

## Measurements of the Branching Fractions of Exclusive Charmless $B$ Meson Decays with $\eta'$ or $\omega$ Mesons

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We present the results of searches for  $B$  decays to charmless two-body final states containing  $\eta'$  or  $\omega$  mesons, based on  $20.7 \text{ fb}^{-1}$  of data collected with the BABAR detector. We find the branching fractions  $\mathcal{B}(B^+ \rightarrow \eta' K^+) = (70 \pm 8 \pm 5) \times 10^{-6}$ ,  $\mathcal{B}(B^0 \rightarrow \eta' K^0) = (42^{+13}_{-11} \pm 4) \times 10^{-6}$ , and  $\mathcal{B}(B^+ \rightarrow \omega \pi^+) = (6.6^{+2.1}_{-1.8} \pm 0.7) \times 10^{-6}$ , where the first error quoted is statistical and the second is systematic. We give measurements of four additional modes for which the 90% confidence level upper limits are  $\mathcal{B}(B^+ \rightarrow \eta' \pi^+) < 12 \times 10^{-6}$ ,  $\mathcal{B}(B^+ \rightarrow \omega K^+) < 4 \times 10^{-6}$ ,  $\mathcal{B}(B^0 \rightarrow \omega K^0) < 13 \times 10^{-6}$ , and  $\mathcal{B}(B^0 \rightarrow \omega \pi^0) < 3 \times 10^{-6}$ .

We report results of searches for  $B$  decays to the charmless two-body final states [1]  $B^+ \rightarrow \omega\pi^+$ ,  $B^+ \rightarrow \omega K^+$ ,  $B^+ \rightarrow \eta'\pi^+$ ,  $B^+ \rightarrow \eta'K^+$ ,  $B^0 \rightarrow \omega K^0$ ,  $B^0 \rightarrow \omega\pi^0$ , and  $B^0 \rightarrow \eta'K^0$ . These processes are manifestations of penguin or suppressed tree amplitudes proportional to small couplings in hadronic flavor mixing [Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]]. Because of the absence of CKM favored  $b \rightarrow c$  amplitudes, these decays are particularly sensitive to potentially new contributions from interference effects and virtual particles in loops. Previous measurements [3] yielded an unexpectedly large rate for  $B \rightarrow \eta'K$ , motivating a number of new theoretical ideas. The precise measurement of these and additional rare  $B$  decay modes will enable a better understanding of the underlying decay mechanism, including the possible contribution of physics beyond the standard model. This in turn will contribute to the measurement of fundamental parameters, including the  $CP$ -violating CKM phases.

The data were collected with the  $BABAR$  detector [4] at the PEP-II asymmetric  $e^+e^-$  collider [5] located at the Stanford Linear Accelerator Center. The results presented in this paper are based on data taken in the 1999–2000 run. An integrated luminosity of  $20.7 \text{ fb}^{-1}$ , corresponding to 22.7 million  $B\bar{B}$  pairs, was recorded at the  $Y(4S)$  resonance (“on resonance,” 10.58 GeV), with an additional  $2.6 \text{ fb}^{-1}$  about 40 MeV below this energy (“off resonance”) for the study of continuum backgrounds.

The asymmetric beam configuration in the laboratory frame provides a boost to the  $Y(4S)$  increasing the momentum range of the  $B$  meson decay products up to  $4.3 \text{ GeV}/c$ . Charged particles are detected and their momenta are measured by a combination of a silicon vertex tracker, consisting of five layers of double-sided detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a solenoid. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC), which provides excellent angular and energy resolution with high efficiency for energies above 20 MeV [4].

Charged particle identification (PID) is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by a unique, ring imaging detector of internally reflecting Cherenkov (DIRC) light covering the central region. A Cherenkov angle  $K - \pi$  separation of better than four standard deviations ( $\sigma$ ) is achieved for tracks below  $3 \text{ GeV}/c$  momentum, decreasing to  $2.5\sigma$  at the highest momenta in the final states considered here [6]. Electrons are identified with the use of the EMC.

We reconstruct a  $B$  meson candidate by combining an  $\omega$  or  $\eta'$  candidate with a charged track,  $\pi^0 \rightarrow \gamma\gamma$ , or  $K_S^0 \rightarrow \pi^+\pi^-$ . The resonance decays  $R$  we reconstruct are  $\omega \rightarrow \pi^+\pi^-\pi^0$ ,  $\eta' \rightarrow \eta\pi^+\pi^-$  ( $\eta'_\eta\pi\pi$ ), or  $\eta' \rightarrow \rho^0\gamma$  ( $\eta'_{\rho\gamma}$ ), with  $\eta \rightarrow \gamma\gamma$  and  $\rho^0 \rightarrow \pi^+\pi^-$ . These modes are kinematically distinct from the dominant  $B$  decays to heavier charmed states. Backgrounds come primarily from combinatorics among continuum events in which a light quark pair is produced instead of an  $Y(4S)$ .

