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Observation of $B^0 \to \omega K^0$, $B^+ \to \eta\pi^+$, and $B^+ \to \eta K^+$ and Study of Related Decays

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We present measurements of branching fractions and charge asymmetries for seven B-meson decays with an η, η' or ω meson in the final state. The data sample corresponds to 89 million $B\overline{B}$ pairs produced from e^+e^- annihilation at the $\Upsilon(4S)$ resonance. We measure the following branching fractions in units of 10^{-6}: $\mathcal{B}(B^+ \to \eta\pi^+) = 5.3\pm1.0\pm0.3$, $\mathcal{B}(B^+ \to \eta K^+) = 3.4\pm0.8\pm0.2$, $\mathcal{B}(B^0 \to \eta K^0) = 2.9\pm1.0\pm0.2$ (< 5.2, 90% C.L.), $\mathcal{B}(B^+ \to \eta'\pi^+) = 2.7\pm1.2\pm0.3$ (< 4.5, 90% C.L.), $\mathcal{B}(B^+ \to \omega\pi^+) = 5.5\pm0.9\pm0.5$, $\mathcal{B}(B^+ \to \omega K^+) = 4.8\pm0.8\pm0.4$, and $\mathcal{B}(B^0 \to \omega K^0) = 5.9^{+1.6}_{-1.3}\pm0.5$. The charge asymmetries are $\mathcal{A}_{ch}(B^+ \to \eta\pi^+) = -0.44 \pm 0.18 \pm 0.01$, $\mathcal{A}_{ch}(B^+ \to \eta K^+) = -0.52 \pm 0.24 \pm 0.01$, $\mathcal{A}_{ch}(B^+ \to \omega\pi^+) = 0.03 \pm 0.16 \pm 0.01$ and $\mathcal{A}_{ch}(B^+ \to \omega K^+) = -0.09 \pm 0.17 \pm 0.01$.

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We report results of measurements of B decays to the charmless final states ηK^0, $\eta\pi^+$, ηK^+, $\eta'\pi^+$, ωK^0, $\omega\pi^+$, and ωK^+ [1]. Only the last two of these decays have been observed previously [2–4]. Measurements of the related $B \to \eta' K$ decays were published recently [5]. Charmless decays with kaons are usually expected to be dominated by $b \to s$ loop ("penguin") amplitudes, while $b \to u$ tree transitions are typically larger for the decays with pions. However the $B \to \eta K$ decays are especially interesting since they are suppressed relative to the abundant $B \to \eta' K$ decays due to destructive interference between two penguin amplitudes [6]. Thus the CKM-suppressed $b \to u$ amplitudes may interfere significantly with the suppressed penguin amplitudes. This tree-penguin interference may lead to large direct CP violation in the ηK^+ decay as well as $\eta\pi^+$, and $\eta'\pi^+$ [7]; numerical estimates have been provided in a few cases [8]. We search for such direct CP violation by measuring the charge asymmetry $\mathcal{A}_{ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ in the rates $\Gamma^\pm = \Gamma(B^\pm \to f^\pm)$, for each observed charged final state $f^\pm$.

Charmless B decays are becoming useful to test the accuracy of theoretical predictions such as QCD factorization [9]. Phenomenological fits to the branching fractions and charge asymmetries can be used to understand the importance of tree and penguin contributions and may even provide sensitivity to the CKM angle γ [10].

The results presented here are based on data collected with the *BABAR* detector [11] at the PEP-II asymmetric e^+e^- collider [12] located at the Stanford Linear Accelerator Center. An integrated luminosity of 81.9 fb^{-1}, corresponding to 88.9 ± 1.0 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV).

