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Search for B-meson decays to $b_1\rho$ and b_1K^*

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We present a search for decays of B mesons to final states with a b_1 meson and a ρ or $K^*(892)$ meson. The search is based on a data sample consisting of 465 million $B\bar{B}$ pairs collected by the *BABAR* detector at the SLAC National Accelerator Laboratory. We do not observe any statistically significant signal. The upper limits we set on the branching fractions range from 1.4 to 8.0×10^{-6} at the 90% confidence level, including systematic uncertainties.

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Measurements of charmless hadronic B decays are a powerful tool to test standard model predictions and search for new physics effects. One of the outstanding problems is represented by the so-called *polarization puzzle* in decays of B mesons to a pair of spin-one mesons. Simple helicity arguments predict a longitudinal polarization f_L close to 1. Contrary to this, several vector-vector (VV) decay modes such as $B \to \phi K^*$ [1], $B \to \rho^+ K^{*0}$ [2], and $B \to \omega K^*$ [3] exhibit $f_L \sim 0.5$. Possible explanations for this puzzle have been proposed within the standard model [4] and in new physics scenarios [5].

The measurement of the branching fractions and polarization of charmless decays of B mesons to an axial-vector and vector meson (AV) may shed light on the size of the amplitudes contributing to charmless B-meson decays and on their helicity structure. Theoretical predictions of decay rates have been performed with the naive factorization [6] and QCD factorization (QCDF) [7] approaches. The naive factorization calculations find the rates of $B \to AV$ decays to be smaller than the corresponding B decays to an axial-vector and pseudoscalar meson (AP). The more complete QCDF calculations find the reverse, primarily due to the larger decay constants (ρ vs π for instance); the expected branching fractions for the AV modes are substantial in several cases, as large as 33×10^{-6} for the $B^0 \to b_1^- \rho^+$ final state.

Additionally, decays of B mesons to charmless AV final states may be sensitive to penguin annihilation effects, which tend to enhance certain modes while suppressing others. It is thus important to investigate the largest possible number of final states.

Measurements of the branching fractions to AP modes $b_1 h$, where h denotes a charged or neutral pion or kaon, are presented in Ref. [8]. The results are in good agreement with the predictions of QCDF [9]. Searches for the AV decays to the final states $a_1^\pm \rho^\mp$ and $a_1^+ K^{*0}$ are presented in Ref. [10], with upper limits on the branching fractions of 30×10^{-6} and 1.6×10^{-6} (at the 90% C.L.), respectively. In this paper we search for all charge combinations of decays of a B meson to a final state containing a b_1 meson and a ρ or $K^*(892)$ meson. No previous searches for these decays have been reported.

The data sample used for these measurements was collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider located at the SLAC National Accelerator Laboratory. The integrated luminosity taken at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV) corresponds to 424 fb^{-1} and is equivalent to $(465 \pm 5) \times 10^6$ $B\bar{B}$ pairs. The *BABAR* detector is described in detail elsewhere [11].

We reconstruct B-meson daughter candidates through the decays $b_1 \to \omega\pi$ (we assume this branching fraction to be 1 [12]), $\omega \to \pi^+\pi^-\pi^0$, $\rho^+ \to \pi^+\pi^0$, $\rho^0 \to \pi^+\pi^-$, $K^{*0} \to K^+\pi^-$, and $K^{*+} \to K^+\pi^0$ or $K_S^0\pi^+$. We impose the following requirements on the masses of the selected candidates: $1000 < m(b_1) < 1550$ MeV, $740 < m(\omega) < 820$ MeV, $470 < m(\rho) < 1070$ MeV, and $755 < m(K^*) < 1035$ MeV; these cuts allow some sidebands, which help estimating the background level. Neutral pions are reconstructed via the decay $\pi^0 \to \gamma\gamma$; photon candidates with a minimum energy of 50 MeV are combined, and we require the pion energy to exceed 250 MeV in the laboratory frame. The invariant mass of the π^0 candidate is required to be in the interval 120–150 MeV. We select $K_S^0 \to \pi^+\pi^-$ candidates in the mass range $486 < m(K_S^0) < 510$ MeV; a kinematic fit constraining the two pion tracks to originate from the same vertex is performed and we require the K_S^0 flight length to be greater than 3 times its uncertainty. The daughters of b_1, ω, ρ, and K^* are rejected if their particle identification signatures are consistent with those of protons or electrons. K^+ candidates must be positively identified as kaons, while π^+ must fail kaon identification. Unless otherwise stated, charge-conjugate reactions are implied.

