1270)^\pm$</td>
<td>25.4 ± 1.4 4.07 ± 0.51</td>
<td>116 ± 26 ± 13</td>
<td>5.0</td>
<td>$0.46^{+0.12}<em>{-0.11}^{+0.06}</em>{-0.07}$</td>
<td>6.1 ± 1.6 ± 1.1</td>
<td>$+0.15 \pm 0.19 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\phi K_1(1400)^\pm$</td>
<td>24.6 ± 1.3 5.19 ± 0.44</td>
<td>7 ± 33 ± 18</td>
<td>0.2</td>
<td>$&lt;3.2 (0.3 \pm 1.6 \pm 0.7)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi K_2(1430)^\pm$</td>
<td>3.34 ± 0.14</td>
<td>130 ± 27 ± 14</td>
<td>5.5</td>
<td>$0.80^{+0.09}_{-0.10}^{+0.03}$</td>
<td>8.4 ± 1.8 ± 1.0</td>
<td>$-0.23 \pm 0.19 \pm 0.06^a$</td>
<td></td>
</tr>
<tr>
<td>$K_0^0\pi^\pm$</td>
<td>11.9 ± 0.6 0.64 ± 0.04</td>
<td>27 ± 6 ± 3</td>
<td>$\delta_0 = 3.59 \pm 0.19 \pm 0.12^a$</td>
<td>$\Delta \delta_0 = -0.05 \pm 0.19 \pm 0.06^a$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^0\pi^+\pi^-$</td>
<td>12.2 ± 0.7 1.00 ± 0.06</td>
<td>39 ± 8 ± 4</td>
<td>8.2</td>
<td>$8.3 \pm 1.4 \pm 0.8$</td>
<td>$+0.04 \pm 0.15 \pm 0.04$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^0\pi^+\pi^-$</td>
<td>24.7 ± 1.3 1.68 ± 0.12</td>
<td>64 ± 14 ± 7</td>
<td>$\phi K_0(1430)^\pm$</td>
<td>3.33 ± 0.13</td>
<td>128 ± 21 ± 12</td>
<td>8.2</td>
<td>$7.0 \pm 1.3 \pm 0.9$</td>
</tr>
<tr>
<td>$K^0\pi^+\pi^-$</td>
<td>10.9 ± 0.6 1.24 ± 0.07</td>
<td>48 ± 8 ± 4</td>
<td>28.0 ± 2.2 5.71 ± 0.44</td>
<td>64 ± 31 ± 20</td>
<td>&lt;2</td>
<td>$&lt;4.3 (2.4 \pm 1.2 \pm 0.9^b)$</td>
<td></td>
</tr>
<tr>
<td>$K^0\pi^+\pi^-$</td>
<td>12.8 ± 0.7 2.09 ± 0.12</td>
<td>80 ± 13 ± 8</td>
<td>$K_2(1770)^\pm$</td>
<td>20.8 ± 1.4 2.27 ± 0.16</td>
<td>(90 ± 32 ± 20)</td>
<td>&lt;2</td>
<td>$&lt;15.0$</td>
</tr>
<tr>
<td>$K_2(1820)^\pm$</td>
<td>21.6 ± 1.5 2.35 ± 0.18</td>
<td>122 ± 40 ± 26</td>
<td>&lt;2</td>
<td>$&lt;16.3$</td>
<td></td>
<td></td>
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</tbody>
</table>

$^a$Two interference parameters $\delta_0$ and $\Delta \delta_0$ for $\phi K_2^*(1430)^\pm$ and $\phi (K\pi)^0$.

The value is obtained with the $\phi K_2(1820)^\pm$ yield constrained to zero.
fit the yields in each charge category $k$ independently and report them in the form of the total yield $n_j = n_j^+ + n_j^-$ and direct-CP asymmetry $\mathcal{A}_{CP} = (n_j^+ - n_j^-)/n_j$.

