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 $\eta$, $\eta'$ or $\omega$ meson in the final state. The data sample corresponds to 89 million
We report results of measurements of $B$ decays to the charmless final states $\eta K^0$, $\eta K^+$, $\eta K^0$, $\eta K^+$, $\omega K^0$, $\omega K^+$, and $\omega K^0$. Only the last two of these decays have been observed previously. Measurements of the related charmless final states were recorded at the PEP-II accelerator. An integrated luminosity of $81.9 \text{ fb}^{-1}$ was collected with the BABAR detector located at the Stanford Linear Accelerator Center. The charge asymmetries are $A_{ch}(B^+ \rightarrow \omega K^+) = -0.44 \pm 0.18 \pm 0.01$, $A_{ch}(B^+ \rightarrow \eta K^+) = -0.52 \pm 0.24 \pm 0.01$, $A_{ch}(B^+ \rightarrow \omega \pi^+) = 0.03 \pm 0.16 \pm 0.01$ and $A_{ch}(B^+ \rightarrow \omega K^+) = -0.09 \pm 0.17 \pm 0.01$.

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selection criteria to reduce $B\bar{B}$ backgrounds from several charmless final states. We reduce background from $B \rightarrow \pi^+\pi^0$, $K^+\pi^0$, and $K^0\pi^0$ by rejecting $\eta'\gamma$ candidates that share a photon with any $\pi^0$ 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 $B \rightarrow K^*\gamma$ and related radiative-penguin decays. From Monte Carlo (MC) simulation we estimate that the residual charmless $B\bar{B}$ background is negligible for all decays except those with $\eta \rightarrow \gamma\gamma$ and $\eta' \rightarrow \rho^0\gamma$, where we include in the fit described below a $B\bar{B}$ component (which is less than 0.5% of the total sample in all cases).

We obtain yields and $A_{ch}$ from extended unbinned maximum-likelihood fits, with input observables $\Delta E$, $m_{ES}$, $F$, $m_{res}$ (the mass of the $\eta$, $\eta'$, or $\omega$ candidate), for the $\omega$ decays, $H \equiv |\cos\theta_H|$, and for charged modes the PID variable $S_{\pi,K}$. The helicity angle $\theta_H$ is defined as the angle, measured in the $\omega$ rest frame, between the normal to the $\omega$ plane and the flight direction of the $\omega$. We incorporate PID information by using $S_{\pi}$ ($S_K$), 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, $B\bar{B}$ background), and flavor (primary $\pi^+$ or $K^+$) $k$, we define the probability density function (PDF) 

$$P_{jk}(\Delta E, m_{ES}, F, m_{res}) = P_j(m_{ES}^i)P_j(\Delta E_k^i)P_j(F^i)P_j(m_{res}^i) \times \left[\frac{P_j(S_i^0\eta_{H}^i)}{P_j(H^i)}\right].$$

The terms in brackets for $S$ and $H$ pertain to modes with charged track or $\omega$ daughters, respectively. The absence of correlations among observables in the background $P_{jk}$ 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 

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

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 $B\bar{B}$ background components, and from $(m_{ES}, \Delta E)$ sideband data for continuum background. We parameterize each of the functions $P_{sig}(m_{ES}), P_{sig}(\Delta E_k), P_j(F), P_j(S)$ and the peaking components of $P_j(m_{res})$ 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 $\omega$ mass spectrum each have their own $H$ shapes. The combinatoric background in $m_{ES}$ is described by the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x \equiv 2m_{ES}/\sqrt{s}$ and parameter $\xi$. Large control samples of $B$ decays to charmful final states of similar topology are used to verify the simulated resolutions in $\Delta E$ and $m_{ES}$. 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 1 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 $A_{ch}$. For calculation of branching fractions, we assume that the decay rates of the $\Upsilon(4S)$ to $B^+B^-$ and $B^0\bar{B}^0$ are equal. For the $\eta$ and $\eta'$ 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 $m_{ES}$ and $\Delta E$ after requiring $S_{\pi,K} \leq 2$ [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 $A_{ch}$ 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 $\eta K^0$ 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 $A_{ch}$.

