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Observation of $B^+ \to b_1^+ K^0$ and search for B-meson decays to $b_1^0 K^0$ and $b_1 \pi^0$

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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 neutral pion or kaon. The data, collected with the *BABAR* detector at the Stanford Linear Accelerator

Center, represent 465 million $B\overline{B}$ pairs produced in e^+e^- annihilation. The results for the branching fractions are, in units of 10^{-6}, $\mathcal{B}(B^+ \to b_1^+ K^0) = 9.6 \pm 1.7 \pm 0.9$, $\mathcal{B}(B^0 \to b_1^0 K^0) = 5.1 \pm 1.8 \pm 0.5$ (< 7.8), $\mathcal{B}(B^+ \to b_1^+ \pi^0) = 1.8 \pm 0.9 \pm 0.2$ (< 3.3), and $\mathcal{B}(B^0 \to b_1^0 \pi^0) = 0.4 \pm 0.8 \pm 0.2$ (< 1.9), with the assumption that $\mathcal{B}(b_1 \to \omega\pi) = 1$. We also measure the charge asymmetry $\mathcal{A}_{ch}(B^+ \to b_1^+ K^0) = -0.03 \pm 0.15 \pm 0.02$. The first error quoted is statistical, the second systematic, and the upper limits in parentheses indicate the 90% confidence level.

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Recent searches for decays of B mesons to final states with an axial-vector meson and a pion or kaon have revealed modes with branching fractions that are rather large among charmless decays: $(15 - 35) \times 10^{-6}$ for $B \to a_1(\pi, K)$ [1, 2], and $(7 - 11) \times 10^{-6}$ for charged pion and kaon in combination with a b_1^0 or a b_1^+ meson [3, 4]. In this paper we present the results of investigations of the remaining charge states with b_1 accompanied by a π^0 or K^0. No previous searches for these modes have been reported.

The mass and width of the b_1 meson are 1229.5 ± 3.2 MeV and 142 ± 9 MeV, respectively, and the dominant decay is to $\omega\pi$ [5]. In the quark model the b_1 is the $I^G = 1^+$ member of the $J^{PC} = 1^{+-}$, ${}^1P_1$ nonet. The Cabibbo-favored amplitudes that mediate these decays are those represented by color-suppressed tree diagrams for the modes with π^0, and "penguin" loop diagrams for those with K^0. Because the b_1 meson has even G-parity, only amplitudes in which the b_1 contains the spectator quark from the B meson are allowed, apart from isospin-breaking effects [6]. Direct CP violation would be indicated by a non-zero value of the asymmetry $\mathcal{A}_{ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ in the rates $\Gamma^\pm(B^\pm \to F^\pm)$ for charged B-meson decays to final states $F^\pm$.

The available theoretical estimates of the branching fractions of B mesons to $b_1\pi$ and $b_1 K$ come from calculations based on naïve factorization [7, 8], and on QCD factorization [9]. The latter incorporate light-cone distribution amplitudes evaluated from QCD sum rules, and predict branching fractions in quite good agreement with the measurements for $B \to b_1\pi^+$ and $B \to b_1 K^+$ [3]. The expected branching fractions from QCD factorization are about 10×10^{-6} for $B^+ \to b_1^+ K^0$, and 3×10^{-6} or less for $B^0 \to b_1^0 K^0$ and $B \to b_1\pi^0$ [9].

The data for these measurements were collected with the *BABAR* detector [10] at the PEP-II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. An integrated luminosity of 424 fb^{-1}, corresponding to $(465 \pm 5) \times 10^6$ $B\overline{B}$ pairs, was produced by e^+e^- annihilation 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 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 [11].

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 other primary daughter of the B meson is reconstructed as either $K_S^0 \to \pi^+\pi^-$ or $\pi^0 \to \gamma\gamma$. For K_S^0, the invariant mass of the pion pair is required to lie between 486 and 510 MeV, i.e., within about 3.5 standard deviations of the nominal K_S^0 mass [5]. The minimum energy for a π^0-daughter photon is 30 MeV (50 MeV for a primary π^0), and the minimum energy of a π^0 is 250 MeV. The invariant mass of the photon pair is required to lie between 120 and 150 MeV, or within about two standard deviations of the nominal π^0 mass. For the b_1 and ω, whose masses are treated as 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 a K_S^0 candidate we require a successful fit of the decay vertex with the flight direction constrained to the pion pair momentum direction, that yields a flight length greater than three times its uncertainty.