The helicity angles of the (axial-) vector mesons are measured in their rest frame. For the b_1 candidate, the helicity angle is defined as the angle between the flight direction of the pion from the $b_1 \to \omega\pi$ decay and the direction of the boost to the b_1 rest frame. We define the helicity angles of the ρ and K^* mesons in an analogous

TABLE I. Selection requirements on the helicity angles of B-daughter resonances.

State	ρ/K^* helicity	b_1 helicity
$b_1^-\rho^+$	$-0.50 < \cos\theta_\rho < 1.00$	$-1.0 < \cos\theta_{b_1} < 1.0$
$b_1^0\rho^+$	$-0.50 < \cos\theta_\rho < 0.80$	$-1.0 < \cos\theta_{b_1} < 0.6$
$b_1^+\rho^0$	$0.0 < \lvert\cos\theta_\rho\rvert < 0.85$	$-1.0 < \cos\theta_{b_1} < 1.0$
$b_1^0\rho^0$	$0.0 < \lvert\cos\theta_\rho\rvert < 0.85$	$-1.0 < \cos\theta_{b_1} < 0.7$
$b_1^\pm K^*$	$-0.85 < \cos\theta_{K^*} < 1.0$	$-1.0 < \cos\theta_{b_1} < 1.0$
$b_1^0 K^*$	$-0.85 < \cos\theta_{K^*} < 1.0$	$-1.0 < \cos\theta_{b_1} < 0.8$

manner using the direction of the daughter pions [for the $\rho^\pm$ (ρ^0) we use the (positively) charged pion]. Finally, the helicity angle of the ω is taken as the angle between the normal to the 3π decay plane and the direction of the boost to the ω rest frame. To suppress backgrounds originating from low-momentum particles, we apply the selection criteria summarized in Table I. Integration over the angle between the b_1 and V decay planes yields the following expression for the distribution $F(\theta_A, \theta_V) \propto d^2\Gamma/d\cos\theta_A d\cos\theta_V$ in the b_1 and ρ/K^* helicity angles θ_A and θ_V:

$$F(\theta_A, \theta_V) = f_L\left[\cos^2\theta_A + \left|\frac{C_1}{C_0}\right|^2 \sin^2\theta_A\right]\cos^2\theta_V + (1 - f_L)\frac{1}{4}\left[\sin^2\theta_A + \left|\frac{C_1}{C_0}\right|^2 (1 + \cos^2\theta_A)\right] \times \sin^2\theta_V. \quad (1)$$

Here f_L is the longitudinal polarization fraction $|A_0|^2/\sum|A_i|^2$, where A_i, $i = -1, 0, 1$, is a helicity amplitude of the $B \to AV$ decay. The C_i are the helicity amplitudes of $b_1 \to \omega\pi$; by parity conservation $C_{-1} = C_1$. The b_1 decays have been studied in terms of the two parity-allowed S and D partial wave amplitudes, which have the measured ratio $D/S = 0.277 \pm 0.027$ [12]. From this we obtain the ratio of helicity amplitudes in Eq. (1) [13]

$$\frac{C_1}{C_0} = \frac{1 + (D/S)/\sqrt{2}}{1 - \sqrt{2}(D/S)}.$$

Two kinematic variables characterize the decay of a B meson: the energy-substituted (ES) mass $m_{\rm ES} \equiv \sqrt{s/4 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E_B - \sqrt{s}/2$, where $(E_B, \mathbf{p}_B)$ is the B-meson four-momentum vector expressed in the $\Upsilon(4S)$ rest frame. The correlation between the two variables is at the few percent level. The resolution on $m_{\rm ES}$ is about 2.6 MeV, while the resolution on ΔE varies between 20 and 40 MeV depending on the number of π^0 mesons in the final state. We select events with $5.25 < m_{\rm ES} < 5.29$ GeV and $|\Delta E| < 0.1$ GeV except that for $b_1^0\rho^+$ we require $-0.12 < \Delta E < 0.10$ GeV to allow for the broader signal distribution when two π^0 mesons are present. The average number of B candidates per event in the data is between 1.3 and 1.6. We choose the candidate with the highest value of probability in the fit to the B vertex.

