Observation of B Meson Decays to $b_1\pi$ and b_1K

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We present the results of searches for decays of B mesons to final states with a b_1 meson and a charged pion or kaon. The data, collected with the *BABAR* detector at the Stanford Linear Accelerator Center, represent 382×10^6 $B\bar{B}$ pairs produced in e^+e^- annihilation. The results for the branching fractions are, in units of 10^{-6}, $\mathcal{B}(B^+ \to b_1^0 \pi^+) = 6.7 \pm 1.7 \pm 1.0$, $\mathcal{B}(B^+ \to b_1^0 K^+) = 9.1 \pm 1.7 \pm 1.0$, $\mathcal{B}(B^0 \to b_1^{\mp} \pi^{\pm}) = 10.9 \pm 1.2 \pm 0.9$, and $\mathcal{B}(B^0 \to b_1^- K^+) = 7.4 \pm 1.0 \pm 1.0$, with the assumption that $\mathcal{B}(b_1 \to \omega\pi) = 1$. We also measure charge and flavor asymmetries $\mathcal{A}_{\rm ch}(B^+ \to b_1^0 \pi^+) = 0.05 \pm 0.16 \pm 0.02$,

$\mathcal{A}_{\rm ch}(B^+ \to b_1^0 K^+) = -0.46 \pm 0.20 \pm 0.02$, $\mathcal{A}_{\rm ch}(B^0 \to b_1^{\mp}\pi^{\pm}) = -0.05 \pm 0.10 \pm 0.02$, $C(B^0 \to b_1^{\mp}\pi^{\pm}) = -0.22 \pm 0.23 \pm 0.05$, $\Delta C(B^0 \to b_1^{\mp}\pi^{\pm}) = -1.04 \pm 0.23 \pm 0.08$, and $\mathcal{A}_{\rm ch}(B^0 \to b_1^- K^+) = -0.07 \pm 0.12 \pm 0.02$. The first error quoted is statistical, and the second systematic.

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Recent searches for decays of B mesons to final states with an axial-vector meson and a pion have revealed modes with rather large branching fractions, e.g., $\mathcal{B}(B^0 \to a_1^{\mp}\pi^{\pm}) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$ [1]. Here, we search for related modes with a b_1^0 or a b_1^- meson plus a π^+ or K^+ [2], in a sample of $(381.8 \pm 4.2) \times 10^6$ $B\bar{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). The integrated luminosity is 346 fb^{-1}.

The mass and width of the b_1 are 1229.5 ± 3.2 MeV and 142 ± 9 MeV, respectively, and the dominant decay is to $\omega\pi$ [3]. In the quark model, the b_1 is the $I^G = 1^+$ member of the $J^{PC} = 1^{+-}$, ${}^1P_1$ nonet, whereas the a_1 is the $I^G = 1^-$ state in the $J^{PC} = 1^{++}$, ${}^3P_1$ nonet. The available theoretical estimates of the branching fractions of B mesons to $b_1\pi$ and b_1K come from calculations based on naive factorization [4,5] and on QCD factorization [6]. The latter incorporates light-cone distribution amplitudes evaluated from QCD sum rules. Expected branching fractions lie in the range 5–10 $\times 10^{-6}$ [6]; estimates as large as 26×10^{-6} are found in the calculations of [4] and 40×10^{-6} in those of [5].

The four modes $B^+ \to b_1^0\pi^+$, $B^+ \to b_1^0 K^+$, $B^0 \to b_1^-\pi^+$, and $B^0 \to b_1^- K^+$ can be mediated by external tree amplitudes in which the weak current produces the pion (kaon) with a Cabibbo-favored (suppressed) coupling. Alternatively, a "penguin" loop amplitude is favored for the kaon modes and suppressed for the pion modes. The fifth mode, $B^0 \to b_1^+\pi^-$, requires a coupling of the current to the b_1^+, which is forbidden for this $G = +1$ state [7], leading to the expectation $\mathcal{B}(B^0 \to b_1^+\pi^-) \ll \mathcal{B}(B^0 \to b_1^-\pi^+)$.