We reconstruct the B-meson candidate by combining the four-momenta of a pair of primary 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 four-momentum vector, and all values are expressed in the $\Upsilon(4S)$ rest frame. The resolution in $m_{\rm ES}$ is $2.4-2.8$ MeV and in ΔE is 22–46 MeV, depending on the decay mode. We require $5.25\ \text{GeV} < m_{\rm ES} < 5.29$ GeV and $|\Delta E| < 100$ MeV.

We also impose restrictions on the helicity-frame decay angles of the b_1 and ω mesons. The helicity frame of a meson is defined as the rest frame of the meson with z axis along the direction of boost to that frame from the parent rest frame. For the decay $b_1 \to \omega\pi$, θ_{b_1} is the polar angle of the daughter pion, and for $\omega \to 3\pi$, θ_ω is polar angle of the normal to the 3π decay plane.

Since many misreconstructed candidates accumulate in a corner of the $\cos\theta_{b_1}$ *vs* $\cos\theta_\omega$ plane, we require $\cos\theta_{b_1} \leq \min(1.0,\ 1.1 - 0.5 \times |\cos\theta_\omega|)$.

Backgrounds arise primarily from random combinations of particles in continuum $e^+e^- \to q\overline{q}$ events ($q = u, d, s, c$). We reduce these with a requirement on the angle $\theta_{\rm T}$ between the thrust axis [12] of the B candidate in the $\Upsilon(4S)$ frame and that of the charged tracks and neutral calorimeter clusters in the rest of the event (ROE). The event is required to contain at least one charged track not associated with the B candidate. The distribution is sharply peaked near $|\cos\theta_{\rm T}| = 1$ for $q\overline{q}$ 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 $|\cos\theta_{\rm T}| < 0.7$.

The average number of candidates found per event in the selected sample is in the range 1.3 to 1.6 (1.4 to 1.6 in signal MC), depending on the final state. We choose the candidate with the largest confidence level for the B-meson geometric fit.

In the ML fit we discriminate further against $q\overline{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines five variables: the polar angles, with respect to the beam axis in the $\Upsilon(4S)$ rest frame, of the B candidate momentum and of the B thrust axis; the flavor tagging category; and the zeroth and second angular moments $L_{0,2}$ of the energy flow, excluding the B candidate, about the B thrust axis. The tagging category [13] is the class of candidate partially reconstructed from the ROE, designed to determine whether, in a signal event, it represents a B or $\overline{B}$ meson. 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 daughters. The Fisher variable provides about one standard deviation of separation between B decay events and combinatorial 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 samples contain $q\overline{q}$ (dominant) and $B\overline{B}$ with $b \to c$ combinatorial background, and a fraction of cross feed from other charmless $B\overline{B}$ modes, which we estimate from the simulation to be (0.5–1.1)%. The last include nonresonant $\omega\pi\pi$, $\omega K\pi$, 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. We account for these with a separate component in the probability density function (PDF).

The likelihood function is

$$\mathcal{L} = \exp\Big(-\sum_j Y_j\Big) \prod_i^N \sum_j Y_j \times \mathcal{P}_j({m_{\rm ES}}^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(\Delta E^i)\mathcal{P}_j(m_{b_1}^i)\mathcal{P}_j(m_\omega^i), \quad (1)$$

where N is the number of events in the sample, and for each component j (signal, combinatorial background, or charmless $B\overline{B}$ cross feed), Y_j is the yield of events 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. The fraction of misreconstructed candidates is 32-40%, depending on the mode. The factored form of the PDF indicated in Eq. 1 is a good approximation, particularly for the combinatorial $q\overline{q}$ component, since we find correlations among observables in the data (which are mostly $q\overline{q}$ background) are generally less than 2%, with none exceeding 5%. 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 $B\overline{B}$ 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. $B \to D(K\pi\pi)\pi$, $B \to D(K\pi\pi)\rho$). We develop PDFs for the combinatorial background with fits to the data from which the signal region ($5.27\ \mathrm{GeV} < m_{\rm ES} < 5.29\ \mathrm{GeV}$ and $|\Delta E| < 75\ \mathrm{MeV}$) 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 $q\overline{q}$ background, the threshold function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with argument $x \equiv 2m_{\rm ES}/\sqrt{s}$ and shape parameter ξ. These functions are discussed in more detail in [14], and are illustrated in Figs. 1 and 2.

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 $q\overline{q}$ background asymmetries. Specifically, the free background parameters are: ξ for $m_{\rm ES}$, linear and quadratic coefficients for ΔE, and the mean, width, width difference, and polynomial fraction parameters for $\mathcal{F}$.

