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Search for $B^0 \rightarrow \phi(K^+ \pi^-)$ decays with large $K^+ \pi^-$ invariant mass

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Motivated by the polarization anomaly in the $B \rightarrow \phi(1020)K^*(892)$ decay, we extend our search for other K^* final states in the decay $B^0 \rightarrow \phi(1020)K^{*0}$ with the $K^{*0} \rightarrow K^+\pi^-$ invariant mass above 1.6 GeV. The final states considered include the $K^*(1680)^0$, $K_3^*(1780)^0$, $K_4^*(2045)^0$, and a $K\pi$ spin-zero nonresonant component. We also search for $B^0 \rightarrow \phi\bar{D}^0$ decay with the same final state. The analysis is based on a sample of about $384 \times 10^6 B\bar{B}$ pairs recorded with the BABAR detector. We place upper limits on the branching fractions $\mathcal{B}(B^0 \rightarrow \phi K^*(1680)^0) < 3.5 \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow \phi K_3^*(1780)^0) < 2.7 \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow \phi K_4^*(2045)^0) < 15.3 \times 10^{-6}$, and $\mathcal{B}(B^0 \rightarrow \phi\bar{D}^0) < 11.7 \times 10^{-6}$ at 90% C.L. The nonresonant contribution is consistent with the measurements in the lower invariant mass range.

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Recent measurements of polarization in rare vector- B meson decays, such as $B \rightarrow \phi K^*$ and ρK^* , have revealed a large fraction of transverse polarization [1–5]. This indicates a significant departure from the expected predominance of the longitudinal amplitude [6]. The rate, polarization, and CP measurements of B meson decays to particles with nonzero spin are sensitive to both strong and weak interaction dynamics, as shown in Fig. 1(a), and are discussed in a recent review [7,8]. This has motivated a number of proposed contributions from new mechanisms within the standard model, such as penguin annihilation or electroweak penguin [9], or QCD rescattering [10], or from physics beyond the standard model [11].

The BABAR experiment extended the study of the $B^0 \rightarrow \phi K^{*0}$ decays with the tensor ($J^P = 2^+$), vector ($J^P = 1^-$), and scalar ($J^P = 0^+$) K^{*0} [5]. In this paper, we extend our search for $B^0 \rightarrow \phi K^{*0}$ to the higher-mass and higher-spin resonances $K^*(1680)^0$, $K_3^*(1780)^0$, and $K_4^*(2045)^0$. Charge conjugate reactions are implied throughout this paper. The respective quantum numbers for these states $J^P = 1^-, 3^-,$ and 4^+ are allowed in the $K^{*0} \rightarrow K^+\pi^-$ decay. Moreover, we extend our study of the $B^0 \rightarrow \phi(K\pi)_0^{*0}$ decay, where $(K\pi)_0^{*0}$ is the $J^P = 0^+$ $K\pi$ component, to a $K\pi$ invariant mass up to 2.15 GeV. We also search for the decay $B^0 \rightarrow \phi\bar{D}^0$, which is expected to be significantly suppressed relative to the observed $B^0 \rightarrow \omega\bar{D}^0$ due to a negligible $u\bar{u} + d\bar{d}$ quark admixture in the ϕ meson [8].

The analysis follows closely our recent study [5] where we fully reconstruct the decay $B^0 \rightarrow \phi(1020)K^{*0} \rightarrow (K^+K^-)(K^+\pi^-)$. The $K\pi$ invariant mass $m_{K\pi}$ window is now moved to the range from 1.60 to 2.15 GeV to cover the

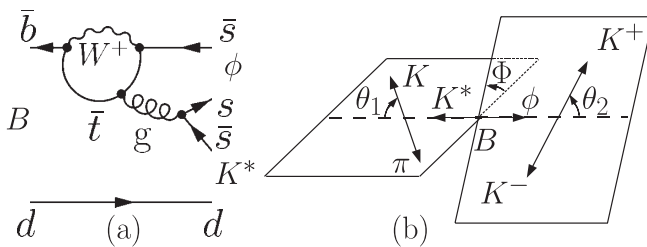


FIG. 1. (a) Feynman diagram describing the $B^0 \rightarrow \phi K^{*0}$ decay; (b) definition of decay angles given in the rest frames of the decaying parents.

above mentioned resonances. In Fig. 2 we show the $m_{K\pi}$ distribution extended from our previous study in Ref. [5] to the mass range from 0.75 to 2.15 GeV.

