RAPID COMMUNICATIONS

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Searches for B^0 decays to ηK^0, $\eta\eta$, $\eta'\eta'$, $\eta\phi$, and $\eta'\phi$

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We search for B^0 meson decays into two-body combinations of K^0, η, η', and ϕ mesons in 324×10^6 $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. We measure the following branching fractions (upper limits at 90% confidence level) in units of 10^{-6}: $\mathcal{B}(B^0 \rightarrow \eta K^0) = 1.8^{+0.7}_{-0.6} \pm 0.1(<2.9)$, $\mathcal{B}(B^0 \rightarrow \eta\eta) = 1.1^{+0.5}_{-0.4} \pm 0.1(<1.8)$, $\mathcal{B}(B^0 \rightarrow \eta\phi) = 0.1 \pm 0.2 \pm 0.1(<0.6)$, $\mathcal{B}(B^0 \rightarrow \eta'\phi) = 0.2^{+0.4}_{-0.3} \pm 0.1(<1.0)$, and $\mathcal{B}(B^0 \rightarrow \eta'\eta') = 1.0^{+0.8}_{-0.6} \pm 0.1(<2.4)$, where the first error is statistical and the second systematic.

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We report the results of searches for B^0 or $\bar{B}^0$ meson decays to two charmless pseudoscalar mesons [1] ηK^0, $\eta\eta$, $\eta'\eta'$, and to the pseudoscalar-vector combinations $\eta\phi$, $\eta'\phi$. None of these decays has been observed previously; the published experimental upper limits on their branching fractions lie in the range (2–10) $\times 10^{-6}$ [2,3]. The theoretical predictions for these branching fractions are less than a few per million by most estimates [4–10]. Theoretical approaches include those based on flavor SU(3) relations [4–6], effective Hamiltonians with factorization and specific B-to-light-meson form factors [7], perturbative QCD [8], QCD factorization [9], and soft collinear effective theory (SCET) [10]. Important advances in the theoretical understanding of hadronic charmless two-body B meson decays have occurred in the past few years [11]. With more precise experimental results one can test and constrain the models. Improved measurements of decays with isoscalar mesons can also help to better understand the large difference between the branching fractions for $B \rightarrow \eta' K$ and $B \rightarrow \eta K$ decays [11,12].

Branching fractions or limits in the $\eta\eta$, $\eta'\eta'$, $\eta\phi$, and $\eta'\phi$ channels are relevant for the accuracy with which CP-violating asymmetry measurements can be interpreted. The coefficient S of the CP-violating sinusoidal factor in the time evolution of $\eta' K^0$ and ϕK^0 can be related to the CKM phase $\beta = \arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ if these decays are dominated by a single weak phase [13]. Additional higher-order amplitudes with different weak phases would lead to deviations ΔS between the value measured in these rare modes and the precise determination in the more copious B^0 decays to charmonium-K^0 final states. SU(3) flavor symmetry [14,15] relates the strength of such additional amplitudes to the decay rates of certain two-body B^0 decays, including $\eta\eta$, $\eta'\eta'$, $\eta\phi$, and $\eta'\phi$.

The results presented here are based on data collected with the *BABAR* detector [16] at the PEP-II asymmetric-energy e^+e^- collider located at the Stanford Linear Accelerator Center. An integrated luminosity of 289 fb^{-1}, corresponding to $N_{B\bar{B}} = 324$ million $B\bar{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV).

Charged particles produced in e^+e^- interactions are detected, and their momenta measured, by a combination of a vertex tracker, consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter. Further charged-particle identification is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region.