We validate the fitting procedure by applying it to ensembles of simulated experiments with the $q\overline{q}$ component drawn from the PDF, into which we have embedded known numbers of signal and $B\overline{B}$ background events randomly extracted from the fully simulated MC samples. By tuning the number of embedded events until the fit reproduces the yields found in the data, we determine the biases that are reported, along with the signal yields, in Table I.

In Figs. 1 and 2 we show the projections of the PDF and data for each fit. The data plotted are subsamples enriched in signal with the requirement of a minimum value of the ratio of signal to total likelihood (computed without the plotted variable) that retains (30–50)% of the signal, depending on the mode.

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 times secondary decay branching fractions 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})	$\mathcal{A}_{ch}$
$b_1^+ K^0$	9841	164^{+27}_{-25}	15±7	3.4	6.3	$9.6 \pm 1.7 \pm 0.9$	$-0.03 \pm 0.15 \pm 0.02$
$b_1^0 K^0$	5420	58^{+19}_{-17}	5±3	2.2	3.4	$5.1 \pm 1.8 \pm 0.5$ (< 7.8)	
$b_1^+ \pi^0$	28787	71^{+35}_{-32}	8±4	7.7	1.6	$1.8 \pm 0.9 \pm 0.2$ (< 3.3)	
$b_1^0 \pi^0$	10554	6^{+19}_{-16}	−2±2	4.8	0.5	$0.4 \pm 0.8 \pm 0.2$ (< 1.9)	

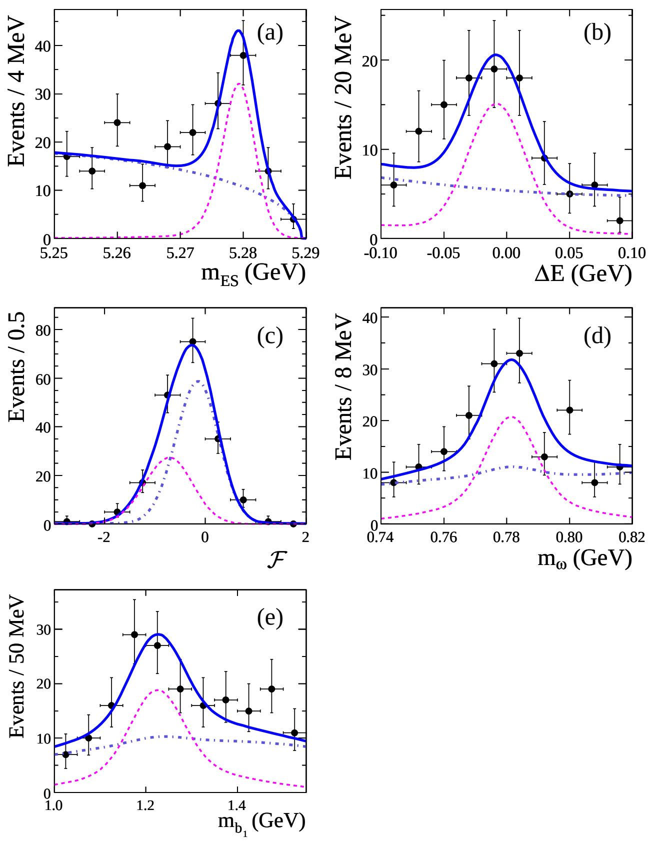

FIG. 1: Distributions for signal-enhanced subsets (see text) of the data projected onto the fit observables for the decay $B^+ \to b_1^+ K^0$; (a) $m_{\rm ES}$, (b) ΔE, (c) $\mathcal{F}$, (d) $m(\pi^+\pi^-\pi^0)$ for the ω candidate, and (e) $m(\omega\pi)$ for the b_1 candidate. The solid lines represent the results of the fits, and the dashed and dot-dashed lines the signal and background contributions respectively.