The angular distribution of the $B \rightarrow \phi K^*$ decay can be expressed as a function of $\mathcal{H}_i = \cos\theta_i$ and Φ shown in Fig. 1(b). Here θ_i with $i = 1, 2$ is the angle between the direction of the K meson from the $K^* \rightarrow K\pi$ (θ_1) or $\phi \rightarrow K\bar{K}$ (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. For each decay mode, the differential decay width has three complex amplitudes A_λ^J corresponding to the spin of the $K\pi$ system $J \geq 1$ and the three helicity states $\lambda = 0$ or ± 1 :

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

where Y_λ^J are the spherical harmonics with $J = 1$ for $K^*(1680)$, $J = 3$ for $K_3^*(1780)$, and $J = 4$ for $K_4^*(2045)$. The angular distribution is simplified when averaged over the azimuthal angle Φ and becomes a function of the fraction of longitudinal polarization $f_L^J = |A_0^J|^2 / (|A_{-1}^J|^2 + |A_0^J|^2 + |A_{+1}^J|^2)$. The angular distribution has only one

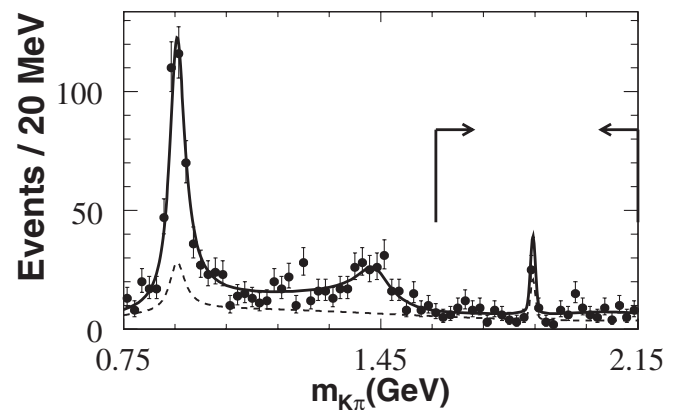


FIG. 2. Distribution of the $K\pi$ invariant mass extended above 1.6 GeV from the study of $B^0 \rightarrow \phi(K^+\pi^-)$ decays in Ref. [5]. The data distribution is shown with a requirement to enhance the signal as discussed in regard to Fig. 3 in the text. The solid (dashed) line shows the signal-plus-background (background) expected distributions. The arrows indicate the higher-mass range, 1.60 to 2.15 GeV, used in this analysis.

contributing amplitude with $J = \lambda = 0$ for each $\phi(K\pi)_0^*$ and $\phi\bar{D}$ final state.

We use data collected with the *BABAR* detector [12] at the PEP-II e^+e^- collider. A sample of 383.6 ± 4.2 million $Y(4S) \rightarrow B\bar{B}$ events was recorded at the center-of-mass 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 $m_{\text{ES}} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}$, where (E_i, \mathbf{p}_i) is the e^+e^- initial state four-momentum, and (E_B, \mathbf{p}_B) is the four-momentum of the B candidate. We require $|\Delta E| < 0.1$ GeV and $m_{\text{ES}} > 5.25$ GeV. The requirements on the invariant masses are $1.60 < m_{K\pi} < 2.15$ GeV and $0.99 < m_{K\bar{K}} < 1.05$ GeV.

To reject the dominant $e^+e^- \rightarrow$ quark-antiquark continuum background, we use event-shape variables calculated in the center-of-mass 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 two moments of the energy flow around the B -candidate thrust axis [13].

We remove signal candidates that have decay products with invariant mass within 12 MeV of the nominal mass values for D_s^+ or $D^+ \rightarrow \phi\pi^+$. In about 8.8% of events more than one candidate is reconstructed and we select the one whose four-track vertex fit has the lowest χ^2 .

We use an unbinned, extended maximum-likelihood fit [5] to extract the event yields n_j and the probability density function (PDF) parameters, denoted by $\zeta = \{f_L^1, f_L^3, f_L^4\}$ for the polarization parameters and ξ for the remaining parameters. The data model has eight event categories j : $B^0 \rightarrow \phi(K\pi)_0^{*0}$, $\phi K^*(1680)^0$, $\phi K_3^*(1780)^0$, $\phi K_4^*(2045)^0$, $\phi\bar{D}^0$, $f_0(980)K^{*0}$, $f_0(980)\bar{D}^0$, and combinatorial background. The $f_0(980)K^{*0}$ and $f_0(980)\bar{D}^0$ categories are included to account for both the resonant and nonresonant K^+K^- contribution in exclusive B decays, while 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 $\mathcal{L}_i = \sum_j n_j \mathcal{P}_j(\mathbf{x}_i; \zeta; \xi)$, where each of the \mathcal{P}_j is the PDF for variables $\mathbf{x}_i = \{\Delta E, m_{\text{ES}}, m_{K\pi}, m_{K\bar{K}}, \mathcal{H}_1, \mathcal{H}_2, \mathcal{F}\}$. We do not allow CP -violation in the decay amplitudes and ignore interference between the final states $B \rightarrow \phi(K\pi)_J$ with different J because no significant signal is observed. Since our acceptance in the decay angles is nearly uniform, the event yields are almost completely unaffected by interference among states of different J .