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 0.8% $N_{\pi}/N_\gamma$, 2.5% $N_{K}/N_{\pi}$, and 3% for a $K^0_{s}$ decay, where $N_{\pi}$ and $N_{K}$ are the number of signal tracks and photons, respectively. Our estimate of the $B$ production systematic error is 1.1%. The neglect 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
For systematic uncertainties, measured branching fraction, background (A_{ch}^{\eta}) and signal (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 (%) | P (%) | $\prod B_i$ (%) | Signif. | $B(10^{-5})$ | $A_{ch}^{\eta}$ | $A_{ch}^{\eta'}$ |
|------|-------|-------|-------|----------------|---------|----------------|----------------|----------------|
| $\eta_{12}\pi^+$ | 28.3 \pm 10.9 | 30 | 23 | 23 | 4.4 | 5.6 \pm 2.4 | -0.004 \pm 0.010 | -0.52 \pm 0.31 |
| $\eta \pi^+$ | 59 \pm 14 | 31 | 31 | 39 | 6.6 | 5.2 \pm 1.3 | -0.001 \pm 0.011 | -0.41 \pm 0.22 |
| $\eta_{12}K^+$ | 7.9 | 5.3 \pm 1.0 | $\pm 0.3$ | 2.6 | 3.1 \pm 1.7 | -0.008 \pm 0.016 | -0.43 \pm 0.51 |
| $\eta_{13}K^+$ | 38 \pm 11 | 33 | 23 | 39 | 5.3 | 3.5 \pm 1.1 | -0.011 \pm 0.016 | -0.55 \pm 0.26 |
| $\eta K^+$ | 6.1 | 3.4 \pm 0.8 | $\pm 0.2$ | 0.8 | 1.8 \pm 2.9 | 3.2 \pm 1.8 | 3.2 \pm 1.8 |
| $\eta \pi^+$ | 2.6 \pm 4.1 | 20 | 23 | 8 | 0.8 | 3.8 \pm 1.7 | 3.8 \pm 1.7 | 3.8 \pm 1.7 |
| $\eta_{12}K^+$ | 8.6 \pm 4.8 | 47 | 24 | 14 | 3.2 | -0.8 \pm 2.4 | 3.2 \pm 1.8 |
| $\eta_{10}K^0$ | 3.3 | 2.9 \pm 1.0 | $\pm 0.2$ (< 5.2) | 3.9 | 3.8 \pm 1.7 | 3.8 \pm 1.7 |
| $\eta_{14}K^0$ | 17 \pm 7 | 38 | 28 | 17 | 3.9 | 3.8 \pm 1.7 | 3.8 \pm 1.7 |
| $\eta_{12}K^+$ | -4 \pm 11 | 17 | 30 | 30 | 3.4 | 2.7 \pm 1.2 | 2.7 \pm 1.2 |
| $\omega \pi^+$ | 101 \pm 17 | 37 | 23 | 89 | 9.1 | 5.5 \pm 0.9 | 0.012 \pm 0.006 | 0.03 \pm 0.16 |
| $\omega K^+$ | 83 \pm 14 | 39 | 22 | 89 | 10.0 | 4.8 \pm 0.8 | 0.003 \pm 0.009 | -0.09 \pm 0.17 |
| $\omega K^0$ | 33 \pm 8 | 51 | 20 | 31 | 7.5 | 5.9 \pm 1.7 | 5.9 \pm 1.7 |

FIG. 1: Projections of the B candidate m_{ES} and $\Delta E$ 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 $B\bar{B}$ 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_{ES} and $\Delta E$ 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.

Published data \cite{14} provide the uncertainties in the B-daughter product branching fractions (1%). Selection efficiency uncertainties are 1% (3% in $B^+ \to \eta_{12} \pi^+$) for $\cos \theta_T$ and $\sim 1\%$ for PID. Using several large inclusive kaon and B-decay samples, we find a systematic uncertainty for $A_{ch}$ of 1.1% due mainly to the dependence of reconstruction efficiency on the charge of the high momentum charged track. The values of $A_{ch}^{\eta}$ (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 3.3$\sigma$ and 3.4$\sigma$, respectively. All branching fraction and charge asymmetry measurements are consistent with, but more precise than, previous measurements \cite{2, 3, 4, 6, 7}. Though uncertainties are large, the values of $A_{ch}$ for the two decays with $\omega$ mesons are small as expected theoretically; the consistencies with zero asymmetry for $B^+ \to \eta \pi^+$ ($B^+ \to \eta K^+$) are 2.4$\sigma$ (2.1$\sigma$). These are channels in which large asymmetries may be anticipated \cite{8}.

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