Direct CP violation would be indicated by a nonzero value of the asymmetry $\mathcal{A}_{\rm ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ in the rates $\Gamma^{\pm}(B^{\pm} \to F^{\pm})$ for decay of a charged B meson, or $\Gamma^+(B^0 \to b_1^- K^+)$ and its charge conjugate. For the decays $B^0 \to b_1^{\mp}\pi^{\pm}$, we define $\mathcal{A}_{\rm ch}$ and two additional asymmetries C and ΔC through

$$\Gamma_{q,f} = \frac{1}{4}(\Gamma + \bar{\Gamma})(1 + q\mathcal{A}_{\rm ch})[1 + f(C + q\Delta C)], \quad (1)$$

where the signal B meson flavor $f = +1$ for B^0, -1 for $\bar{B}^0$, and q is the sign of charge of the b_1. To measure C and ΔC, we use the flavor η ($+1$ for B^0 and -1 for $\bar{B}^0$) of the second meson $B_{\rm tag}$ produced in $\Upsilon(4S)$ decay [8]. The yields are given by

$$\begin{aligned} Y_{q\eta} = \frac{1}{4}Y_S(1 + q\mathcal{A}_{\rm ch})\{1 - \eta\Delta w + \eta\mu(1 - 2w) \\ - \eta(1 - 2\chi_d)[1 - 2w + \mu(\eta - \Delta w)] \\ \times (C + q\Delta C)\}, \end{aligned} \quad (2)$$

where Y_S is the total signal yield, $\chi_d = 0.188 \pm 0.003$ the time-integrated mixing probability [3], w the mistag fraction, and Δw and μ the $B - \bar{B}$ differences in the mistag rate and tagging efficiency, respectively.

The data were collected with the *BABAR* detector [9] at the PEP-II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. Charged particles from the e^+e^- interactions are detected, and their momenta measured, by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified with 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. A detailed Monte Carlo program (MC) is used to simulate the B production and decay sequences, and the detector response [10].

The b_1 candidates are reconstructed through the decay sequence $b_1 \to \omega\pi$, $\omega \to \pi^+\pi^-\pi^0$, and $\pi^0 \to \gamma\gamma$. The invariant mass of the photon pair is required to lie between 120 and 150 MeV, i.e., within about 2 standard deviations of the nominal mass [3]. For the b_1 and ω whose masses are observables in the maximum likelihood (ML) fit described below, we accept a range that includes wider sidebands (see Fig. 1). Secondary charged pions in b_1 and ω candidates are rejected if classified as protons, kaons, or electrons by their DIRC, dE/dx, and EMC PID signatures. For the primary pion (kaon) from the B-meson decay, we define the PID variable S_π (S_K) as the number of standard deviations between the measured DIRC Cherenkov angle and that expected for a pion (kaon), requiring $-2 < S_\pi < 5$ ($-5 < S_K < 2$).

We reconstruct the B-meson candidate by combining the 4-momenta of a pair of daughter mesons, using a fit that constrains all particles to a common vertex and the π^0 mass to its nominal value. From the kinematics of $\Upsilon(4S)$ decay, we determine the energy-substituted mass $m_{\rm ES} = \sqrt{\frac{1}{4}s - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B - \frac{1}{2}\sqrt{s}$, where $(E_B, \mathbf{p}_B)$ is the B-meson 4-momentum vector, and all values are expressed in the $\Upsilon(4S)$ rest frame. The resolu-