The PDF $\mathcal{P}_j(\mathbf{x}_i; \zeta; \xi)$ for a given candidate i is a joint PDF for the helicity angles, 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) averaged over azimuthal angle Φ , where the amplitudes A_λ^J are expressed in terms of the polarization fractions ζ , multiplied by an empirically determined acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2) \equiv \mathcal{G}_1(\mathcal{H}_1) \times \mathcal{G}_2(\mathcal{H}_2)$.

A relativistic spin- J Breit-Wigner amplitude parametrization is used for the resonance mass [8,14], except for the nonresonant $(K\pi)_0^{*0}$ contribution which has no $m_{K\pi}$ amplitude dependence beyond the phase-space factor. In the previous analysis with the $K\pi$ mass below 1.6 GeV, we parametrized the $(K\pi)_0^{*0}$ $m_{K\pi}$ amplitude with the LASS function [5,15], which includes the $K_0^*(1430)^0$ resonance together with a nonresonant component. However, above 1.6 GeV the validity of the LASS parametrization is not certain and we use the phase-space model for the nonresonant $(K\pi)_0^{*0}$ parametrization.

The parameters ξ 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 [16] and calibration of B -decay channels for the exclusive B decays. We use a sum of Gaussian functions for the parametrization of the signal PDFs for ΔE , m_{ES} , \mathcal{F} , and of the D^0 meson $m_{K\pi}$ distribution. For the combinatorial background, we use polynomial functions, except for m_{ES} and \mathcal{F} distributions which are parametrized by an empirical phase-space function [17] and by Gaussian functions, respectively. The ϕ and D^0 meson production can occur in the background, and we take this into account in the PDF.

In the mass range $1.60 < m_{K\pi} < 2.15$ GeV, we do not find significant signal in any of the four decays $B^0 \rightarrow \phi(K^+\pi^-)$ with $K^*(1680)^0$, $K_3^*(1780)^0$, $K_4^*(2045)^0$, or $\bar{D}^0 \rightarrow K^+\pi^-$ and we place limits on their branching fractions as shown in Table I. We see evidence for the nonresonant $\phi(K\pi)_0^{*0}$ contribution of $47 \pm 16 \pm 15$ events consistent with extrapolation (33 events) from the lower-mass range studied in Ref. [5]. Due to large correlation among various signal yields of the decay modes with broad $K\pi$ distributions, the errors on individual decay modes are relatively large. However, the significance of the $B^0 \rightarrow \phi(K^+\pi^-)$ decay with $(K\pi)_0^{*0}$, $K^*(1680)^0$, $K_3^*(1780)^0$, and $K_4^*(2045)^0$ combined is larger than 5σ . 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} .

Since we do not determine the flavor of the neutral B meson, our limits refer to the sum of two flavor final states, such as $\phi\bar{D}^0$ and ϕD^0 . We assume equal production of B^+B^- and $B^0\bar{B}^0$ pairs in $Y(4S)$ decays. In Fig. 3 we show projections onto the variables. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. In each plot, this requirement is independently optimized to

TABLE I. Fit results for each decay mode: the reconstruction efficiency $\varepsilon_{\text{long}}$ and $\varepsilon_{\text{trans}}$ obtained from MC simulation for longitudinally and transversely polarized events; the total efficiency ε , including the daughter branching fractions [8] and assuming the smaller reconstruction efficiency; the number of signal events n_{sig} ; significance (\mathcal{S}) of the signal; the branching fraction \mathcal{B} ; and the upper limit (UL) on the branching fraction at 90% C.L. The branching fraction $\mathcal{B}(B^0 \rightarrow \phi(K\pi)_{0^+}^*)$ refers to the nonresonant $J^P = 0^+ K\pi$ components quoted for $1.60 < m_{K\pi} < 2.15$ GeV. The systematic errors are quoted last and are included in the \mathcal{S} and UL calculations. The negative event yield (or \mathcal{B}) for $B^0 \rightarrow \phi K_3^*(1780)^0$ is extrapolated from the likelihood distribution in the physical range.

