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We search for B meson decays into two-body combinations of η, η', ω, and ϕ mesons from 89×10^6 $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. We find the branching fraction $\mathcal{B}(B^0 \to \eta\omega) = (4.0^{+1.3}_{-1.2} \pm 0.4) \times 10^{-6}$ with a significance of 4.3σ. For the other decay modes we set the following 90% confidence level upper limits on the branching fractions, in units of 10^{-6}: $\mathcal{B}(B^0 \to \eta\eta) < 2.8$, $\mathcal{B}(B^0 \to \eta\eta') < 4.6$, $\mathcal{B}(B^0 \to \eta'\eta') < 10$, $\mathcal{B}(B^0 \to \eta'\omega) < 2.8$, $\mathcal{B}(B^0 \to \eta\phi) < 1.0$, $\mathcal{B}(B^0 \to \eta'\phi) < 4.5$, and $\mathcal{B}(B^0 \to \phi\phi) < 1.5$.

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We report the results of searches for B^0 meson decays to two charmless pseudoscalar mesons $\eta\eta$, $\eta\eta'$, $\eta'\eta'$, to the pseudoscalar-vector combinations $\eta\omega$, $\eta'\omega$, $\eta\phi$, $\eta'\phi$, and to the vector-meson pair $\phi\phi$. These, together with $\omega\omega$ and $\omega\phi$, constitute all combinations involving isospin singlet members of the ground state pseudoscalar and vector-meson nonets. These decay modes have not been observed previously; the published experimental upper limits on their branching fractions lie in the range $(9\text{–}60) \times 10^{-6}$ [1].

The all-neutral-meson final states studied here are described theoretically by suppressed amplitudes, with predicted branching fractions less than a few per million by most estimates [2–9]. By bringing the experimental sensitivity down to this level we can test and constrain the models. In particular, these branching fractions or limits bear on the accuracy with which *CP*-violating asymmetry measurements can be interpreted.

Theoretical approaches include those based on flavor SU(3) relations among many modes [2–4], effective Hamiltonians with factorization and specific B-to-light-meson form factors [5], perturbative QCD [6], and QCD factorization [7]. The decays to combinations of $\eta^{(\prime)}$ and ω involve color-suppressed tree, Cabibbo-Kobayashi-Maskawa (CKM)-suppressed penguin, and flavor-singlet penguin amplitudes, while only the last of these contributes to those with a single ϕ meson. The $B^0 \to \phi\phi$ decay is a pure penguin annihilation process with an expected branching fraction of order 10^{-9} in the standard model [8]; this mode would therefore be particularly sensitive to physics beyond the standard model.

In the time evolution of $B^0 \to \eta' K_S^0$ and $B^0 \to \phi K_S^0$, a sinusoidal term arises from interference between decays with and without mixing. The coefficient S of this term is related to the CKM phase $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ if these decays are dominated by the single amplitude expected in the standard model. 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 charmonium K_S^0 decays. Flavor SU(3) [3,9] relates the strength of such additional amplitudes to the decay rates of two-body B^0 decays to final states containing π^0, η, and η'. The $\eta^{(\prime)}$ combinations reported here provide the strongest constraints.

The results presented here are based on data collected with the *BABAR* detector [10] at the PEP-II asymmetric e^+e^- collider [11] located at the Stanford Linear Accelerator Center. An integrated luminosity of $81.9\ \text{fb}^{-1}$, corresponding to $N_{B\overline{B}} = 88.9 \pm 1.0$ million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). A $9.6\ \text{fb}^{-1}$ off-resonance data sample, with a center-of-mass energy 40 MeV below the $\Upsilon(4S)$ resonance, is used to study background contributions resulting from $e^+e^- \to q\bar{q}$ ($q = u$, d, s, or c) continuum events.

Charged particles from 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.

