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Searches for B meson decays to $\phi\phi$, $\phi\rho$, $\phi f_0(980)$, and $f_0(980)f_0(980)$ final states

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We present the results of searches for B decays to charmless final states involving ϕ, $f_0(980)$, and charged or neutral ρ mesons. The data sample corresponds to $384{\times}10^6$ $B\overline{B}$ pairs collected with the *BABAR* detector operating at the PEP-II asymmetric-energy e^+e^- collider at SLAC. We find no significant signals and determine the following 90% confidence level upper limits on the branching fractions, including systematic uncertainties: $\mathcal{B}(B^0 \to \phi\phi) < 2.0{\times}10^{-7}$, $\mathcal{B}(B^+ \to \phi\rho^+) < 30{\times}10^{-7}$,

$\mathcal{B}(B^0 \to \phi\rho^0) < 3.3{\times}10^{-7}$, $\mathcal{B}[B^0 \to \phi f_0(980)] \times \mathcal{B}[f_0(980) \to \pi^+\pi^-] < 3.8{\times}10^{-7}$, and $\mathcal{B}[B^0 \to f_0(980)f_0(980)] \times \mathcal{B}[f_0(980) \to \pi^+\pi^-] \times \mathcal{B}[f_0(980) \to K^+K^-] < 2.3{\times}10^{-7}$.

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We report the results of searches for the decays $B^0 \to \phi\phi$, $\phi\rho^0$, $\phi f_0(980)$, $f_0(980)f_0(980)$, and $B^\pm \to \phi\rho^\pm$ [1] using data collected with the *BABAR* detector. The $B^0 \to \phi\phi$ decay is an OZI suppressed process with an expected branching fraction in the range (0.1 to 3) $\times 10^{-8}$ in the Standard Model (SM) [2–4]. The decays $B^0 \to \phi\rho^0$ and $B^+ \to \phi\rho^+$ are pure $b \to d$ loop processes; the expected branching fractions for these modes range from $(0.2 \text{ to } 5.3){\times}10^{-7}$ [5–12]. The presence of new physics (NP) would give rise to additional amplitudes that could enhance the branching fractions for these decay modes relative to the SM predictions [2, 3, 10]. The branching fraction for $B^0 \to \phi\phi$ could be enhanced to 10^{-7} [2], and the branching fractions for $B \to \phi\rho$ decays could be enhanced by 20% [12] in the presence of NP. We are not aware of branching fraction predictions for $B^0 \to \phi f_0$ and $B^0 \to f_0 f_0$.

The B decays to $\phi\phi$ and $\phi\rho$ are complicated by the presence of one amplitude with longitudinal polarization and two amplitudes with transverse polarization. The fraction of longitudinally polarized events is denoted by f_L. Integrating over the angle between the vector meson decay planes, the angular distribution $(1/\Gamma)d^2\Gamma/d\cos\theta_1 d\cos\theta_2$ is

$$\frac{9}{4}\left[f_L \cos^2\theta_1\cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2\right], \quad (1)$$

where the indices $1, 2$ label the two vector mesons in the final state, and the helicity angles $\theta_{1,2}$ are the angles between the direction opposite to that of the B^0 (B^+) and the K^+ or π^+ (π^0) momentum in the ϕ or ρ^0 (ρ^+) rest frame. We define the angles $\theta_{1,2}$ for f_0 mesons in an analogous way. The expected values of f_L range from 0.6 to 0.8 [3, 4, 10, 11] for $B^0 \to \phi\phi$, $\phi\rho^0$, and $B^\pm \to \phi\rho^\pm$. The presence of NP could lead to enhancements of the transverse polarization amplitudes [2, 3, 10].