Charged particles from the e^+e^- interactions are detected, and their momenta measured, by a combination of a vertex tracker (SVT) 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 (EMC). Further charged particle identification (PID) 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', ω, K^0_S, and π^0 candidates through the decays $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$), $\eta' \to \eta\pi^+\pi^-$ ($\eta'_{\eta\pi\pi}$), $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$), $\omega \to \pi^+\pi^-\pi^0$, $\rho^0 \to \pi^+\pi^-$, $K^0_S \to \pi^+\pi^-$, and $\pi^0 \to \gamma\gamma$. We make the following requirements on the invariant mass (in MeV) of their final states: $490 < m_{\gamma\gamma} < 600$ for $\eta_{\gamma\gamma}$, $520 < m_{\pi\pi\pi} < 570$ for $\eta_{3\pi}$, $910 < (m_{\eta\pi\pi}, m_{\rho\gamma}) < 1000$ for η', $735 < m_{\pi\pi\pi} < 825$ for ω, $510 < m_{\pi\pi} < 1070$ for ρ^0, and $120 < m_{\gamma\gamma} < 150$ for π^0. For K^0_S candidates we require $488 < m_{\pi\pi} < 508$, the three-dimensional flight distance from the event primary vertex to be greater than 2 mm, and the angle between flight and momentum vectors, in the plane perpendicular to the beam direction, to be less than 40 mrad.

We make several PID requirements to ensure the identity of the pions and kaons. Secondary tracks in $\eta_{3\pi}$, η', and ω candidates must have DIRC, dE/dx, and EMC outputs consistent with pions. For the B^+ decays to an η or ω meson and a charged pion or kaon, the latter (primary) track must have an associated DIRC signal with a Cherenkov angle within 3.5 standard deviations (σ) of the expected value for either a π or K hypothesis.

A B-meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = [(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2]^{\frac{1}{2}}$ 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 $\Upsilon(4S)$ frame. The resolution on ΔE ($m_{\rm ES}$) is about 30 MeV (3.0 MeV). We require $|\Delta E| \le 0.2$ GeV and $5.2 \le m_{\rm ES} \le 5.29$ GeV.

Backgrounds arise primarily from random combinations in $e^+e^- \to q\overline{q}$ events. We reject these 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 charged tracks and neutral clusters in the event. The distribution of $|\cos\theta_{\rm T}|$ is sharply peaked near 1.0 for combinations drawn from jet-like $q\overline{q}$ pairs, and nearly uniform for B-meson decays. We require $|\cos\theta_{\rm T}| < 0.9$, for all modes except the high-background $B^+ \to \eta'_{\rho\gamma}\pi^+$ decay, where we determine that the sensitivity is maximal for a 0.65 requirement. We also use, in the fit described below, a Fisher discriminant $\mathcal{F}$ that 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 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 the $\eta \to \gamma\gamma$ modes we use additional event-selection criteria to reduce $B\overline{B}$ backgrounds from several charmless final states. We reduce background from $B \to \pi^+\pi^0$, $K^+\pi^0$, and $K^0\pi^0$ by rejecting $\eta_{\gamma\gamma}$ candidates that share a photon with any π^0 candidate having momentum between 1.9 and 3.1 GeV/c in the $\Upsilon(4S)$ frame. Additionally, we require $E_\gamma < 2.4$ GeV to suppress background from $B \to K^*\gamma$ and related radiative-penguin decays. From Monte Carlo (MC) simulation [13] we estimate that the residual charmless $B\overline{B}$ background is negligible for all decays except those with $\eta \to \gamma\gamma$ and $\eta' \to \rho^0\gamma$, where we include in the fit described below a $B\overline{B}$ component (which is less than 0.5% of the total sample in all cases).

We obtain yields and $\mathcal{A}_{ch}$ from extended unbinned maximum-likelihood fits, with input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, $m_{\rm res}$ (the mass of the η, η', or ω candidate), for the ω decays, $\mathcal{H} \equiv |\cos\theta_H|$, and for charged modes the PID variable $S_{\pi,K}$. The helicity angle θ_H is defined as the angle, measured in the ω rest frame, between the normal to the ω decay plane and the flight direction of the ω. We incorporate PID information by using S_π (S_K), the number of standard deviations between the measured Cherenkov angle and the expectation for pions (kaons).