Mode	$\varepsilon_{\text{long}}$ (%)	$\varepsilon_{\text{trans}}$ (%)	ε (%)	n_{sig} (events)	\mathcal{S} (σ)	\mathcal{B} (10^{-6})	\mathcal{B} UL (10^{-6})
$\phi K^*(1680)^0$	20.8 ± 2.9	21.6 ± 3.0	2.64 ± 0.41	$8_{-7}^{+10} \pm 11$	0.6	$0.7_{-0.7}^{+1.0} \pm 1.1$	3.5
$\phi K_3^*(1780)^0$	27.7 ± 2.0	28.2 ± 2.1	1.71 ± 0.16	$-6 \pm 10 \pm 7$	0.0	$-0.9 \pm 1.4 \pm 1.1$	2.7
$\phi K_4^*(2045)^0$	23.6 ± 2.1	24.5 ± 2.2	0.77 ± 0.12	$18_{-12}^{+14} \pm 12$	1.2	$6.0_{-4.0}^{+4.8} \pm 4.1$	15.3
$\phi(K\pi)_{0^+}^*$	34.8 ± 1.6	—	11.42 ± 0.56	$47 \pm 16 \pm 15$	2.2	$1.1 \pm 0.4 \pm 0.3$	1.7
$\phi \bar{D}^0$	33.1 ± 1.6	—	0.62 ± 0.03	$16 \pm 7 \pm 3$	2.4	$6.5_{-2.7}^{+3.1} \pm 1.4$	11.6

enhance the signal, and results in an additional efficiency factor of (60–90)%.

In the fit, we constrain both event yields and polarization fractions f_L^J to the physically allowed ranges. The negative event yield in the $B^0 \rightarrow \phi K_3^*(1780)^0$ decay is obtained by using the likelihood in the positive event region and fitting its shape with a parabolic function whose minimum is in

the negative event region. For the three $B^0 \rightarrow \phi K_J^{*0}$ decay modes with $J \geq 1$, the f_L^J fit results are consistent with any allowed value between 0 and 1 and we assume polarization which gives the smallest reconstruction efficiency in the branching fraction calculation. We integrate the likelihood distributions in the physically allowed ranges to compute the upper limits on the branching fractions.