The current upper limit on the $B^0 \to \phi\phi$ branching fraction, obtained from a data sample of 82 fb^{-1}, is $1.5{\times}10^{-6}$ [13]. The upper limits on $B^0 \to \phi\rho^0$ and $B^+ \to \phi\rho^+$, determined using 3.1 fb^{-1} of data, are $1.3{\times}10^{-5}$ and $1.6{\times}10^{-5}$ [14], respectively. Using a data sample of 349 fb^{-1}, *BABAR* recently reported an upper limit of $1.6{\times}10^{-7}$ for $B^0 \to f_0 f_0$ [15]. This last result relies on the assumption that the $f_0 \to \pi^+\pi^-$ branching fraction is 100%. In this analysis, we make the complimentary assumption that one f_0 decays to $\pi^+\pi^-$ and the other to K^+K^- and search for $B^0 \to f_0 f_0$ in a cleaner final state than Ref [15]. All these limits correspond to a confidence level (C.L.) of 90%.

The results presented here are based on an integrated luminosity of 349fb^{-1}, corresponding to (384 ± 4) million $B\overline{B}$ pairs. These data were recorded at the $\Upsilon(4S)$ resonance (on-peak) with a center-of-mass energy $\sqrt{s} = 10.58$ GeV. An additional 37fb^{-1} of data, collected approximately 40 MeV below the $\Upsilon(4S)$ resonance (off-peak), were used to study background from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum events. The *BABAR* detector is described in detail elsewhere [16], and is situated at the interaction region of the PEP-II asymmetric energy e^+e^- collider located at the Stanford Linear Accelerator Center (SLAC). We use Monte Carlo (MC) simulated events generated using the GEANT4 based [17] *BABAR* simulation.

Photons are reconstructed from localized energy deposits in the electromagnetic calorimeter that are not associated with a charged track. We require γ candidates to have an energy greater than 50 MeV and a lateral shower profile [18] that is consistent with the expectation for photons. π^0 candidates are reconstructed from two distinct γ candidates with invariant mass $0.10 < m_{\gamma\gamma} < 0.16$ GeV/c^2.

We use information from the vertex detector, drift chamber and detector of internally reflected Cherenkov light to select charged tracks that are consistent with kaon or pion signatures in the detector [19]. We reconstruct ϕ (ρ^0) candidates from pairs of oppositely charged kaon (pion) candidates with invariant mass $0.99 < m_{KK} < 1.05\,\text{GeV}/c^2$ ($0.55 < m_{\pi\pi} < 1.05\,\text{GeV}/c^2$). For ρ^0 candidates we require the helicity angles to satisfy $|\cos\theta_i| < 0.98$ since signal efficiency falls off near $|\cos\theta_i| = 1$.

Charged ρ candidates are reconstructed from a charged track consistent with the pion signature and a π^0 candidate. The invariant mass $m_{\pi\pi^0}$ of the ρ^+ candidate is required to lie between 0.5 and 1.0 GeV/c^2. We also require that the helicity angles satisfy $-0.8 < \cos\theta_i < 0.98$ as signal efficiency is asymmetric because of the π^0 meson, and falls off near $\cos\theta_i = \pm 1$, and background peaks near -1.

We select f_0 candidates from two charged tracks that are both either consistent with the kaon or the pion signature in the detector. We apply the same selection criteria to $f_0 \to \pi^+\pi^-$ candidates as for ρ^0 mesons. Similarly we apply the same selection criteria to $f_0 \to K^+K^-$ candidates as for ϕ mesons as the minimum m_{KK} we can reconstruct in the detector is 0.99 GeV/c^2.

We reconstruct signal B candidates (B_{rec}) from combinations of two ϕ mesons, one ϕ and one ρ or f_0, and two f_0 mesons. The $f_0 f_0$ mode is required to have one f_0 decaying into $\pi^+\pi^-$, and the other decaying into K^+K^-. We require the f_0 in ϕf_0 to decay into $\pi^+\pi^-$.