Monte Carlo (MC) simulations [7] of the target decay modes and of continuum background are used to establish the event selection criteria. The selection is designed to achieve high efficiency and retain sidebands sufficient to characterize the background for subsequent fitting. Photons must satisfy  $E_\gamma > 50$  (100) MeV for  $\pi^0$  ( $\eta$ ) candidates. For  $\eta' \rightarrow \rho^0\gamma$  candidates from  $B^+ \rightarrow \eta'K^+$  and  $B^+ \rightarrow \eta'\pi^+$  the requirement is  $E_\gamma > 200$  MeV, while for  $B^0 \rightarrow \eta'K^0$  it is looser ( $E_\gamma > 100$  MeV) because of smaller combinatoric background.

We select  $\omega$ ,  $\eta'$ ,  $\eta$ , and  $\rho$  candidates with the following requirements on the invariant masses in  $\text{MeV}/c^2$  of their final states:  $735 < m(\pi^+\pi^-\pi^0) < 830$ ,  $930 < m(\eta\pi^+\pi^-) < 990$ ,  $900 < m(\rho\gamma) < 1000$ ,  $490 < m(\gamma\gamma) < 600$ , and  $500 < m(\pi^+\pi^-) < 995$ . For  $\pi^0$  and  $K_S^0$  candidates we require  $120 < m(\gamma\gamma) < 150$  and  $488 < m(\pi^+\pi^-) < 508$ .

Tracks in  $\omega$ ,  $\eta'$ , or  $\rho$  candidates must have DIRC,  $dE/dx$ , and EMC responses consistent with pions. For charged  $B$  decays, the  $B$  primary track must have an associated DIRC Cherenkov angle within  $3.5\sigma$  of the expected value for a kaon or pion. For modes with  $K_S^0$  the three-dimensional flight distance from the production point must exceed 2 mm, and the angle between the flight and momentum vectors projected perpendicular to the beam must be less than 40 mrad.

A  $B$  meson candidate is characterized by two kinematic observables. The minimally correlated pair we use is the energy constrained mass  $m_{EC}$  and energy difference  $\Delta E$ . In the  $Y(4S)$  frame the  $B$  meson energy  $E^*$  equals the beam energy  $E_{\text{beam}}^*$ . A kinematic fit of the measured candidate four momentum in this frame with the constraint  $E^* = E_{\text{beam}}^*$  yields  $m_{EC}$ , while  $\Delta E \equiv E^* - E_{\text{beam}}^*$  measures the consistency of this constraint. We require  $|\Delta E| \leq 0.2 \text{ GeV}$  and  $m_{EC} \geq 5.2 \text{ GeV}/c^2$ . The resolutions on these quantities are mode dependent but average about 30 MeV and  $2.8 \text{ MeV}/c^2$ , respectively.

To discriminate against tau-pair and two-photon background we require the event to contain at least five charged tracks. To reject continuum background we make use of the angle  $\theta_T$  between the thrust axes of the  $B$  candidate and the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of  $\cos\theta_T$  is sharply peaked near  $\pm 1$  for combinations drawn from jetlike  $q\bar{q}$  pairs, and nearly uniform for the isotropic  $B$  meson decays.

The yields are obtained from extended unbinned maximum likelihood (ML) fits, with two variants specified in the following paragraphs. The first (ML1), which provides our results for all modes except  $B^0 \rightarrow \omega\pi^0$ , uses several uncorrelated variables for the kinematics of the  $B$  decay chain and a Fisher discriminant for the production and energy flow. The second (ML2) is applied to all channels with an  $\omega$  meson; it uses  $\Delta E$  and the output of a neural network built from the remaining inputs. Comparisons of the  $\omega\pi^+$ ,  $\omega K^+$ , and  $\omega K^0$  modes show that the central values and errors for the yields obtained by the two approaches

are in very good agreement. Simple cut-based analyses are performed as checks for each final state. Agreement of central values is good in all cases, although, as expected, errors are larger than for the ML analyses, particularly for modes having high background.