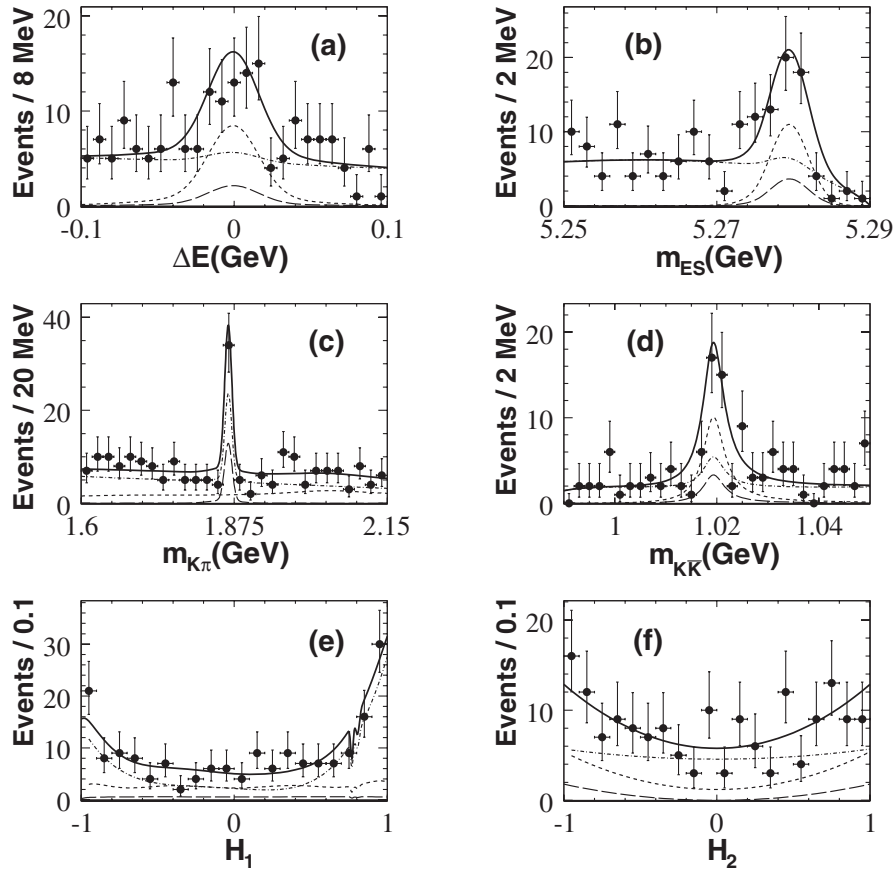


FIG. 3. Projections onto the variables ΔE (a), m_{ES} (b), $m_{K\pi}$ (c), $m_{K\bar{K}}$ (d), \mathcal{H}_1 (e), and \mathcal{H}_2 (f) for the signal $B^0 \rightarrow \phi(K\pi)$ and $B^0 \rightarrow \phi \bar{D}^0$ candidates. The solid (dotted-dashed) line shows the signal-plus-background (background only) PDF projection, while the dashed (long-dashed) line shows PDF projection for the sum of four $B^0 \rightarrow \phi(K\pi)$ categories (for $B^0 \rightarrow \phi \bar{D}^0$). The pronounced D^0 mass peak in (c) is predominantly due to background. The $D_{(s)}^+$ -meson veto causes the sharp acceptance dips seen in (e).

The nonresonant K^+K^- contribution under the ϕ is accounted for with the $B^0 \rightarrow f_0 K^{*0}$ category with the broad f_0 invariant mass distribution [14]. Its yield is consistent with zero for any of the K^{*0} spin assumptions. We find evidence for a nonzero event yield in this nonresonant K^+K^- region under the ϕ with a \bar{D}^0 of (31_{-8}^{+9}) events, with statistical errors only quoted. However, due to the broad K^+K^- invariant mass distribution, we cannot distinguish between f_0 , a_0 , or any other broad K^+K^- contribution under the ϕ . The uncertainties due to $m_{K\bar{K}}$ parametrization are estimated with variation of the shape model from the resonant f_0 to phase space and account for the errors between 3 and 11 events in different channels.

We vary those parameters in ξ not used to model combinatorial background within their uncertainties and derive the associated systematic errors between one and three events. The signal PDF model excludes the fake combinations originating from misreconstructed events. The biases from the dilution due to the presence of fake combinations, the finite resolution of the angle measurement, or other imperfections in the signal PDF model are estimated with MC simulation and generated samples. This results in an uncertainty between 1 and 11 events.

Additional systematic uncertainty originates from B background, where we estimate that only a few events can fake the signal. The systematic errors in selection efficiencies are dominated by those in particle identification (4%), track finding (2%), and uncertainty due to the K^* resonance parameters [8] of 2%–13%. Other systematic effects arise from event-selection criteria, ϕ , K^{*0} , or D^0 branching fractions [8], and the number of B mesons.

Our results place stringent limits on the $B^0 \rightarrow \phi K^{*0}$ branching fractions with the higher-mass and spin reso-

nances $K^*(1680)^0$, $K_3^*(1780)^0$, and $K_4^*(2045)^0$ when compared with the lower-mass states [1,2,5]. The decay rate suppression may serve as an additional tool to study the mechanism of the anomalous transverse amplitude in the $B \rightarrow \phi K^*(892)$ decay. We find the $B^0 \rightarrow \phi(K\pi)_0^{*0}$ rate with scalar $(K\pi)_0^{*0}$ to be consistent for $K\pi$ invariant mass above and below 1.6 GeV. Our limit on the $B^0 \rightarrow \phi \bar{D}^0$ decay provides a test of the B decay mechanisms involving ϕ mesons in the final state.

In summary, we have searched for the $B^0 \rightarrow \phi K^{*0}$ decays with the tensor $K_3^*(1780)^0$ and $K_4^*(2045)^0$, vector $K^*(1680)^0$, and scalar nonresonant $(K\pi)_0^{*0}$ contributions with $K^{*0} \rightarrow K^+\pi^-$ invariant mass above 1.6 GeV. Our results are summarized in Table I. We do not find significant signal with either one of the above resonances and place upper limits on these and $B^0 \rightarrow \phi \bar{D}^0$ decays. However, the combined significance of the $B^0 \rightarrow \phi K^{*0}$ decays in this mass range with nonresonant $(K\pi)_0^{*0}$ and resonance $K^*(1680)^0$, $K_3^*(1780)^0$, and $K_4^*(2045)^0$ contributions is larger than 5σ .

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