We use two kinematic variables, m_{ES} and ΔE, in order to isolate the signal: $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ is the beam-energy substituted mass and $\Delta E = E_B^* - \sqrt{s}/2$ is the difference between the B candidate energy and the beam energy in the e^+e^- center-of-mass frame. Here the $B_{\rm rec}$ momentum $\mathbf{p}_B$ and four-momentum of the initial state $(E_i, \mathbf{p}_i)$ are defined in the laboratory frame, and E_B^* is the $B_{\rm rec}$ energy in the e^+e^- center-of-mass (CM) frame. The distribution of $m_{\rm ES}$ (ΔE) peaks at the B mass (near zero) for signal events and does not peak for background. We require $m_{\rm ES} > 5.25\,{\rm GeV}/c^2$. For the $\phi\phi$ final state we require $|\Delta E| < 0.15\,{\rm GeV}$. To reduce background from non-signal B meson decays we apply the more stringent cut of $-0.07 < \Delta E < 0.15$ GeV for all other modes.

The angle in CM frame between the thrust axis of the rest of the event (ROE) and that of the B candidate is required to satisfy $|\cos(\theta_{TB,TR})| < 0.8$ in order to reduce background from continuum events. The variable $|\cos(\theta_{TB,TR})|$ is strongly peaked near 1 for $q\overline{q}$ events, whereas $B\overline{B}$ events are more isotropic because the B mesons are produced close to the kinematic threshold. Additional separation between signal and continuum events is obtained by combining several kinematic and topological variables into a Fisher discriminant $\mathcal{F}$, which we use in the maximum-likelihood fit described below. The variables $|\cos(\theta_{TB,TR})|$, $|\Delta t|/\sigma(\Delta t)$, $|\cos(\theta_{B,Z})|$, $|\cos(\theta_{TB,Z})|$, and the output of a multivariate tagging algorithm [20] are used as inputs to $\mathcal{F}$. The time interval Δt is calculated from the measured separation distance Δz between the decay vertices of $B_{\rm rec}$ and the other B in the event ($B_{\rm ROE}$) along the beam axis (z). The vertex of $B_{\rm rec}$ is reconstructed from the tracks that come from the signal candidate; the vertex of $B_{\rm ROE}$ is reconstructed from tracks in the ROE, with constraints from the beam spot location and the $B_{\rm rec}$ momentum. The uncertainty on the measured value of Δt is $\sigma(\Delta t)$. The variable $\theta_{B,Z}$ is the angle between the direction of $B_{\rm rec}$ and the z axis in the CM frame. This variable follows a sine squared distribution for $B\overline{B}$ events, whereas it is almost uniform for $q\overline{q}$. The variable $\theta_{TB,Z}$ is the angle between the B thrust direction and the z axis in the laboratory frame.

The decay modes studied are classified into three groups according to the final state particles: (i) $B^0 \to \phi\phi$, (ii) $B^+ \to \phi\rho^+$, and (iii) $B^0 \to \phi\rho^0$, $B^0 \to \phi f_0$, and $B^0 \to f_0 f_0$. We find that 6% of events for the mode in group (ii) and 3% of events for the modes in group (iii) have more than one candidate that passes our selection criteria. For such events we retain the candidate with the smallest χ^2 for the $B_{\rm rec}$ vertex for use in the fits described below. The numbers of selected candidates are given in Table I.

The dominant background for all modes comes from continuum events. The yield of this background component is determined from the fit to data. The dominant B backgrounds for group (i) are $B^0 \to \phi K^{*0}$ and $f_0 K^{*0}$, which are estimated to contribute 1.4 and 0.6 events to the data, respectively. The B backgrounds for group (ii) are events from B decays to final states including charm, $B^0 \to \phi K_2^{*0}(1430)$, $B^+ \to \phi K^{*+}$, and $B^+ \to \rho^+ K^{*0}$. These are estimated to contribute 107, 0.8, 5.5, and 0.7 events to the data. The B backgrounds for group (iii) are events from B decays to final states including charm, B^0 decays to ϕK^{*0}, $f_0 K^{*0}$, $\phi K_2^{*0}(1430)$, $a_1^{\pm}\pi^{\mp}$, and B^+ decays to ϕK^+, ϕK^{*+}, and $\phi\rho^+$, estimated to contribute 249, 25.9, 9.1, 2.3, 0.6, 4.7, 1.8, and 0.9 events to the data. The branching fractions for the B backgrounds are taken from Ref. [21], except for $B^0 \to f_0 K^{*0}$, which has not yet been measured, and $\phi\rho^+$ where we use the results obtained here. The current upper limit on the $B^0 \to f_0 K^{*0}$ branching fraction is 4.3×10^{-6} and we assume a branching fraction of $(2\pm2)\times10^{-6}$.