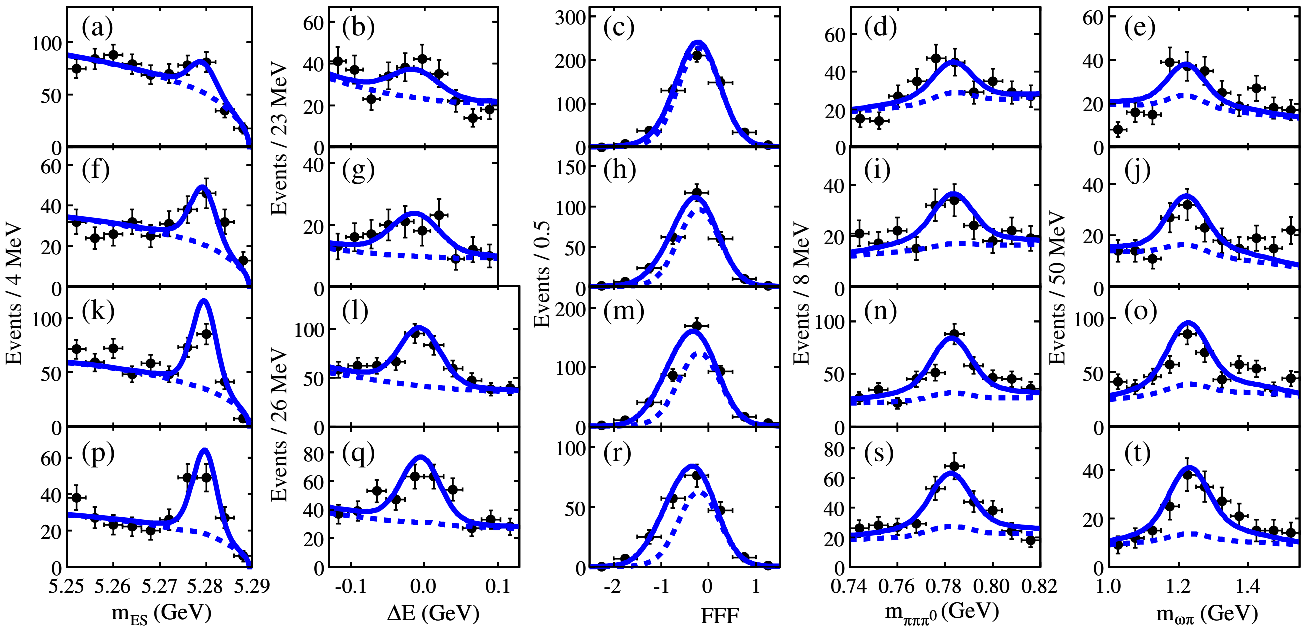

FIG. 1 (color online). Distributions for signal-enhanced subsets of the data projected onto the fit observables for the decays: (a–e) $B^+ \to b_1^0\pi^+$, (f–j) $B^+ \to b_1^0 K^+$, (k–o) $B^0 \to b_1^\mp \pi^\pm$, and (p–t) $B^0 \to b_1^- K^+$. The solid line represents the result of the fit and the dashed line the background contribution.

tion in $m_{\rm ES}$ is 2.4–2.7 MeV and in ΔE is 25–32 MeV, depending on the decay mode. We require $5.25\ \text{GeV} < m_{\rm ES} < 5.29\ \text{GeV}$ and $-0.13\ \text{GeV} < \Delta E < \Delta E_{\rm max}$, with $\Delta E_{\rm max} = 0.1(0.13)$ GeV for b_1^0 (b_1^+), where the tighter restriction serves to limit the number of combinatorial candidates per event.

We also impose restrictions on resonance decay angles to exclude the most asymmetric decays where soft-particle backgrounds accumulate and the acceptance changes rapidly. We require $\cos\theta_{b_1} \le 1.1 - 0.5|\cos\theta_\omega|$, where θ_{b_1} is the angle between the momenta of the pion from $b_1 \to \omega\pi$ and its parent B meson, measured in the b_1 rest frame, and θ_ω is the angle between the normal to the $\omega \to 3\pi$ decay plane and the momentum of its parent b_1, measured in the ω rest frame. Backgrounds arise primarily from random combinations of particles in continuum $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$). We reduce these with a requirement on the angle θ_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 calorimeter clusters in the event. The distribution is sharply peaked near $|\cos\theta_T| = 1$ for $q\bar{q}$ jet pairs and nearly uniform for B-meson decays. The requirement, which optimizes the expected signal yield relative to its background-dominated statistical error, is $|\cos\theta_T| < 0.7$. The average number of candidates found per selected event is in the range 1.3 to 1.4 (1.4 to 1.6 in signal MC calculations), depending on the final state. We choose the candidate with $\omega\pi$ invariant mass closest to the nominal value of the b_1 mass [3]. In the ML fit, we discriminate further against $q\bar{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines several variables which characterize the energy flow in the event [11]. It provides about 1 standard deviation of separation between B decay events and $q\bar{q}$ background.

We obtain yields for each channel from an extended ML fit with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, and the resonance masses m_{b_1} and m_ω. The selected data sample sizes are given in Table I. Besides the signal events, these

TABLE I. Number of events N in the sample, fitted signal yield Y_S, and measured bias (to be subtracted from Y_S) in events (ev.), detection efficiency ϵ, significance $\mathcal{S}$ (with systematic uncertainties included), and branching fraction and charge asymmetry with statistical and systematic error.