The ML1 fit method is applied to events satisfying  $|\cos\theta_T| \leq 0.9$ . The input observables are  $\Delta E$ ,  $m_{EC}$ , the invariant mass  $m_R$  of the intermediate resonance, the Fisher discriminant  $\mathcal{F}$ , and, where relevant, the  $\eta$  mass  $m_\eta$ , the measured DIRC angle for the  $B$  primary track, and the cosine  $\mathcal{H}$  of the helicity angle, the angle in the  $\omega$  rest frame between the normal to the  $\omega$  decay plane and the  $B$  flight direction. The Fisher discriminant [8] combines eleven variables: the angles with respect to the beam axis in the  $Y(4S)$  frame of the  $B$  momentum and the  $B$  two-body decay axis, and a nine bin representation of the energy flow about the  $B$  decay axis.

For the ML2 method we relax the preliminary requirements to  $100 < m(\gamma\gamma) < 160$  MeV/ $c^2$  and  $|\Delta E| < 0.3$  GeV. The neural network is constructed with the  $B$  momentum  $p^*$ , a  $\chi^2$  for resonance masses,  $\mathcal{H}$ , and variables representing energy flow and angular distributions, including  $\theta_T$ .

We use MC to estimate backgrounds from other  $B$  decays, including final states with and without charm. For most of our modes we find contributions that are negligible. For the  $\eta' \rightarrow \rho^0 \gamma$  modes we account for small cross feed contributions in the systematic error estimate.

The likelihood function for  $N$  events is

$$\mathcal{L} = \frac{e^{-(\sum n_j)}}{N!} \prod_{i=1}^N \mathcal{L}_i, \quad \mathcal{L}_i = \sum_{j=1}^m n_j \mathcal{P}_j(\mathbf{x}_i).$$

Here  $n_j$  is the population size for species  $j$  (e.g., signal, background) and  $\mathcal{P}_j(\mathbf{x}_i)$  is the corresponding probability distribution function (PDF), evaluated with the observables  $\mathbf{x}_i$  of the  $i$ th event.

For the fits of charged  $B$  decays,  $\mathcal{L}_i$  becomes

$$\mathcal{L}_i = n_\pi \mathcal{P}_{\pi S}(\mathbf{x}_i) + n_K \mathcal{P}_{KS}(\mathbf{x}_i) + n_C [f_{KC} \mathcal{P}_{KC}(\mathbf{x}_i) + (1 - f_{KC}) \mathcal{P}_{\pi C}(\mathbf{x}_i)],$$

where  $n_\pi$  ( $n_K$ ) is the number of  $B^+ \rightarrow R\pi^+$  ( $B^+ \rightarrow RK^+$ ) signal events,  $n_C$  is the number of continuum background events, and  $f_{KC}$  is the fraction of continuum background events for which the  $B$  primary track is identified as a kaon. These quantities are the free parameters of the ML fit. The probabilities for the components are  $\mathcal{P}_{\pi S}$  ( $\mathcal{P}_{KS}$ ) for  $B^+ \rightarrow R\pi^+$  ( $B^+ \rightarrow RK^+$ ) signal and  $\mathcal{P}_{\pi C}$  ( $\mathcal{P}_{KC}$ ) for background where the primary track is a pion (kaon). Since we measure the correlations among the observables in the data to be small, we take each  $\mathcal{P}_j$  to be a product of the PDFs for the separate observables. The analyses involving a  $K_S^0$  are treated identically, except that there is only one component of signal and of continuum background.

A second  $B$  candidate satisfying the preliminary cuts occurs in about 10%–20% of the events. In this case the

“best” combination is selected according to a  $\chi^2$  quantity computed with  $m_{EC}$ ,  $m_R$ ,  $m_\eta$  (for  $\eta' \rightarrow \eta\pi^+\pi^-$  modes), and the Fisher discriminant.

We determine the PDFs for the likelihood fits from simulation for the signal component, and from off-resonance and sideband data for the continuum background. Peaking distributions (signal masses,  $\Delta E$ ,  $\mathcal{F}$ ) are parametrized as Gaussians, with or without a second Gaussian or asymmetric width as required to describe the distributions. Slowly varying distributions (combinatoric background under mass or energy peaks,  $\mathcal{H}$  or  $\mathcal{F}$ ) have first or second order polynomial shapes. The combinatoric background in  $m_{EC}$  is described by a phase space motivated empirical function [9]. Control samples of  $B$  decays to charmed final states of similar topology are used to verify the simulated resolutions in  $\Delta E$  and  $m_{EC}$ . Inclusive resonance production samples, such as those shown in Fig. 1, are used similarly for the relevant  $B$  daughter mass spectra.