We obtain yields for each mode from extended unbinned maximum likelihood (ML) fits with the input observables $m_{\rm ES}$, ΔE, and $\cos\theta_{1,2}$. In addition, for all modes except $\phi\phi$, we include $m_{1,2}$ and $\mathcal{F}$ in the likelihood, where $m_{1,2}$ is $m_{\pi\pi}$ or m_{KK} for the ϕ, ρ or f_0 candidates. A total of three fits are performed, one for each group of signal modes. We include event hypotheses for signal events and the aforementioned backgrounds in each of the fits. For each event i and hypothesis j, the likelihood function is

$$\mathcal{L} = \frac{e^{-(\sum n_j)}}{N!} \prod_{i=1}^{N} \left[\sum_{j=1}^{N_j} n_j \mathcal{P}_j(\mathbf{x}_i) \right] ,$$

where N is the number of input events, N_j is the number of hypotheses, n_j is the number of events for hypothesis j and $\mathcal{P}_j(\mathbf{x}_i)$ is the corresponding probability density function (PDF) evaluated for the observables $\mathbf{x}_i$ of the i^{th} event. The correlations between input observables are small and are assumed to be negligible. Possible biases due to residual correlations are evaluated as described below. We compute the combined PDFs $\mathcal{P}_j(\mathbf{x}_i)$ as the product of PDFs for each of the input observables. These combined PDFs are used in the fit to the data.

For B decays to $\phi\phi$ and $\phi\rho$, the $m_{\rm ES}$ distribution is parametrized with the sum of a Gaussian and a Gaussian with a low-side exponential component. The ΔE distribution is described by the sum of two Gaussian distributions, and the $\cos\theta_{1,2}$ distributions are described by Eq. (1) multiplied by an acceptance function. The acceptance function is a polynomial for all $\cos\theta_{1,2}$, with the exception of the ρ^+ helicity angle distribution for longitudinally polarized $\phi\rho^+$, which uses a polynomial multiplied by the sigmoid function $1/(1+\exp[\alpha(\cos\theta_{1,2}+\beta)])$, where the parameters α and β are determined from MC simulated data. For the $\phi\rho$ final states we use a Gaussian to describe the $\mathcal{F}$ distribution, and the sum of a relativistic Breit-Wigner (BW) with two Gaussians for $m_{1,2}$. The continuum background $m_{\rm ES}$ distribution is described by an ARGUS function [22]. We parameterize the

TABLE I: Number of events N in the data sample, signal yield $\mathcal{Y}_{\mathcal{S}}$ (corrected for fit bias), fit bias, detection efficiency ϵ, daughter branching fraction product ($\prod \mathcal{B}_i$), significance σ (including additive systematic uncertainties, taken to be zero if the fitted yield is negative), measured branching fraction where the first error is statistical, and the second systematic (see text), and the 90% C.L. upper limit on this branching fraction (including systematic uncertainties). For B decays to $\phi\phi$ and $\phi\rho$, two efficiencies are reported, one for longitudinally and one for transversely polarized events. The reported branching fractions for ϕf_0 and $f_0 f_0$ are product branching fractions that are not corrected for the probability of f_0 decaying into $\pi^+\pi^-$ or K^+K^-.