For each event i, hypothesis j (signal, continuum background, $B\overline{B}$ background), and flavor (primary π^+ or K^+) k, we define the probability density function (PDF)

$$\begin{aligned}\mathcal{P}^i_{jk} \;=\; & \mathcal{P}_j({m_{\rm ES}}^i)\mathcal{P}_j(\Delta E^i_k)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(m^i_{\rm res}) \\ & \times \left[\mathcal{P}_j(S^i_k)\right]\left[\mathcal{P}_j(\mathcal{H}^i)\right]. \end{aligned} \quad (1)$$

The terms in brackets for S and $\mathcal{H}$ pertain to modes with charged track or ω daughters, respectively. The absence of correlations among observables in the background $\mathcal{P}^i_{jk}$ is confirmed in the (background-dominated) data samples entering the fit. For the signal component, we correct for the effect of the neglect of small correlations (see below). The likelihood function is

$$\mathcal{L} = \exp\,(-\sum_{j,k} Y_{jk}) \prod_i^N \left[\sum_{j,k} Y_{jk}\mathcal{P}^i_{jk}\right], \quad (2)$$

where Y_{jk} is the yield of events of hypothesis j and flavor k found by maximizing $\mathcal{L}$, and N is the number of events in the sample.

We determine the PDF parameters from simulation for the signal and $B\overline{B}$ background components, and from $(m_{\rm ES}, \Delta E)$ sideband data for continuum background. We parameterize each of the functions $\mathcal{P}_{\rm sig}(m_{\rm ES})$, $\mathcal{P}_{\rm sig}(\Delta E_k)$, $\mathcal{P}_j(\mathcal{F})$, $\mathcal{P}_j(S_k)$ and the peaking components of $\mathcal{P}_j(m_{\rm res})$ with either a Gaussian, the sum of two Gaussians or an asymmetric Gaussian function as required to describe the distribution. Slowly varying distributions (mass, energy or helicity-angle for combinatoric background) are represented by linear or quadratic dependencies. The peaking and combinatoric components of the ω mass spectrum each have their own $\mathcal{H}$ shapes. The combinatoric background in $m_{\rm ES}$ is described by the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x \equiv 2m_{\rm ES}/\sqrt{s}$ and parameter ξ. 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 offset or resolution, we shift or scale the resolution used in the likelihood fits.

In Table I we show for each decay mode the measured branching fraction, together with the quantities entering into its computation. Typically seven parameters of the background PDF are free in the fit, along with signal and background yields, and for charged modes the signal and background $\mathcal{A}_{ch}$. For calculation of branching fractions, we assume that the decay rates of the $\Upsilon(4S)$ to B^+B^- and $B^0\overline{B}^0$ are equal. For the η and η' decays, we combine results from the two decay channels by adding the values of $-2\ln\mathcal{L}$, taking proper account of the correlated and uncorrelated systematic errors. The estimated purity is the ratio of the signal yield to the effective background plus signal; we estimate the effective background by taking the square of the uncertainty of the signal yield as the sum of effective background plus signal. In Figs. 1 and 2 we show projections onto $m_{\rm ES}$ and ΔE after requiring $S_{\pi,K} \lesssim 2$ [for (a)–(d)] and requiring that the signal likelihood (computed ignoring the PDF associated with the variable plotted) exceeds a mode-dependent threshold.

The statistical error on the signal yield and $\mathcal{A}_{ch}$ 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. For ηK^0 and $\eta'\pi^+$ we quote a 90% confidence level (C.L.) upper limit, 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 charged modes we also give the charge asymmetry $\mathcal{A}_{ch}$.

Most of the yield uncertainties arising from lack of knowledge of the PDFs have been included in the statistical error since most background parameters are free in the fit. Varying the signal PDF parameters within their estimated uncertainties, we estimate the uncertainties in the signal PDFs to be 1–3 events. We verify the validity of the fit procedure and PDF shapes by demonstrating that the likelihood of each fit is consistent with the distribution found in simulation.