The event selection criteria have been established with studies of off-resonance data and simulated Monte Carlo (MC) [12] events of the target decay modes, $B\overline{B}$, and continuum. We select η, η', ω, and ϕ candidates through the decays $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$), $\eta' \to \eta\pi^+\pi^-$ with $\eta \to \gamma\gamma$ ($\eta'_{\eta\pi\pi}$), $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$), $\omega \to \pi^+\pi^-\pi^0$, and $\phi \to K^+K^-$. The photon energy E_γ must be greater than 50 MeV for π^0 and η candidates, and greater than 200 MeV in $\eta' \to \rho\gamma$. We make the following requirements on the invariant mass (in MeV): $490 < m_{\gamma\gamma} < 600$ for $\eta_{\gamma\gamma}$, $120 < m_{\gamma\gamma} < 150$ for π^0, $510 < m_{\pi\pi} < 1070$ for ρ^0, $520 < m_{\pi\pi\pi} < 570$ for $\eta_{3\pi}$, $910 < (m_{\eta\pi\pi}, m_{\rho\gamma}) < 1000$ for η', $735 < m_{\pi\pi\pi} < 825$ for ω, and $1009 < m_{K^+K^-} < 1029$ for ϕ. We make requirements on DIRC measurements and dE/dx to identify pions and kaons. Secondary tracks in $\eta_{3\pi}$, η', and ω candidates must be identified as pions, and in ϕ candidates as kaons.

A B-meson candidate is characterized kinematically by the energy-substituted mass $\text{m}_{\text{ES}} = [(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2]^{\frac{1}{2}}$ 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 track combinations in $e^+e^- \to q\bar{q}$ events. We reject these by using the angle θ_{T} between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and that of the rest of the event. The distribution of $|\cos\theta_{\text{T}}|$ is sharply peaked near 1.0 for combinations drawn from jetlike $q\bar{q}$ pairs, and is nearly uniform for $\Upsilon(4S) \to B\overline{B}$ events. We require $|\cos\theta_{\text{T}}| < 0.9$. To discriminate against τ-pair and two-photon backgrounds we require the event to contain at least the number of charged tracks in the decay mode plus one. For $\eta_{\gamma\gamma}\eta_{\gamma\gamma}$ we require at least three charged tracks in the event.

The decay mode $B^0 \to \phi\phi$ is very clean. Resolutions on $m_{\rm ES}$ and ΔE are 3.0 MeV and 13.1 MeV, respectively. We define the signal region with cuts of $\pm 3\sigma$ in ΔE and $\pm 4\sigma$ in $m_{\rm ES}$. The number of $B^0 \to \phi\phi$ candidates in this signal region is $4.0^{+3.2}_{-1.9}$. The only source of background is the continuum, estimated with on-resonance data sidebands to contribute 2.7 ± 0.4 events.

We obtain yields in all other decay modes from unbinned extended maximum-likelihood (ML) fits. The principal input observables are ΔE and $m_{\rm ES}$. Where relevant, the invariant masses $m_{\rm res}$ of the intermediate resonances, a Fisher discriminant $\mathcal{F}$ [13], and angular variables $\mathcal{H}$ are used. For $\eta_{\gamma\gamma}$, $\mathcal{H}_\eta$ is defined as the cosine of the angle between the direction of a daughter γ and the flight direction of the η relative to its parent in the η 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; for ω, $\mathcal{H}_\omega$ is the cosine of the angle in the ω rest frame between the normal to the ω decay plane and the B^0 flight direction. The Fisher discriminant $\mathcal{F}$ combines four variables: the angles with respect to the beam axis of the B momentum

TABLE I. Signal yield (before fit bias correction), detection efficiency ϵ, daughter branching fraction product, significance (including systematic errors), measured branching fraction $\mathcal{B}$, and 90% C.L. upper limits (UL) from this and previous work.