Mode	N (ev.)	Y_S (ev.)	Bias (ev.)	ϵ (%)	$\mathcal{S}$ (σ)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{\rm ch}$
$b_1^0\pi^+$	32176	178^{+39}_{-37}	26 ± 14	6.78	4.0	$6.7 \pm 1.7 \pm 1.0$	$0.05 \pm 0.16 \pm 0.02$
$b_1^0K^+$	18036	219^{+38}_{-36}	24 ± 12	6.73	5.3	$9.1 \pm 1.7 \pm 1.0$	$-0.46 \pm 0.20 \pm 0.02$
$b_1^\mp\pi^\pm$	36901	387^{+41}_{-39}	34 ± 17	9.54	8.9	$10.9 \pm 1.2 \pm 0.9$	$-0.05 \pm 0.10 \pm 0.02$
$b_1^-K^+$	17497	267^{+33}_{-32}	32 ± 16	9.43	6.1	$7.4 \pm 1.0 \pm 1.0$	$-0.07 \pm 0.12 \pm 0.02$

samples contain $q\bar{q}$ (dominant) and $B\bar{B}$ with $b \to c$ combinatorial background, and a fraction of cross feed from other charmless $B\bar{B}$ modes, which we estimate from the simulation to be (0.5–0.8)%. The last include nonresonant $\omega\pi(\pi, K)$, and modes that have final states different from the signal, but with similar kinematics so that broad peaks near those of the signal appear in some observables, requiring a separate component in the probability density function (PDF). The likelihood function is

$$\mathcal{L} = \exp\Big(-\sum_{j,q,\eta} Y_{j,q\eta}\Big)\prod_{i}^{N}\sum_{j,q,\eta} Y_{j,q\eta} \times \mathcal{P}_j(m_{\rm ES}{}^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(\Delta E^i)\mathcal{P}_j(m^i_{b_1})\mathcal{P}_j(m^i_{\omega}), \quad (3)$$

where N is the number of events in the sample, and for each component j (signal, combinatorial background, or charmless $B\bar{B}$ cross feed), $Y_{j,q\eta}$ is the yield of events [Eq. (2)] and $\mathcal{P}_j(x^i)$ the PDF for observable x in event i. The signal component is further separated into two components (with proportions fixed in the fit for each mode) representing the correctly and incorrectly reconstructed candidates in events with true signal, as determined with MC calculations. The factored form of the PDF indicated in Eq. (3) is a good approximation, particularly for the combinatorial $q\bar{q}$ component, since we find correlations among observables in the data (which are mostly $q\bar{q}$ background) to be small. The effects of this approximation are determined in simulation and included in the bias corrections and systematic errors discussed below.

We determine the PDFs for the signal and $B\bar{B}$ background components from fits to MC samples. We calibrate the resolutions in ΔE and $m_{\rm ES}$ with large data control samples of B decays to charmed final states of similar topology (e.g., $B \to D(K\pi\pi)\pi$). We develop PDFs for the combinatorial background with fits to the data from which the signal region ($5.27\ \text{GeV} < m_{\rm ES} < 5.29\ \text{GeV}$ and $|\Delta E| < 0.1\ \text{GeV}$) has been excluded.

The functions $\mathcal{P}_j$ are constructed as linear combinations of Gaussian and polynomial functions, or in the case of $m_{\rm ES}$, for $q\bar{q}$ background the threshold function $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$, with argument $x \equiv 2m_{\rm ES}/\sqrt{s}$ and parameter ξ. These functions are discussed in more detail in [11], and are illustrated in Fig. 1.

We allow the parameters most important for the determination of the combinatorial background PDFs to vary in the fit, along with the yields for all components, and the signal and $q\bar{q}$ background asymmetries. Specifically, the free background parameters are: ξ for $m_{\rm ES}$, linear and quadratic coefficients for ΔE, and the mean, width and width difference, and polynomial fraction parameters for $\mathcal{F}$.

We validate the fitting procedure by applying it to ensembles of simulated experiments with the $q\bar{q}$ component drawn from the PDF, into which we have embedded the expected number of signal and $B\bar{B}$ background events randomly extracted from the fully simulated MC samples. Biases obtained by this procedure with inputs that reproduce the yields found in the data are reported, along with the signal yields, in Table I.