We select η, η', ϕ, ρ^0, K^0_S, and π^0 candidates through the decays $\eta \rightarrow \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \rightarrow \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$), $\eta' \rightarrow \eta\pi^+\pi^-$ with $\eta \rightarrow \gamma\gamma$ ($\eta'_{\eta\pi\pi}$), $\eta' \rightarrow \rho^0\gamma$ ($\eta'_{\rho\gamma}$), $\phi \rightarrow K^+K^-$, $\rho^0 \rightarrow \pi^+\pi^-$, $K^0_S \rightarrow \pi^+\pi^-$, and $\pi^0 \rightarrow \gamma\gamma$. The photon energy E_γ must be greater than 30 (100) MeV for π^0 (prompt η from B) candidates, greater than 200 MeV in $\eta' \rightarrow \rho\gamma$, and greater than 50 (100) MeV in $\eta'_{\eta\pi\pi}$ (in the $B \rightarrow \eta'_{\eta\pi\pi}\eta'_{\eta\pi\pi}$ decay mode). We make the following requirements on the invariant masses (in MeV$/c^2$): $490 < m_{\gamma\gamma} < 600$ for $\eta_{\gamma\gamma}$, $120 < m_{\gamma\gamma} < 150$ for π^0, $510 < m_{\pi\pi} < 1000$ for ρ^0, $520 < m_{\pi\pi\pi} < 570$ for $\eta_{3\pi}$, $930 < m_{\eta\pi\pi} < 990$ for $\eta'_{\eta\pi\pi}$, $910 < m_{\rho\gamma} < 1000$ for $\eta'_{\rho\gamma}$, $1005 < m_{K^+K^-} < 1035$ for ϕ, and $486 < m_{\pi\pi} < 510$ for K^0_S. For K^0_S candidates we also require a vertex χ^2 probability larger than 0.001 and a reconstructed decay length greater than 3 times its uncertainty. Secondary charged pions in η and η' candidates are rejected, if their DIRC and dE/dx signatures are consistent with protons, electrons, or kaons. Similarly, tracks from ϕ decays are required to be inconsistent with protons, electrons, and pions.

We reconstruct the B meson candidate by combining the four-momenta of the final state particles imposing a vertex constraint. We also constrain the η, η', and π^0 masses to world average values [13]. A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = [(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2]^{1/2}$ and energy difference $\Delta E = E^*_B - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame.

Backgrounds arise primarily from random combinations of tracks and neutral clusters in $e^+e^- \rightarrow q\bar{q}$ continuum events, where $q = u$, d, s or c. We reject these events by using the angle $\theta_{\rm T}$ between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and that of the rest of the event. The thrust axis of the B candidate is obtained as the thrust axis of the B decay products. The distribution of $|\cos\theta_{\rm T}|$ is sharply peaked near 1.0 for combinations drawn from jetlike $q\bar{q}$ pairs, and is nearly uniform for $\Upsilon(4S) \to B\bar{B}$ events. We require $|\cos\theta_{\rm T}| < 0.9$. To discriminate against τ-pair and two-photon backgrounds we require the event to contain at least three tracks or one track more than the topology of our final state, whichever is larger. In decays containing a prompt $\eta_{\gamma\gamma}$ from B we require $|\mathcal{H}_\eta| < 0.9$ to remove random combinations with soft photons, where $\mathcal{H}_\eta$ is defined below. If an event has multiple B candidates, we select the candidate with the highest B vertex χ^2 probability or using a χ^2 quantity computed with the η or η' masses, depending on the decay mode. More details on the analysis technique can be found in Ref. [17].

We obtain yields from unbinned extended maximum-likelihood (ML) fits. The principal input observables are ΔE, $m_{\rm ES}$, and a Fisher discriminant $\mathcal{F}$ [18]. Where relevant, the invariant masses $m_{\rm res}$ of the intermediate resonances and angular variables $\mathcal{H}$ defined below are used. The Fisher discriminant $\mathcal{F}$ combines four variables: the angles with respect to the beam axis of the B momentum and B thrust axis (in the $\Upsilon(4S)$ frame), and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B^0 thrust axis. The moments are defined by $L_j = \sum_i p_i \times |\cos\theta_i|^j$, where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes the B candidate. For $\eta_{\gamma\gamma}$ (ϕ), $\mathcal{H}_\eta$ ($\mathcal{H}_\phi$) is defined as the cosine of the angle between the direction of a daughter γ (K) and the flight direction of the parent of η (ϕ) in the η (ϕ) rest frame; for $\eta'_{\rho\gamma}$, $\mathcal{H}_\rho$ is the cosine of the angle between the direction of a ρ daughter and the flight direction of the η' in the ρ rest frame. The set of probability density functions (PDF) used in ML fits, specific to each decay mode, is determined on the basis of studies with Monte Carlo (MC) simulated samples [19]. We estimate $B\bar{B}$ backgrounds using MC samples of B decays. The estimated $B\bar{B}$ background is found to be negligible for all of our decay modes except $\eta_{\gamma\gamma}K^0_S$ and $\eta_{\gamma\gamma}\phi$.