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 pairs. To determine the reconstruction efficiency, including any yield bias of the likelihood fit, we apply the method to simulated samples with the signal and continuum background populations expected in the data. Table I shows for each decay chain the branching fraction we measure, together with the quantities entering into its computation. The statistical error on the number of events is taken as the shift from the central value that changes the quantity  $\chi^2 \equiv -2 \log(\mathcal{L} / \mathcal{L}_{\max})$  by one unit. We also give the significance  $S$ , computed as the square root of the difference between the value of  $\chi^2$  for zero signal and the value at its minimum. The  $\chi^2$  used for significance includes a term that accounts for the additive systematic

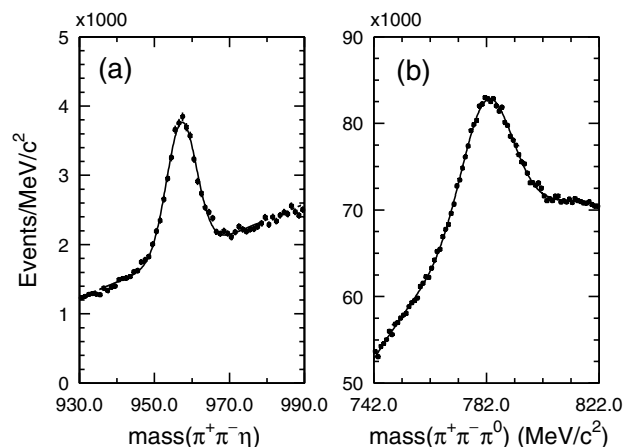


FIG. 1. Invariant mass distributions for inclusive data samples of candidates with  $Y(4S)$  frame momentum greater than 2.3 GeV/ $c$  for (a)  $\eta'$ , with  $520 < m(\gamma\gamma) < 575$  MeV/ $c^2$ , and (b)  $\omega$  candidates, with  $120 < m(\gamma\gamma) < 150$  MeV/ $c^2$ . From the overlaid fit curves, the Gaussian peak widths are 4 and 10 MeV/ $c^2$ , respectively.

TABLE I. Signal event yield with statistical uncertainty, detection efficiency  $\epsilon$ , daughter branching fractions that were forced to 100% in our signal mode simulations, significance  $S$  (defined in the text), and branching fraction result for each decay chain or mode, with the final (combined) result given in bold type. We show 90% confidence upper limits in parentheses where appropriate.

Mode	Yield	$\epsilon$ (%)	$\prod \mathcal{B}_i$ (%)	$S$ ( $\sigma$ )	$\mathcal{B}$ ( $10^{-6}$ )
$\eta'_{\eta\pi\pi}K^+$	$49.5^{+8.1}_{-7.3}$	20	17.4	15	$63^{+10}_{-9}$
$\eta'_{\rho\gamma}K^+$	$87.6^{+13.4}_{-12.5}$	18	29.5	11	$80^{+12}_{-11}$
$\eta'K^+$	...	...	...	17	<b><math>70 \pm 8 \pm 5</math></b>
$\eta'_{\eta\pi\pi}K^0$	$6.3^{+3.3}_{-2.5}$	16	6.0	4.7	$28^{+15}_{-11}$
$\eta'_{\rho\gamma}K^0$	$20.8^{+7.4}_{-6.5}$	16	10.1	4.2	$61^{+22}_{-19}$
$\eta'K^0$	...	...	...	5.9	<b><math>42^{+13}_{-11} \pm 4</math></b>
$\eta'_{\eta\pi\pi}\pi^+$	$5.7^{+3.8}_{-2.8}$	20	17.4	3.2	$7.1^{+4.8}_{-3.5}$
$\eta'_{\rho\gamma}\pi^+$	$-0.9^{+7.8}_{-6.2}$	19	29.5	0.1	$-0.7^{+6.7}_{-5.3}$
$\eta'\pi^+$	...	...	...	2.8	<b><math>5.4^{+3.5}_{-2.6} \pm 0.8</math></b> ( $<12$ )
$\omega K^+$	$6.4^{+5.6}_{-4.4}$	22	88.8	1.3	<b><math>1.4^{+1.3}_{-1.0} \pm 0.3</math></b> ( $<4$ )
$\omega K^0$	$8.1^{+4.6}_{-3.6}$	18	30.5	3.2	<b><math>6.4^{+3.6}_{-2.8} \pm 0.8</math></b> ( $<13$ )
$\omega\pi^+$	$27.6^{+8.8}_{-7.7}$	21	88.8	4.9	<b><math>6.6^{+2.1}_{-1.8} \pm 0.7</math></b>
$\omega\pi^0$	$-0.9^{+5.0}_{-3.2}$	18	88.8	...	<b><math>-0.3 \pm 1.1 \pm 0.3</math></b> ( $<3$ )

error discussed below. Where the significance is less than four standard deviations, we quote also (Bayesian) 90% C.L. upper limits, defined by the solution  $B$  to the condition  $\int_0^B \mathcal{L}(b) db / \int_0^\infty \mathcal{L}(b) db = 0.9$ .