In Fig. 1, we show the projections of the PDF and data for each fit. The data plotted are subsamples enriched in signal with a threshold requirement on the ratio of signal to total likelihood (computed without the plotted variable) that retains (29–53)% of the signal, depending on the mode.

We compute the branching fraction by subtracting the fit bias from the measured yield, and dividing the result by the efficiency times $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0) = 89.1 \pm 0.7\%$ [3], and by the number of produced $B\bar{B}$ pairs. We assume $\Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\bar{B}^0) = 1$, consistent with measurements [3]. The results are given in Table I, along with the significance, computed as the square root of the difference between the value of $-2\ln\mathcal{L}$ (with additive systematic uncertainties included) for zero signal and the value at its minimum.

Systematic uncertainties on the branching fractions arise from the PDFs, $B\bar{B}$ backgrounds, fit bias, and efficiency. PDF uncertainties not already accounted for by free parameters in the fit are estimated from the consistency of fits to MC calculations and data in control modes. Varying the signal-PDF parameters within these errors, we estimate yield uncertainties of (2.4–3.3)%, depending on the mode. The uncertainty from fit bias (Table I) includes its statistical uncertainty from the simulated experiments, and half of the correction itself, added in quadrature. For the $B\bar{B}$ backgrounds, we vary the fixed fit component by 100% and include in quadrature a term derived from MC studies of the inclusion of a $b \to c$ component with the dominant $q\bar{q}$ background. Uncertainties in our knowledge of the efficiency include $0.5\% \times N_t$ and $1.5\% \times N_\gamma$, where N_t and N_γ are the numbers of tracks and photons, respectively, in the B candidate. The uncertainties in the efficiency from the event selection are below 0.5%.

We study asymmetries from the track reconstruction (found negligible), and from imperfect modeling of the interactions with material in the detector, by measuring the asymmetries in the $q\bar{q}$ background in the data and control samples mentioned previously, in comparison with MC calculations [12]. We apply corrections, and assign systematic errors, to $\mathcal{A}_{\rm ch}$ equal to -0.010 ± 0.005 for modes with a primary kaon and 0.000 ± 0.005 for those with a primary pion. The leading systematic errors on C and ΔC come from the fit bias.

With the assumption that $\mathcal{B}(b_1 \to \omega\pi) = 1$, we obtain for the branching fractions

$$\mathcal{B}(B^+ \to b_1^0\pi^+) = (6.7 \pm 1.7 \pm 1.0) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to b_1^0K^+) = (9.1 \pm 1.7 \pm 1.0) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to b_1^\mp\pi^\pm) = (10.9 \pm 1.2 \pm 0.9) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to b_1^-K^+) = (7.4 \pm 1.0 \pm 1.0) \times 10^{-6}.$$

For the asymmetries, we find

$$\mathcal{A}_{ch}(B^+ \to b_1^0\pi^+) = 0.05 \pm 0.16 \pm 0.02$$
$$\mathcal{A}_{ch}(B^+ \to b_1^0K^+) = -0.46 \pm 0.20 \pm 0.02$$
$$\mathcal{A}_{ch}(B^0 \to b_1^\mp\pi^\pm) = -0.05 \pm 0.10 \pm 0.02$$
$$C(B^0 \to b_1^\mp\pi^\pm) = -0.22 \pm 0.23 \pm 0.05$$
$$\Delta C(B^0 \to b_1^\mp\pi^\pm) = -1.04 \pm 0.23 \pm 0.08$$
$$\mathcal{A}_{ch}(B^0 \to b_1^-K^+) = -0.07 \pm 0.12 \pm 0.02.$$

The first error quoted is statistical and the second systematic. The QCD factorization estimates [6] for the branching fractions and charge asymmetries agree with these measurements within experimental and theoretical errors. The authors of [6] note that the observation $\mathcal{B}(B^+ \to b_1^0K^+)/\mathcal{B}(B^0 \to b_1^-K^+) > 0.5$, if confirmed with higher precision, would indicate the presence of a weak annihilation contribution to these modes. The value of the CP-conserving ΔC near -1 for $B^0 \to b_1^\mp\pi^\pm$ agrees with the expected suppression of $B^0 \to b_1^+\pi^-$; our results imply the ratio $\Gamma(B^0 \to b_1^+\pi^-)/\Gamma(B^0 \to b_1^\mp\pi^\pm) = -0.01 \pm 0.12$. We find no evidence for direct CP violation in these decays.

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