Mode	Yield	ϵ (%)	$\prod \mathcal{B}_i$ (%)	S(σ)	$\mathcal{B}(10^{-6})$	This UL (10^{-6})	Previous UL (10^{-6}) [1]
$\eta_{\gamma\gamma}\eta_{\gamma\gamma}$	$-7.5^{+6.9}_{-5.9}$	21.6	15.5	0.0	$-2.4^{+2.3}_{-2.0}$		
$\eta_{\gamma\gamma}\eta_{3\pi}$	$0.6^{+6.8}_{-5.8}$	16.9	17.9	0.1	$0.4^{+2.5}_{-2.2}$		
$\eta_{3\pi}\eta_{3\pi}$	$-0.1^{+3.5}_{-2.3}$	12.3	5.1	0.0	$-0.4^{+6.2}_{-4.2}$		
$\eta\eta$				0.0	$-0.9^{+1.6}_{-1.4} \pm 0.7$	<2.8	<18
$\eta_{\gamma\gamma}\eta'_{\eta\pi\pi}$	$-7.1^{+3.7}_{-2.5}$	21.5	6.9	0.0	$-2.4^{+2.9}_{-1.8}$		
$\eta_{\gamma\gamma}\eta'_{\rho\gamma}$	$0.6^{+5.9}_{-4.3}$	20.2	11.6	0.2	$0.5^{+3.4}_{-2.4}$		
$\eta_{3\pi}\eta'_{\eta\pi\pi}$	$4.3^{+4.7}_{-3.6}$	13.7	4.0	1.0	$8.0^{+10.0}_{-7.3}$		
$\eta_{3\pi}\eta'_{\rho\gamma}$	$1.9^{+7.7}_{-6.2}$	13.8	6.7	0.3	$2.5^{+9.1}_{-7.3}$		
$\eta\eta'$				0.3	$0.6^{+2.1}_{-1.7} \pm 1.1$	<4.6	<27
$\eta'_{\eta\pi\pi}\eta'_{\eta\pi\pi}$	$0.3^{+2.6}_{-1.5}$	14.1	3.1	0.1	$0.2^{+6.8}_{-4.0}$		
$\eta'_{\eta\pi\pi}\eta'_{\rho\gamma}$	$4.0^{+7.3}_{-6.2}$	12.7	10.2	0.6	$3.2^{+6.4}_{-5.5}$		
$\eta'\eta'$				0.4	$1.7^{+4.8}_{-3.7} \pm 0.6$	<10	<47
$\eta_{\gamma\gamma}\omega$	$24.2^{+8.2}_{-7.1}$	18.1	35.1	5.1	$4.4^{+1.5}_{-1.3}$		
$\eta_{3\pi}\omega$	$2.2^{+9.4}_{-8.2}$	12.9	20.1	0.3	$0.9^{+4.1}_{-3.6}$		
$\eta\omega$				4.3	$4.0^{+1.3}_{-1.2} \pm 0.4$	<6.2	<12
$\eta'_{\eta\pi\pi}\omega$	$-3.9^{+4.9}_{-3.4}$	14.5	15.6	0.0	$-1.8^{+2.5}_{-1.7}$		
$\eta'_{\rho\gamma}\omega$	$1.1^{+6.1}_{-4.0}$	13.5	26.3	0.2	$0.4^{+1.9}_{-1.3}$		
$\eta'\omega$				0.0	$-0.2^{+1.3}_{-0.9} \pm 0.4$	<2.8	<60
$\eta_{\gamma\gamma}\phi$	$-10.1^{+5.0}_{-3.9}$	29.7	19.4	0.0	$-2.0^{+1.0}_{-0.7}$		
$\eta_{3\pi}\phi$	$-2.0^{+2.9}_{-1.6}$	20.9	11.1	0.0	$-0.9^{+1.4}_{-0.8}$		
$\eta\phi$				0.0	$-1.4^{+0.7}_{-0.4} \pm 0.2$	<1.0	<9
$\eta'_{\eta\pi\pi}\phi$	$0.5^{+4.0}_{-3.0}$	23.2	8.6	0.1	$0.3^{+2.2}_{-1.7}$		
$\eta'_{\rho\gamma}\phi$	$8.0^{+8.1}_{-6.9}$	22.0	14.5	1.2	$2.8^{+2.9}_{-2.4}$		
$\eta'\phi$				0.8	$1.5^{+1.8}_{-1.5} \pm 0.4$	<4.5	<31
$\phi\phi$	$1.3^{+3.2}_{-1.9}$	19.9	24.2	0.3	$0.3^{+0.7}_{-0.4} \pm 0.1$	<1.5	<12