Group	N	Mode	$\mathcal{Y}_{\mathcal{S}}$	Bias	ϵ(%)	$\prod \mathcal{B}_i$(%)	σ	$\mathcal{B}$($\times 10^{-7}$)	UL($\times 10^{-7}$)
(i)	209	$\boldsymbol{\phi\phi}$	$-1.5^{+3.7}_{-2.9}$	-0.4 ± 0.2	40.4 [28.7]	24.3 ± 1.2	0.0	$-0.4^{+1.2}_{-0.9} \pm 0.3$	<2.0
(ii)	3175	$\boldsymbol{\phi\rho^+}$	$22.5^{+11.3}_{-9.7}$	$+2.3 \pm 1.1$	5.7 [9.8]	49.3 ± 0.6	2.2	$15^{+7}_{-6} \pm 9$	<30
(iii)	3949	$\boldsymbol{\phi\rho^0}$	$3.9^{+6.3}_{-4.4}$	$+0.8 \pm 0.4$	24.1 [26.5]	49.3 ± 0.6	1.0	$0.9^{+1.3}_{-0.9} \pm 0.9$	<3.3
		$\boldsymbol{\phi f_0}$	$0.8^{+2.4}_{-1.4}$	-1.7 ± 0.5	22.1	…	0.0	$0.2^{+0.6}_{-0.3} \pm 0.3$	<3.8
		$\boldsymbol{f_0 f_0}$	$-13.6^{+4.8}_{-3.5}$	-1.8 ± 0.5	25.5	…	0.0	$-1.4^{+0.5}_{-0.4} \pm 1.5$	<2.3

continuum ΔE distribution using a second-order polynomial and use polynomials to describe $\cos\theta_{1,2}$. Where appropriate, we parameterize the $\mathcal{F}$ distributions for the continuum background using a Gaussian, and we parameterize the $m_{1,2}$ distributions using the sum of a BW and a polynomial. We use smoothed histograms of MC simulated data as the PDFs for all other signal and background modes. We generate $B^0 \to \phi f_0$ assuming that the ϕ is longitudinally polarised, and we use phase space distributions for $B^0 \to f_0 f_0$. Before fitting the data, we validate the fitting procedure using the methods described in Ref. [23]. We determine a bias correction on our ability to correctly determine the signal yield using ensembles of simulated experiments generated from samples of MC simulated data for the signal and exclusive backgrounds and from the PDFs for the other backgrounds.

Our results are summarized in Table I where we show the measured yield, fit bias, efficiency, and the product of daughter branching fractions for each decay mode. We compute the branching fractions from the fitted signal event yields corrected for the fit bias, reconstruction efficiency, daughter branching fractions, and the number of produced B mesons, assuming equal production rates of charged and neutral B pairs. As we do not know the value of f_L for the $\phi\phi$ and $\phi\rho$ modes, we fit the data for different physically allowed values of f_L in steps of 0.1. We find no evidence for any of the signal modes and calculate 90% C.L. branching fraction upper limits x_{UL} such that $\int_0^{x_{UL}} L(\mathcal{Y}_{\mathcal{S}}, f_L) d\mathcal{Y}_{\mathcal{S}} / \int_0^{+\infty} L(\mathcal{Y}_{\mathcal{S}}, f_L) d\mathcal{Y}_{\mathcal{S}} = 0.9$, where $L(\mathcal{Y}_{\mathcal{S}}, f_L)$ is the likelihood as a function of signal yield $\mathcal{Y}_{\mathcal{S}}$ and f_L multiplied by a uniform prior. We report the most conservative (largest) upper limits for each mode, for which $f_L = 0.5$, 0.7, and 0.2 for groups (i), (ii), and (iii), respectively. The central values of the branching fractions given in Table I correspond to these values of f_L. Figure 1 shows the $m_{\rm ES}$ distributions in subsamples of the data where $|\Delta E| < 0.05$ GeV for $B^+ \to \phi\rho^+$, and $|\Delta E| < 0.025$ GeV for all other modes.