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. We use polynomials for the PDFs, except for $m_{ES}$ and $J$ 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 nonzero $B^\pm \rightarrow \phi K_1(1270)^\pm$ and $B^\pm \rightarrow \phi K_2^*(1430)^\pm$ yields with significance (excluding systematic uncertainties in parentheses) of 5.0(5.3)$\sigma$ and 5.5(6.0)$\sigma$, respectively. The combined $\phi K_1(1270)^\pm$ and $\phi K_2^*(1400)^\pm$ significance is 5.7(6.4)$\sigma$. The significance is defined as the square root of the change in $2 \ln L$ when the yield is constrained to zero in the likelihood $L$. We have tested this procedure with the generated MC samples and account for a small observed deviation from the one-dimensional $\chi^2$ statistical treatment.

In Table I, results of the fit are presented, where the combined results are obtained from the simultaneous fit to the three decay subchannels. In the branching fraction calculations we assume $K_2 \rightarrow K_2^*(1430)\pi$ and $\mathcal{B}(K^*(1410) \rightarrow K^+\pi) = 0.934 \pm 0.013$ [4]. The signal is illustrated in the projection plots in Figs. 1 and 2, where in the latter we enhance either the $\phi K_1(1270)^\pm$ signal (left) or the $\phi K_2^*(1430)^\pm$ signal (right). The nonresonant $K^+K^-$ contribution under the $\phi$ is accounted for with the $B^0 \rightarrow f_0 K_1$ category, and its yield $7 \pm 16$ is consistent with zero. Similarly, the nonresonant category $\phi K\pi\pi$ yield is $148 \pm 54$ with statistical errors only.

We vary those parameters in $\xi$ not used to model combinatorial background within their uncertainties and derive the associated systematic errors. Interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ is one of the dominant systematic uncertainties on both yields and is modeled with simulated samples. We take the flavor-dependent reconstruction efficiency into account in the study of asymmetries. The biases from the finite resolution of the angle measurement, the dilution due to the presence of false combinations, and other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainty originates from possible $B$ background, where we estimate from MC simulation that only a few events can fall in the signal region.

The $\phi K_2(1770)^\pm$ yield is not considered in the nominal fit due to large correlation with $\phi K_2(1820)^\pm$. But we substitute the $K_2(1820)$ resonance for the $K_2(1770)$ resonance and find consistent results. The difference is ac-
counted as a systematics uncertainty, while the yield of decay \( B^\pm \rightarrow \varphi K_s(1770)^\pm \) is used to obtain its branching fraction. We quote only upper limits on the two branching fractions as their correlation is not accounted for in the central values. For the \( \varphi K_2 \) and \( \varphi K^*(1410) \) decays, we vary the longitudinal polarization fraction between 0.5 and 0.93, and constrain it to 0.8 in the nominal fit. Polarization variations are included in the branching fraction calculations. We vary the kinematic parameter describing \( K^0 \rightarrow K^\pm \pi^+ \pi^- \) decay \((r_{02} \text{ in Ref. [10]})\) for various partial waves of the quasi-two-body \( K_2 \) decay channels and take the largest variations as the systematic uncertainties. The systematic uncertainties in efficiencies are dominated by those in particle identification, track finding, and \( K^0_S \) and \( \pi^0 \) selection. Other systematic effects arise from event-selection criteria, \( \varphi \) and \( K^*_f \) branching fractions, and the number of \( B \) mesons.

In summary, we have performed an amplitude analysis and searched for \( CP \) violation with the \( B^\pm \rightarrow \varphi K^*_f \) decays which include significant \( K_1(1270) \) and \( K^*_2(1430) \) contributions. Our results are summarized in Table I. The polarization measurement in the vector-tensor \( B^\pm \) decay is consistent with our earlier measurement in the \( B^0 \rightarrow \varphi K^*(1430)^0 \) decay [1] and with the naive expectation of the longitudinal polarization dominance. However, our first measurement of polarization in a vector–axial-vector \( B \) meson decay indicates a large fraction of transverse amplitude, similar to polarization observed in the vector–vector final state \( B \rightarrow \varphi K^*(892) \) [1,2]. Both measurements indicate substantial \( A_{1+1} \) (or still possible \( A_{1-1} \) for vector–axial-vector decay) amplitude from an uncertain source. Among potential sources are penguin annihilation, electro-weak penguin contributions, QCD scattering, or physics beyond the standard model [3].

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