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. Further cuts on discriminating variables and the set of probability density functions (PDF) used in ML fits, specific to each decay mode, are determined on the basis of studies with MC samples. For $\eta_{\gamma\gamma}\eta'_{\rho\gamma}$, the requirement $|\mathcal{H}_\eta| < 0.86$ is used to reduce significantly the background from the decay $B^0 \to K^*\gamma$. In other decays containing $\eta_{\gamma\gamma}$, we require $|\mathcal{H}_\eta| < 0.9$ to remove random combinations with soft photons. In $\eta_{\gamma\gamma}\omega$, we apply a cut on the maximum γ energy in the center-of mass system (< 2.4 GeV) to suppress cross-feed from other $B\bar{B}$ decays with energetic photons, and a π^0 veto to suppress potential cross feed from $\omega\pi^0$.

We estimate $B\bar{B}$ backgrounds using simulated samples of B decays. The branching fractions in the simulation are based on measured values or theoretical predictions. The estimated $B\bar{B}$ background is negligible.

For each event i and hypothesis j ($j = 1$ signal or $j = 2$ continuum background), the likelihood function is

$$\mathcal{L} = \frac{e^{-(\sum n_j)}}{N!}\prod_{i=1}^{N}\left[\sum_{j=1}^{2} n_j \mathcal{P}_j(\mathbf{x}_i)\right], \qquad (1)$$

where N is the number of input events, n_j is the number of events for hypothesis j, and $\mathcal{P}_j(\mathbf{x}_i)$ the corresponding PDF, evaluated with the observables $\mathbf{x}_i$ of the ith event. Since the correlations among the observables in the data are small, we take each $\mathcal{P}$ as the product of the PDFs for the separate variables. We determine the PDF parameters from simulation for the signal and from sideband data ($5.20 < \mathrm{m_{ES}} < 5.27$ GeV; $0.1 < |\Delta E| < 0.2$ GeV) for continuum background. We float some of the continuum PDF parameters in the maximum-likelihood fit. We parameterize each of the functions $\mathcal{P}_{\rm sig}(\mathrm{m_{ES}})$, $\mathcal{P}_{\rm sig}(\Delta E)$, $\mathcal{P}_j(\mathcal{F})$, and the peaking components of $\mathcal{P}_j(m_{\rm res})$ with either a Gaussian, the sum of two Gaussian distributions, or an asymmetric Gaussian function as required to describe the distribution. Slowly varying distributions (mass, energy for combinatoric background and angular variables) are represented by linear or quadratic dependencies. The combinatoric background in $m_{\rm ES}$ is described by the ARGUS function $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$, with $x \equiv 2\mathrm{m_{ES}}/\sqrt{s}$ and parameter ξ [14]. Large control samples of B decays to charmed final states of similar topology are used to verify the simulated resolutions in ΔE and $m_{\rm ES}$. Where the control data samples reveal differences from 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. If an event has multiple combinations, we select the best one using a χ^2 quantity computed with η or η' masses. The variable used in the choice is not used in the fit. More details on the analysis technique can be found here [15].