The extended likelihood function is

$$\mathcal{L} = \exp\left(-\sum_{j=1}^{3} n_j\right)\prod_{i=1}^{N}\left[\sum_{j=1}^{3} n_j \mathcal{P}_j(\mathbf{x}_i)\right], \tag{1}$$

where N is the number of input events, n_j is the number of events for hypothesis j ($j = 1$ for signal, $j = 2$ for continuum background, and $j = 3$ for $B\bar{B}$ background), and $\mathcal{P}_j(\mathbf{x}_i)$ is the corresponding PDF evaluated with the observables $\mathbf{x}_i$ of the ith event. The $B\bar{B}$ background component is used in the decay modes $\eta_{\gamma\gamma}K^0_S$ and $\eta_{\gamma\gamma}\phi$. Since the correlations among the observables in the data are small, we take each $\mathcal{P}_j$ as the product of the PDFs for the separate variables. We determine the PDF parameters from simulation for the signal and from sideband data ($5.25 < m_{\rm ES} < 5.27$ GeV$/c^2$; $0.1 < |\Delta E| < 0.2$ GeV) for continuum background. We float some of the continuum PDF parameters in the ML fit. We parameterize each of the functions $\mathcal{P}_1(m_{\rm ES})$, $\mathcal{P}_1(\Delta E)$, $\mathcal{P}_j(\mathcal{F})$, and the peaking components of $\mathcal{P}_j(m_{\rm res})$ with either a Gaussian, the sum of two Gaussians, or a Crystal Ball function [20] as required to describe the distribution. Slowly varying distributions ($m_{\rm res}$ and ΔE for combinatorial background, and angular variables) are represented by linear or quadratic functions. The combinatorial background in $m_{\rm ES}$ is described by the ARGUS function [21]. Large data control samples of B decays to charmed final states of similar topology are used to verify the simulated resolutions in $m_{\rm ES}$ and ΔE. Where the control samples reveal differences between data and MC in mass or energy resolution, we shift or scale the resolution used in the likelihood fits. The bias in the fit is determined from a large set of simulated experiments, each one with the same number of $q\bar{q}$ and signal events as in data.

Table I shows the measured yields, efficiencies, and products of daughter branching fractions for each decay mode. The efficiency is calculated as the ratio of the numbers of signal MC events after the cut based selection to the total generated. We compute the branching fractions from the fitted signal event yields, reconstruction efficiency, daughter branching fractions, and the number of produced B mesons, assuming equal production rates of charged and neutral B pairs at $\Upsilon(4S)$. We correct the yield for any bias measured with the simulations. We combine results from different channels by adding the values of $-2\ln\mathcal{L}$ (parameterized in terms of the branching fraction), taking into account the correlated and uncorrelated systematic errors. We report the statistical significance and the branching fractions for the individual decay channels. For the combined measurements we also report the 90% confidence level (CL) upper limits.

The statistical error on the signal yield is taken as the change in the central value when the quantity $-2\ln\mathcal{L}$ increases by one unit from its minimum value. The significance is taken as the square root of the difference between the value of $-2\ln\mathcal{L}$ (with systematic uncertainties included) for zero signal and the value at its minimum. We determine a Bayesian 90% CL upper limit assuming a uniform prior probability distribution by finding the branching fraction below which lies 90% of the total of the likelihood integral in the positive branching fraction region.