The dominant background originates from continuum $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$). The angle θ_T between the thrust axis [14] of the B candidate in the $\Upsilon(4S)$ rest frame and that of the remaining particles in the event is a powerful discriminating variable to suppress this background. Continuum events peak near 1.0 in the $|\cos\theta_T|$ distribution, while B decays are almost flat. We require $|\cos\theta_T| < 0.7$ for all the decay modes except $b_1^+\rho^0$ for which we require $|\cos\theta_T| < 0.55$, because of substantially higher backgrounds. To further reduce continuum background we define a Fisher discriminant ($\mathcal{F}$) based on five variables related to the event topology: the polar angles, with respect to the beam axis, of the B candidate momentum and the B thrust axis; the zeroth and second angular moments L_0 and L_2 of the energy flow, excluding the B candidate; and the flavor tagging category [15]. The first four variables are calculated in the $\Upsilon(4S)$ rest frame. 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. The Fisher variable provides about 1 standard deviation of separation between B-decay events and combinatorial background.

The signal yields are obtained from extended maximum likelihood fits to the distribution of the data in nine observables: ΔE, $m_{\rm ES}$, $\mathcal{F}$, m_k, and $\cos\theta_k$; m_k and θ_k are the mass and the helicity angle of meson k ($k = b_1$, ω, and either ρ or K^*). For each category j (signal, $q\bar{q}$ background and backgrounds originating from $B\bar{B}$ decays), we define the probability density functions (PDFs) $\mathcal{P}_j(x)$ for the variable x, with the associated likelihood $\mathcal{L}$:

$$\mathcal{L} = \frac{e^{-(\sum_j Y_j)}}{N!}\prod_{i=1}^{N}\sum_j Y_j \mathcal{P}_j(\Delta E^i)\mathcal{P}_j(m_{\rm ES}^i)\mathcal{P}_j(\mathcal{F}^i) \times \prod_k(\mathcal{P}_j(m_k^i)\mathcal{P}_j(\cos\theta_k^i)), \quad (2)$$

where Y_j is the event yield for component j and N is the number of events entering the fit. We separately model correctly reconstructed signal events and self-cross feed (SXF) events, which are signal events for which particles are incorrectly assigned to the intermediate resonances, or particles from the rest of the event are selected. The fraction of SXF is 0.33–0.57 depending on the final state. The signal yields for the branching fraction measurements are extracted with the use of correctly reconstructed signal events only.

Backgrounds originating from B decays are modeled from Monte Carlo (MC) simulation [16]. We select the most significant charmless modes (20–40 for each signal final state) entering our selection and build a sample taking into account measured branching fractions or theoretical predictions. The expected charmless $B\bar{B}$ background yield varies between 26 and 330 events, depending on the final state. The samples include the nonresonant contributions affecting $b_1\rho$ (b_1K^*), measured in our data by fitting the central regions of the $b_1\pi\pi$ ($b_1K\pi$) and $\omega\pi\rho$ ($\omega\pi K^*$) Dalitz plots. We assume the probability of the four-body nonresonant contributions to pass our selections to be negligible. We do not introduce a component modeling B decays to charmed mesons, since this background is effectively absorbed in the $q\bar{q}$ component.

For the K^* modes we consider the potential background contribution originating from $K\pi$ S-wave entering the $K^*(892)$ selection. We model this component using the LASS model [17,18] which accounts for the interference between the $K_0^*(1430)$ resonance and the nonresonant component. The shape of the $K\pi$ invariant mass is kept fixed to the results found in [17]; we fit for the LASS yield in the range $1035 < m(K\pi) < 1550$ MeV and extrapolate the expected yield to the signal region $755 < m(K\pi) < 1035$ MeV. We find yields that are consistent with zero, ranging from -56 to 65 events. We fix this yield to zero if it is negative and take the estimated value otherwise.

PDF shapes for signal, $K\pi$, and $B\bar{B}$ backgrounds are determined from fits to MC samples, while for the $q\bar{q}$ background we use data samples from which the signal region, $5.27 < m_{ES} < 5.29$ GeV and $|\Delta E| < 0.075$ GeV, is excluded. The calibration of m_{ES} and ΔE is validated using high-statistics data control samples of B decays to charmed mesons with similar topologies (e.g. $B \to D(K\pi\pi)\pi$, $B \to D(K\pi\pi)\rho$).

We use linear combinations of polynomial, exponential, and Gaussian functions to parametrize most of the PDFs. For $q\bar{q}$ background, we adopt a parametrization motivated by phase-space arguments [19].

We allow the most important parameters of the $q\bar{q}$ background to vary in the fit, along with the signal yield. Given that the signal yields we extract are small, we cannot vary the longitudinal polarization fraction f_L. Since no strong theoretical predictions exist about its value, we impose $f_L = 0.5$ and vary it within the physical range to evaluate the systematic uncertainty. We do not include the SXF component in fits with signal yields that are consistent with zero to avoid instabilities in the SXF fitted yield. In the case of the $b_1^0K^{*0}$mode, where the (statistical only) signal significance exceeds 3 standard deviations, we retain the SXF component, fixing its yield to correspond to the rate given by the simulation for its size compared with the signal yield. In this case, introducing the SXF component causes the signal yield to vary by a small fraction of the statistical error.