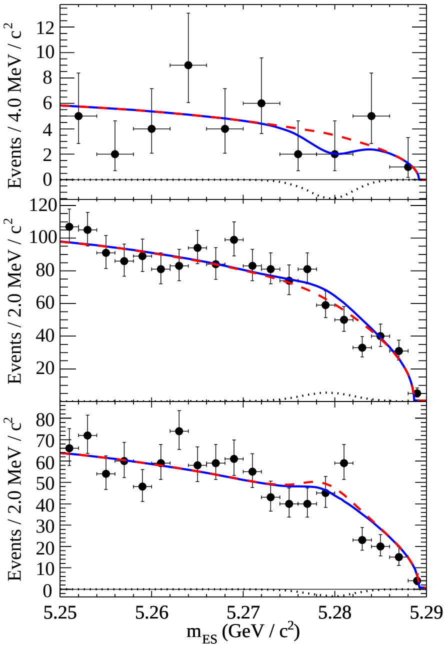

FIG. 1: (color online) Signal-enhanced distributions of $m_{\rm ES}$ in on-peak data, with a projection of the fitted likelihood for (top) $B^0 \to \phi\phi$, (middle) $B^+ \to \phi\rho^+$, and (bottom) $B^0 \to \phi\rho^0$, $B^0 \to \phi f_0$, and $B^0 \to f_0 f_0$. The solid line represents the total PDF, the dotted line represents signal, and the dashed line represents the sum of continuum and B backgrounds.

We estimate the systematic uncertainty related to the parameterization of the PDF by varying each parameter by its estimated uncertainty, and by substituting smoothed histograms by un-smoothed ones. The total contribution of all variations in signal yields, when added in quadrature, gives an error between 0.2 and 5.6 events, depending on the mode. We account for possible differences between data and MC events from studies of a control sample of $B \to D\pi$ events, yielding an uncertainty of 0.1 to 12.2 events depending on the mode. The uncertainty from fit bias is taken to be half the correction listed in Table I. Incorporating the statistical uncertainty of the bias has a negligible effect. The uncertainty on B-daughter branching fractions is in the range (1.2 to 4.9)% [21]. The modes in group (iii), $\phi\rho^0$, ϕf_0, and $f_0 f_0$ have systematic uncertainties from the f_0 lineshape [24] of 0.2, 3.1, and 15.9 events, respectively. The mode $B^+ \rightarrow \phi\rho^+$ has a fractional systematic uncertainty of 3.0% from the reconstruction efficiency of π^0 mesons. Other sources of systematic errors are track reconstruction efficiency [$(2.4 - 3.2)$%], uncertainty on the number of B meson pairs (1.1%), particle identification efficiency (3.5%), and differences between data and MC efficiencies related to the cut on the vertex χ^2 (0.6%).

Assuming isospin is conserved in $f_0 \rightarrow hh$ decays, where $h = \pi, K$, we correct for factors of $\mathcal{B}(f_0 \rightarrow hh)/\mathcal{B}(f_0 \rightarrow h^+h^-)$, to obtain the product branching fraction upper limits of $\mathcal{B}(B^0 \rightarrow \phi f_0) \times \mathcal{B}(f_0 \rightarrow \pi\pi) < 5.7{\times}10^{-7}$, and $\mathcal{B}(B^0 \rightarrow f_0 f_0) \times \mathcal{B}(f_0 \rightarrow \pi\pi) \times \mathcal{B}(f_0 \rightarrow KK) < 6.9{\times}10^{-7}$ at 90% C.L.

In summary we have performed searches for the decays $B^0 \rightarrow \phi\phi$, $\phi\rho^0$, ϕf_0, $f_0 f_0$, and $B^\pm \rightarrow \phi\rho^\pm$. Since we find no evidence for a signal, we report upper limits on these modes. The upper limit on the $B^0 \rightarrow \phi\rho^0$ branching fraction is within the range of predictions of the SM. This upper limit can be used to constrain possible NP contributions to $b \rightarrow d$ loop processes. The upper limit on $B^0 \rightarrow \phi\phi$ reported here can be used to constrain possible NP enhancements suggested in Ref. [2].

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