In Table I we show the measured yield, the efficiency, and the product of daughter branching fractions for each decay mode. The efficiency is calculated as the ratio of the numbers of signal MC events entering into the ML fit 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. We correct the yield for any bias measured with the simulations. We combine results from different channels by adding the values of $-2\ln\mathcal{L}$, taking account of the correlated and uncorrelated systematic errors. We report the statistical significance and the branching fractions for the individual decay channels, and for the combined measurements also the 90% C.L. 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. The 90% C.L. upper limit is taken to be the branching fraction below which lies 90% of the total of the likelihood integral in the positive branching fraction region. For the $B^0 \to \phi\phi$ decay mode, the 90% C.L. upper limit is calculated with the Feldman-Cousins method [16].

In Fig. 1, we show projections onto $m_{\rm ES}$ and ΔE in the analysis of the decays $B^0 \to \eta\omega$. The histograms show the data after a cut on the probability ratio $\mathcal{P}_{\rm sig}/(\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg})$, where $\mathcal{P}_{\rm sig}$ and $\mathcal{P}_{\rm bkg}$ are the signal and the continuum background PDFs. The curve represents a projec-

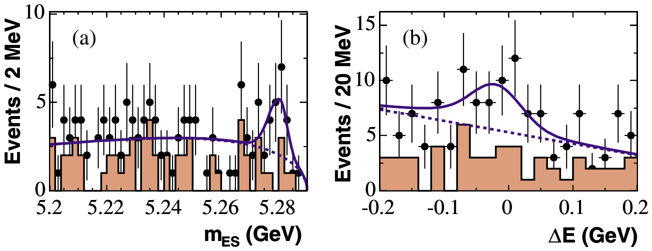

FIG. 1 (color online). Projections of the B^0 candidate $m_{\rm ES}$ and ΔE for $B^0 \to \eta\omega$. Points with errors represent data, shaded histograms the $B^0 \to \eta_{3\pi}\omega$ subset, solid curves the full fit functions, and dashed curves the background functions. These plots are made with cuts on probability ratio and thus do not show all events in data samples.

tion of the PDF obtained from a fit in which the plotted variable was removed.

The main sources of systematic errors include uncertainty in PDF parametrization (1–2 events) and ML fit bias (0.5–2 events). We estimate these errors with simulated experiments by varying PDF parameters within their errors and by embedding MC signal events inside background events simulated from PDFs. The uncertainty on $N_{B\overline{B}}$ is 1.1%. Published data [17] provide the uncertainties in the B-daughter branching fractions (1%–4%). Other sources of systematic errors are track reconstruction efficiency (1%–3%) and neutral reconstruction efficiency (5%–10%). The validity of the fit procedure and PDF parametrization, including the effects of unmodeled correlations among observables, is checked with simulated experiments. The value of the likelihood function found in data is consistent with the likelihood distribution found in simulated experiments.

In the $B^0 \to \phi\phi$ decay mode, the total systematic error is 7.6%, which we obtain by adding in quadrature the errors due to the different selection cuts, branching fractions of daughters, B^0 production, and statistics of the Monte Carlo samples.

In Grossman *et al.* [9], $\Delta S = S - \sin2\beta$ for $B^0 \to \eta' K^0_S$ is proportional (Eq. 10) to the absolute value of a parameter $\xi_{\eta' K_S}$ defined in their Eq. 8. A bound $|\xi_{\eta' K_S}| < 0.36$ is extracted via Eq. 18 from previously measured B^0 branching ratios to two-body combinations of π^0, η, and η'. The present data improve this limit: $|\xi_{\eta' K_S}| < 0.17$.

In conclusion, we have searched for eight B^0 decays to charmless isoscalar meson pairs. We obtain evidence for $B^0 \to \eta\omega$, with a branching fraction $\mathcal{B}(B^0 \to \eta\omega) = (4.0^{+1.3}_{-1.2} \pm 0.4) \times 10^{-6}$ with 4.3σ significance. For the other modes, our results represent substantial improvements on the previous upper limits [1].

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