To evaluate the potential bias Y_0 that arises from neglecting the correlations among the variables entering the fit, we perform fits to ensembles of simulated experiments. Each such experiment has the same number of signal and background events as the data; $q\bar{q}$ events are generated from the PDFs, while for the other categories events are taken from fully simulated MC samples.

We compute the branching fraction $\mathcal{B}$ for each mode by subtracting Y_0 from the fitted signal yield Y and dividing by the efficiency ε and the number of B mesons in our data sample. We assume the branching fractions of the $\Upsilon(4S)$ to B^+B^- and $B^0\bar{B}^0$ to be each 50%, consistent with measurements [12]. We evaluate ε from signal MC samples, taking into account the difference in reconstruction efficiency for longitudinally and transversely polarized events. For the K^{*+} modes, we combine the branching fraction results from the two submodes by adding their $-2\ln\mathcal{L}$ curves. The significance S is computed from the difference between the value of $-2\ln\mathcal{L}$ at zero signal and its minimum value. The results are summarized in Table II while in Fig. 1 we show the projection plots onto the m_{ES} variable for the ten final states we investigated. We do not observe a statistically significant signal for any of the eight decay

TABLE II. Signal yield Y and its statistical uncertainty, bias Y_0, detection efficiency ε, significance S (including systematic uncertainties) and central value of the branching fraction $\mathcal{B}$ with associated upper limit (U.L.) at 90% C.L. The efficiency ε takes into account the product of the branching fractions of the intermediate resonances.

Mode	Y (events)	Y_0 (events)	ε (%)	S (σ)	$\mathcal{B}$ (10^{-6})	$\mathcal{B}$ U.L. (10^{-6})
$b_1^-\rho^+$	-33 ± 10	4 ± 2	3.0		$-1.8 \pm 0.5 \pm 1.0$	1.4
$b_1^0\rho^+$	-18 ± 5	-4 ± 2	1.1		$-3.0 \pm 0.9 \pm 1.8$	3.3
$b_1^+\rho^0$	37 ± 25	8 ± 4	3.6	0.4	$1.5 \pm 1.5 \pm 2.2$	5.2
$b_1^0\rho^0$	-8 ± 19	5 ± 3	2.4		$-1.1 \pm 1.7^{+1.4}_{-0.9}$	3.4
$b_1^-K^{*+}$				1.7	$2.4^{+1.5}_{-1.3} \pm 1.0$	5.0
$b_1^-K^{*+}_{K^+\pi^0}$	3 ± 8	-5 ± 3	0.8	0.9	$1.8 \pm 1.9 \pm 1.4$	
$b_1^-K^{*+}_{K_S^0\pi^+}$	17 ± 9	4 ± 2	0.9	1.5	$3.2 \pm 2.1^{+1.0}_{-1.5}$	
$b_1^0K^{*+}$				0.1	$0.4^{+2.0+3.0}_{-1.5-2.6}$	6.7
$b_1^0K^{*+}_{K^+\pi^0}$	-8 ± 7	-3 ± 2	0.5		$-2.2 \pm 3.0^{+5.0}_{-2.3}$	
$b_1^0K^{*+}_{K_S^0\pi^+}$	3 ± 4	0 ± 0	0.4	0.4	$1.6 \pm 2.5 \pm 3.3$	
$b_1^+K^{*0}$	55 ± 21	15 ± 8	2.8	1.5	$2.9 \pm 1.5 \pm 1.5$	5.9
$b_1^0K^{*0}$	30 ± 15	-6 ± 3	1.7	2.0	$4.8 \pm 1.9^{+1.5}_{-2.2}$	8.0