Uncertainties in our knowledge of the efficiency, found from auxiliary studies, include $0.8N_t$%, $2.5N_\gamma$%, and 3% for a K^0_S decay, where N_t and N_γ are the number of signal tracks and photons, respectively. Our estimate of the B production systematic error is 1.1%. The neglect

TABLE I: Signal yield, estimated purity P, detection efficiency ϵ, daughter branching fraction product, significance (including systematic uncertainties), measured branching fraction, background ($\mathcal{A}_{ch}^{qq}$) and signal ($\mathcal{A}_{ch}$) charge asymmetries for each mode. For $B^0 \to \eta K^0$ and $B^+ \to \eta'\pi^+$, the 90% C.L. upper limit is also given.

Mode	Yield	P (%)	ϵ (%)	$\prod \mathcal{B}_i$ (%)	Signif.	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{ch}^{qq}$	$\mathcal{A}_{ch}$
$\eta_{3\pi}\pi^+$	28^{+10}_{-9}	30	23	23	4.4	$5.6^{+2.1}_{-1.8}$	-0.004 ± 0.010	-0.52 ± 0.31
$\eta_{\gamma\gamma}\pi^+$	59 ± 14	31	31	39	6.6	5.2 ± 1.3	-0.001 ± 0.011	-0.41 ± 0.22
$\boldsymbol{\eta\pi^+}$					**7.9**	$\mathbf{5.3 \pm 1.0 \pm 0.3}$	-0.003 ± 0.008	$\mathbf{-0.44 \pm 0.18 \pm 0.01}$
$\eta_{3\pi}K^+$	15^{+8}_{-7}	24	23	23	2.6	$3.1^{+1.7}_{-1.5}$	-0.008 ± 0.016	-0.43 ± 0.51
$\eta_{\gamma\gamma}K^+$	38 ± 11	33	23	39	5.3	3.5 ± 1.1	-0.011 ± 0.016	-0.55 ± 0.26
$\boldsymbol{\eta K^+}$					**6.1**	$\mathbf{3.4 \pm 0.8 \pm 0.2}$	-0.010 ± 0.011	$\mathbf{-0.52 \pm 0.24 \pm 0.01}$
$\eta_{3\pi}K^0$	$2.6^{+4.1}_{-3.1}$	20	23	8	0.8	$1.8^{+2.9}_{-2.2}$		
$\eta_{\gamma\gamma}K^0$	$8.6^{+4.8}_{-3.8}$	47	24	14	3.2	$3.2^{+1.8}_{-1.4}$		
$\boldsymbol{\eta K^0}$					**3.3**	$\mathbf{2.9 \pm 1.0 \pm 0.2\ (< 5.2)}$		
$\eta'_{\eta\pi\pi}\pi^+$	17^{+7}_{-6}	38	28	17	3.9	$3.8^{+1.7}_{-1.4}$		
$\eta'_{\rho\gamma}\pi^+$	-4^{+11}_{-9}		17	30		$-0.8^{+2.4}_{-2.0}$		
$\boldsymbol{\eta'\pi^+}$					**3.4**	$\mathbf{2.7 \pm 1.2 \pm 0.3\ (< 4.5)}$		
$\boldsymbol{\omega\pi^+}$	101 ± 17	37	23	89	**9.1**	$\mathbf{5.5 \pm 0.9 \pm 0.5}$	0.012 ± 0.006	$\mathbf{0.03 \pm 0.16 \pm 0.01}$
$\boldsymbol{\omega K^+}$	83 ± 14	39	22	89	**10.0**	$\mathbf{4.8 \pm 0.8 \pm 0.4}$	-0.003 ± 0.009	$\mathbf{-0.09 \pm 0.17 \pm 0.01}$
$\boldsymbol{\omega K^0}$	33^{+9}_{-8}	51	20	31	**7.5**	$\mathbf{5.9^{+1.6}_{-1.3} \pm 0.5}$		