Figure 1 shows, for representative fits, the projections onto $m_{\rm ES}$ and ΔE for the five decay modes. The points show the data after a channel-dependent requirement on the probability ratio $\mathcal{P}_1/(\mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3)$, optimized to enhance the signal sensitivity and with the probabilities $\mathcal{P}_{\rm j}$ evaluated without using the variable plotted. The solid curves show the total rescaled fit functions.

The main sources of systematic error include uncertainties in the PDF parameterization (0–2 events) and ML fit bias (0–2 events). We evaluate these uncertainties with simulated experiments by varying the PDF parameters

TABLE I. Fitted signal event yield, fit bias, detection efficiency ϵ, daughter branching fraction product $\prod \mathcal{B}_i$, significance $\mathcal{S}$, and measured branching fraction $\mathcal{B}$ with statistical error for each decay mode. For the combined measurements we give the significance (with systematic uncertainties included) and the branching fraction with statistical and systematic uncertainty (in parentheses the 90% CL upper limit).

Mode	Yield (ev)	Fit bias (ev)	ϵ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{S}$ (σ)	$\mathcal{B}(10^{-6})$	
$\eta_{\gamma\gamma}K^0$	19^{+10}_{-9}	$+0.8 \pm 0.6$	26.7 ± 0.9	13.5	2.6	$1.5^{+0.9}_{-0.8}$	
$\eta_{3\pi}K^0$	11^{+6}_{-5}	$+1.1 \pm 0.4$	17.3 ± 0.6	7.8	2.7	$2.4^{+1.4}_{-1.1}$	
$\boldsymbol{\eta K^0}$					**3.5**	$\mathbf{1.8^{+0.7}_{-0.6} \pm 0.1}$	$(<\mathbf{2.9})$
$\eta_{\gamma\gamma}\eta_{\gamma\gamma}$	17^{+10}_{-9}	$+3.9 \pm 0.6$	20.8 ± 1.3	15.5	1.9	$1.3^{+1.0}_{-0.9}$	
$\eta_{\gamma\gamma}\eta_{3\pi}$	10^{+7}_{-5}	$+0.5 \pm 0.4$	18.3 ± 1.2	17.9	2.1	$0.9^{+0.6}_{-0.5}$	
$\eta_{3\pi}\eta_{3\pi}$	2^{+3}_{-2}	$+0.3 \pm 0.4$	11.6 ± 0.8	5.1	1.1	$1.1^{+1.6}_{-1.0}$	
$\boldsymbol{\eta\eta}$					**3.0**	$\mathbf{1.1^{+0.5}_{-0.4} \pm 0.1}$	$(<\mathbf{1.8})$
$\eta_{\gamma\gamma}\phi$	-11^{+7}_{-5}	-2.4 ± 0.6	32.3 ± 1.2	19.4	0.0	$-0.4^{+0.3}_{-0.2}$	
$\eta_{3\pi}\phi$	6^{+5}_{-4}	$+0.8 \pm 0.3$	20.7 ± 1.0	11.1	1.5	$0.7^{+0.7}_{-0.5}$	
$\boldsymbol{\eta\phi}$					0.0	$\mathbf{0.1 \pm 0.2 \pm 0.1}$	$(<\mathbf{0.6})$
$\eta'_{\eta\pi\pi}\phi$	1^{+3}_{-2}	-0.6 ± 0.3	23.1 ± 1.1	8.6	0.7	$0.3^{+0.5}_{-0.3}$	
$\eta'_{\rho\gamma}\phi$	-3^{+9}_{-8}	-1.0 ± 0.4	22.5 ± 0.9	14.5	0.0	$-0.2^{+0.9}_{-0.7}$	
$\boldsymbol{\eta'\phi}$					**0.5**	$\mathbf{0.2^{+0.4}_{-0.3} \pm 0.1}$	$(<\mathbf{1.0})$
$\eta'_{\eta\pi\pi}\eta'_{\eta\pi\pi}$	1^{+2}_{-1}	$+0.3 \pm 0.2$	15.2 ± 1.0	3.1	1.2	$0.8^{+1.3}_{-0.7}$	
$\eta'_{\eta\pi\pi}\eta'_{\rho\gamma}$	9^{+7}_{-5}	$+1.5 \pm 0.3$	17.6 ± 0.8	10.3	1.5	$1.2^{+1.1}_{-0.9}$	
$\boldsymbol{\eta'\eta'}$					**1.8**	$\mathbf{1.0^{+0.8}_{-0.6} \pm 0.1}$	$(<\mathbf{2.4})$