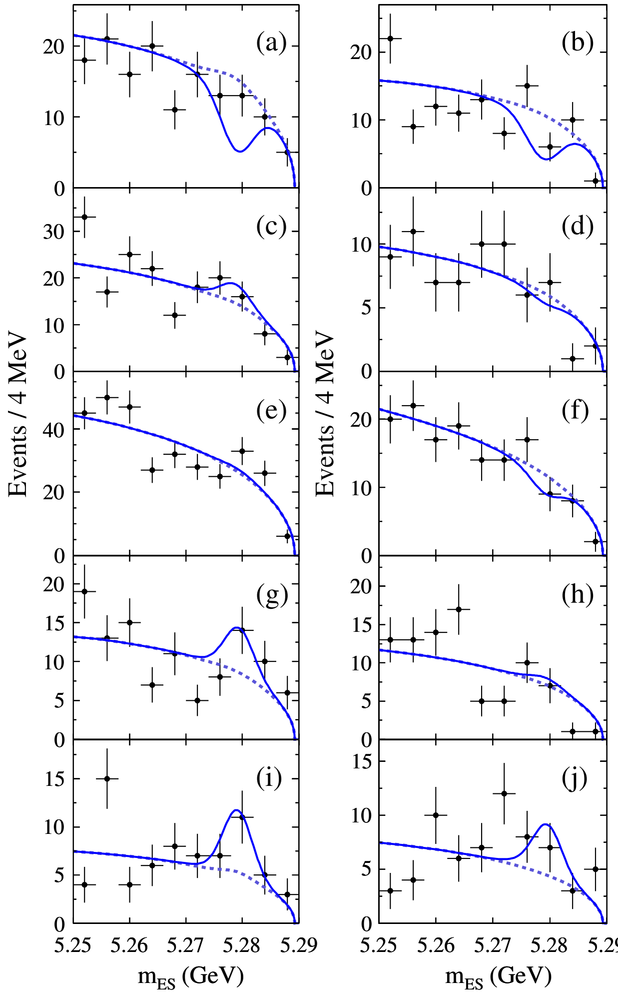

FIG. 1 (color online). Projections onto $m_{\rm ES}$ for the modes (a) $b_1^-\rho^+$, (b) $b_1^0\rho^+$, (c) $b_1^+\rho^0$, (d) $b_1^0\rho^0$, (e) $b_1^-K^{*+}_{K^+\pi^0}$, (f) $b_1^0K^{*+}_{K^+\pi^0}$, (g) $b_1^-K^{*+}_{K_S^0\pi^+}$, (h) $b_1^0K^{*+}_{K_S^0\pi^+}$, (i) $b_1^+K^{*0}$, (j) $b_1^0K^{*0}$. Points with error bars represent the data, the solid (dashed) line represents the total (sum of the backgrounds) fitting function. The background is suppressed by a cut on $\ln\mathcal{L}$, optimized separately for each final state.

modes. We quote upper limits on their branching fractions at the 90% C.L., taken as the branching fractions below which lie 90% of the totals of the likelihood integrals, constraining the branching fractions to be positive. The systematic uncertainties are taken into account by convolving the likelihood function with a Gaussian of width corresponding to the total systematic uncertainties.

We study the systematic uncertainties due to imperfect modeling of the signal PDFs by varying the relevant parameters by their uncertainties, derived from the consistency of fits to data and control samples (the systematic uncertainty on the signal yield varies from 0.6 to 4.1 events, depending on the final state). The uncertainty due to the bias correction is taken as the sum in quadrature of half the correction itself and its statistical uncertainty (0.4–7.5 events). We vary the yield of the $B\bar{B}$ backgrounds by $\pm 50\%$ (the resulting uncertainty is 0.1–8.5 events) and the yield of the S-wave $K\pi$ component by the larger of $\pm 100\%$ of the extrapolated yield and its statistical uncertainty (0.2–14.3 events). The asymmetric uncertainty associated with f_L is estimated by taking the difference in the measured $\mathcal{B}$ between the nominal fit ($f_L = 0.5$) and the maximum and minimum values found in the scan along the range [0, 1]. We divide these values by $\sqrt{3}$, motivated by our assumption of a flat prior for f_L in its physical range; this is one of the largest sources of systematic uncertainty, ranging from 0.1 to 3.6×10^{-6}. Another large source of uncertainty is imperfect knowledge of the SXF fraction; based on studies of control samples performed in similar analyses, we assign a 5% multiplicative systematic uncertainty on the SXF fraction (relative to correctly reconstructed signal) for each π^0 in the final state. Other uncertainties arise from the reconstruction of charged particles (0.4% per track), K_S^0 (1.5%), and π^0 mesons (3% for π^0); the uncertainty in the number of B mesons is 1.1%.

In summary, we present a search for decays of B mesons to $b_1\rho$ and b_1K^* final states. We find no significant signals and determine upper limits at 90% C.L. between 1.4 and 8.0×10^{-6}, including systematic uncertainties. Though these results are in agreement with the small predictions from naive factorization calculations [6], they are much smaller than the predictions from the more complete QCD factorization calculations [7]. The fact that the branching fractions for these AV modes are smaller than our previously measured AP modes [8] is surprising given that the opposite is expected based on the ratio of the vector and pseudoscalar decay constants.

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