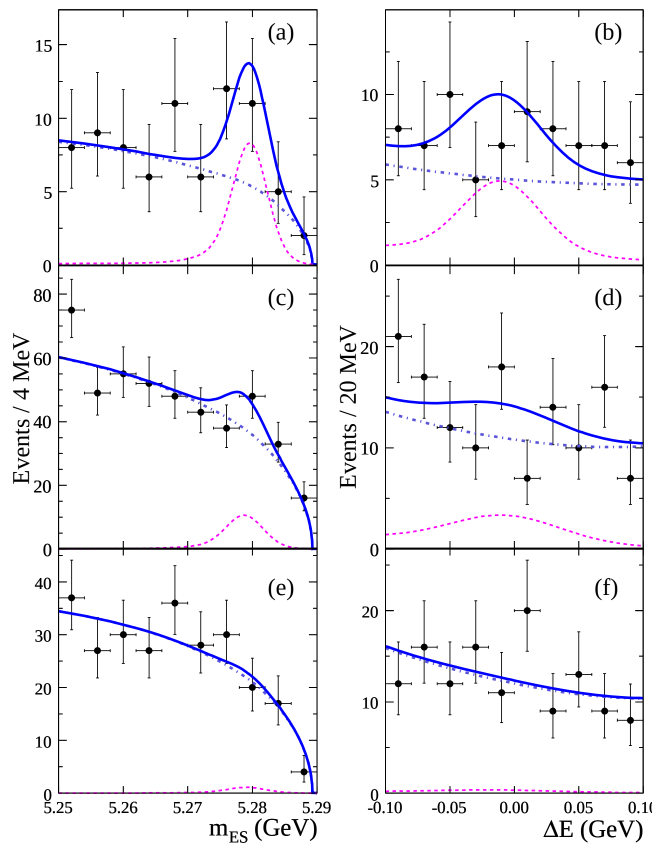

FIG. 2: Distributions for signal-enhanced subsets (see text) of the data projected onto $m_{\rm ES}$ (a, c, e) and ΔE (b, d, f) for the decays $B^0 \to b_1^0 K^0$ (a, b), $B^+ \to b_1^+ \pi^0$ (c, d), and $B^0 \to b_1^0 \pi^0$ (e, f). The solid lines represent the results of the fits, and the dashed and dot-dashed lines the signal and background contributions respectively.

We compute the branching fraction by subtracting the fit bias from the measured yield, and dividing the result by the number of produced $B\overline{B}$ pairs and by the efficiency times $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0) = 89.1 \pm 0.7\%$ (and for the modes with K^0_S, $\mathcal{B}(K^0 \to K^0_S \to \pi^+\pi^-) = \frac{1}{2}(69.20 \pm 0.05)\%$) [5]. The efficiency is obtained from the MC signal model. We assume that the branching fractions of the $\Upsilon(4S)$ to B^+B^- and $B^0\overline{B}^0$ are each equal to 0.5, consistent with measurements [5]. 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, $B\overline{B}$ 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 and data in control modes. Varying the signal-PDF parameters within these errors, we estimate yield uncertainties of (1.6–6.4)%, depending on the mode. We estimate the uncertainty of the MC model of misreconstructed signal by performing alternate fits with a signal PDF determined from true signal events only; we find differences of 1-4 events between these and the nominal fits. 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 $B\overline{B}$ 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 $q\overline{q}$ 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 to be negligible), and from imperfect modeling of the interactions with material in the detector, by measuring the asymmetries in the $q\overline{q}$ background in the data and control samples mentioned previously, in comparison with MC [15]. We assign a systematic error for $\mathcal{A}_{ch}$ equal to 0.01.

With the assumption that $\mathcal{B}(b_1 \to \omega\pi) = 1$, we obtain for the branching fractions (in units of 10^{-6}):

$$\begin{aligned}
\mathcal{B}(B^+ \to b_1^+ K^0) &= 9.6 \pm 1.7 \pm 0.9 \\
\mathcal{B}(B^0 \to b_1^0 K^0) &= 5.1 \pm 1.8 \pm 0.5 \ (< 7.8) \\
\mathcal{B}(B^+ \to b_1^+ \pi^0) &= 1.8 \pm 0.9 \pm 0.2 \ (< 3.3) \\
\mathcal{B}(B^0 \to b_1^0 \pi^0) &= 0.4 \pm 0.8 \pm 0.2 \ (< 1.9).
\end{aligned}$$

The first error quoted is statistical and the second systematic. We find no evidence for the modes with π^0; the evidence for $\mathcal{B}(B^0 \to b_1^0 K^0)$ has a significance of 3.4 standard deviations. For these modes we quote also 90% confidence level upper limits, given in parentheses. We observe the decay $\mathcal{B}(B^+ \to b_1^+ K^0)$, and measure the charge asymmetry

$$\mathcal{A}_{ch}(B^+ \to b_1^+ K^0) = -0.03 \pm 0.15 \pm 0.02.$$

The QCD factorization estimates [9] for the branching fractions and charge asymmetry (0.014) agree with these measurements within experimental and theoretical errors. We find no evidence for direct *CP* violation in $\mathcal{B}(B^+ \to b_1^+ K^0)$.

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