within their errors and by embedding MC signal events inside background distributions simulated from PDFs. The uncertainty on $N_{B\bar{B}}$ is 1.1%. Published world averages [13] provide the uncertainties in the B-daughter branching fractions (1–7%). Other sources of systematic uncertainty are track (1–3%) and neutral cluster (2–6%) reconstruction efficiencies. The validity of the fit procedure and PDF parameterization, including the effects of unmodeled correlations among observables, is checked with simulated experiments.

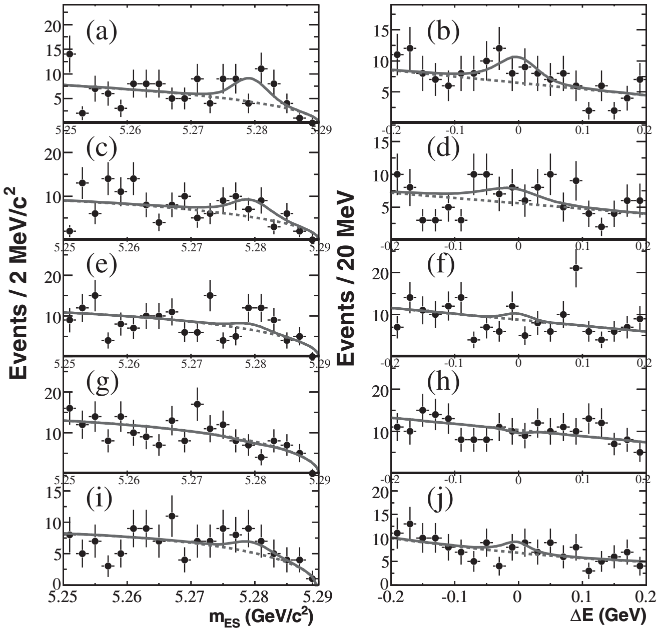

FIG. 1. Signal enhanced projections on $m_{\rm ES}$ (left) and ΔE (right) in the decays: (a, b) ηK^0_S, (c, d) $\eta\eta$, (e, f) $\eta\phi$, (g, h) $\eta'\phi$, (i, j) $\eta'\eta'$. Points with error bars (statistical only) represent the data (combined measurements), the solid line the full fit function, and the dashed line its background component.

Grossman *et al.* [14] introduced a method to determine a bound on $|\Delta S_f| \equiv |S_f - \sin 2\beta|$ where f is a CP eigenstate produced in charmless B^0 decays and S is the coefficient of the CP-violating sinusoidal factor mentioned above. The method relies on SU(3) flavor symmetry and the measured branching fractions of charmless, strangeness-conserving B^0 decays to constrain the unknown contributions of suppressed amplitudes in $B^0 \to f$. Two of the channels in our study, $\eta\eta$ and $\eta'\eta'$, are relevant to the ΔS_f bound for $f = \eta' K^0$, while two others, $\eta\phi$ and $\eta'\phi$, are relevant for $f = \phi K^0$. Using the technique described in Ref. [22] and evaluating 90% CL upper limits, we find $|\Delta S_{\eta' K^0}| < 0.15$ and $|\Delta S_{\phi K^0}| < 0.38$. This new $\Delta S_{\eta'} K^0$ bound also makes use of our recent results [23] on the $B^0 \to \eta'\eta$, $\eta'\pi^0$, and $\eta\pi^0$ channels.

In summary, we present updated measurements of branching fractions for five B^0 decays to charmless meson pairs. Our results represent substantial improvements on the previous upper limits [2,3].

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[1] The charge conjugate of the named state is implicitly included here and throughout this paper.

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