In Fig. 2 we show projections of  $m_{EC}$  and  $\Delta E$  for the modes with significant yields. The projections are made by

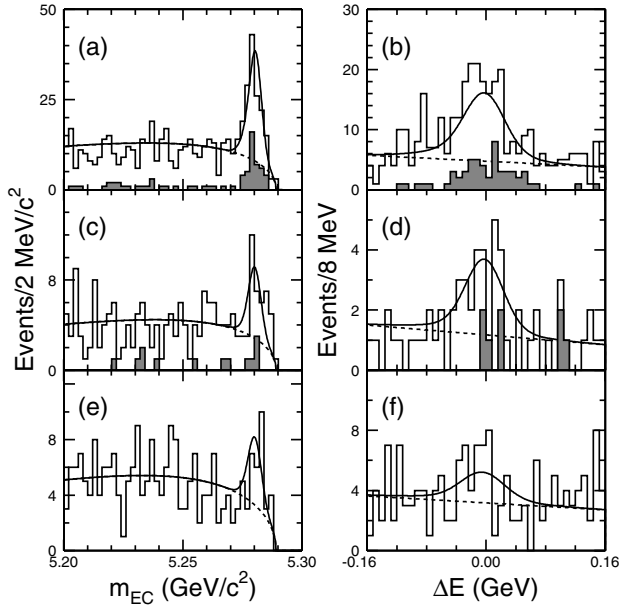


FIG. 2.  $B$  candidate  $m_{EC}$  and  $\Delta E$  for  $B^+ \rightarrow \eta'K^+$  (a),(b),  $B^0 \rightarrow \eta'K^0$  (c),(d), and  $B^+ \rightarrow \omega\pi^+$  (e),(f). Histograms represent data, with the  $\eta' \rightarrow \eta\pi\pi$  subset shaded, the solid curves represent the full fit functions, and the dashed curves represent the background functions.

selecting events with signal likelihood (computed without the variable plotted) exceeding a mode-dependent threshold that optimizes the expected sensitivity.

We have evaluated systematic errors, which are dominated in most cases by the PDF uncertainties (3%–18%, depending on the decay mode). To determine these we vary parameters of the PDFs within their uncertainties and observe the impact on the fit yield. We include them in upper limits by convolution with the likelihood function. This is the only additive systematic error; all others are multiplicative. The estimate of any systematic bias from the fitter itself (1%–4%) comes from fits of simulated samples with varying background populations.

The uncertainty in our knowledge of the efficiency is found from auxiliary studies to be 1% per track, 1.25% per photon, and 5% per  $K_S^0$  for the candidate  $B$  and the unreconstructed  $B$ , which must contribute tracks to fulfill the event multiplicity requirement. We add these errors linearly for the required tracks in the event and, similarly, for the photons and neutral kaons. Our estimate of the  $B$  production systematic error is 1.6%. Published world averages [10] provide the  $B$  daughter branching fraction uncertainties.

Systematic errors associated with the event selection are minimal given the generally loose requirements. We account explicitly for  $\cos\theta_T$  (1%), for which we observe a nearly uniform distribution in the signal simulation. We also include errors of 4% from those PID requirements that are imposed via cuts rather than the fit.

We observed signals of at least  $4\sigma$  in five of the decay chains studied here, as reported in Table I. Where we have multiple chains for a given mode, we combine the results

by adding the  $\chi^2$  distributions that represent them and their uncorrelated statistical and systematic errors.

The final results are generally in agreement with those previously reported [3,11], with somewhat smaller errors. In particular, we confirm the expected  $\mathcal{B}(B^+ \rightarrow \omega \pi^+) > \mathcal{B}(B^+ \rightarrow \omega K^+)$ , and the rather larger than predicted [12] rate for  $B \rightarrow \eta' K$  obtained by the CLEO Collaboration [3]. Conjectured sources of  $\eta'$  enhancement include flavor singlet [13], charm enhanced [14], and constructively interfering internal penguin diagrams [12,15]. Our results in combination with expected measurements of related modes involving  $\eta$  and  $K^*$  should help to clarify this situation.

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

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