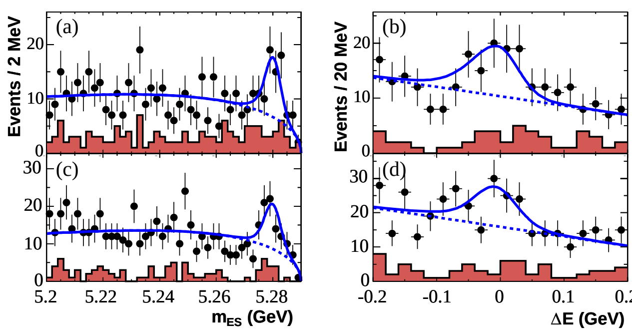

FIG. 1: Projections of the B candidate $m_{\rm ES}$ and ΔE for (a, b) $B^+ \to \eta\pi^+$, and (c, d) $B^+ \to \eta K^+$. Points with errors represent data, shaded histograms the $\eta \to \pi^+\pi^-\pi^0$ subset, solid curves the full fit functions, and dashed curves the background functions (the peaking $B\overline{B}$ background component is negligible). These plots are made with a requirement on the likelihood and thus do not show all events in the data samples.

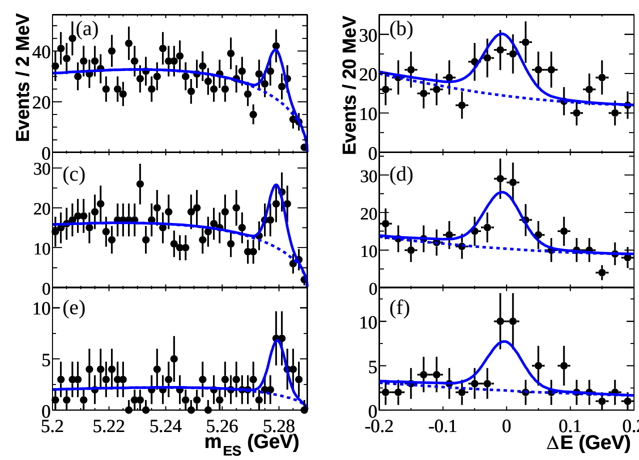

FIG. 2: Projections of the B candidate $m_{\rm ES}$ and ΔE for (a, b) $B^+ \to \omega\pi^+$; (c, d) $B^+ \to \omega K^+$; and (e, f) $B^0 \to \omega K^0$. Points with errors represent data, solid curves the full fit functions, and dashed curves the background functions. These plots are made with a requirement on the likelihood and thus do not show all events in the data samples.

of correlations among observables in the fit can cause a systematic bias; the correction for this bias (< 10% in all cases) and assignment of systematic uncertainty (1–5%), is determined from simulated samples with varying background populations. Published data [14] provide the uncertainties in the B-daughter product branching fractions (1%). Selection efficiency uncertainties are 1% (3% in $B^+ \to \eta'_{\rho\gamma}\pi^+$) for $\cos\theta_{\rm T}$ and ∼1% for PID. Using several large inclusive kaon and B-decay samples, we find a systematic uncertainty for $\mathcal{A}_{ch}$ of 1.1% due mainly to the dependence of reconstruction efficiency on the charge of the high momentum charged track. The values of $\mathcal{A}_{ch}^{qq}$ (see Table I) provide confirmation of this estimate.

In conclusion, we find significant signals for five B-meson decays. The measured branching fractions, and for the $B^\pm$ modes the charge asymmetries, are given in Table I. These are the first charge asymmetry measurements for the decays $B^+ \to \eta\pi^+$ and $B^+ \to \eta K^+$, since these modes along with $B^0 \to \omega K^0$ have not been observed previously. We quote 90% C.L. upper limits for the $B^0 \to \eta K^0$ and $B^+ \to \eta'\pi^+$ branching fractions, where the significances are only 3.3σ and 3.4σ, respectively. All branching fraction and charge asymmetry measurements are consistent with, but more precise than, previous measurements [2–4, 15]. Though uncertainties are large, the values of $\mathcal{A}_{ch}$ for the two decays with ω mesons are small as expected theoretically; the consistencies with zero asymmetry for $B^+ \to \eta\pi^+$ ($B^+ \to \eta K^+$) are 2.4σ (2.1σ). These are channels in which large asymmetries may be anticipated [7].

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[1] The named member of a charge-conjugate pair of particles stands for either.

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