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 $\rho$ 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 $8.0 \times 10^{-6}$ at the 90% confidence level (C.L.), 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 pu-
which tend to enhance certain modes while suppressing states may be sensitive to penguin annihilation effects, AV are presented in Ref. [8]. The results are in good agreement at the collected with the B searches for these decays have been reported. 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 [8]. Searches for the AV decays to the final states \( a_1^+ \rho \) and \( a_1^+ K^{*0} \) are presented in Ref. [10], with upper limits on the branching fractions of \( 30 \times 10^{-6} \) and \( 16 \times 10^{-6} \) (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 \( \rho \) 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 \( (465 \pm 5) \times 10^6 B\overline{B} \) pairs. The BaBar detector is described in detail elsewhere [12].

We reconstruct \( B \)-meson daughter candidates through the decays \( b_1 \to \omega \pi \) (we assume this branching fraction to be 1 [11]), \( \omega \to \pi^+ \pi^- \pi^0 \), \( \rho^+ \to \pi^+ \pi^0 \), \( \rho^0 \to \pi^+ \pi^- \), \( K^{*0} \to K^+ \pi^- \), and \( K^{*+} \to K^{*0} \) or \( K^{*0} \). 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 \( \pi^0 \) candidate is required to be in the interval 120–150 MeV. We select \( K^0_S \to \pi^+ \pi^- \) candidates in the mass range \( 486 < m(K^0_S) < 510 \) MeV; a kinematic fit constraining the two pion tracks to originate from the same vertex is performed and we require the \( K^0_S \) flight length to be greater than three times its uncertainty. The daughters of \( b_1, \omega, \rho \) 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 \( \pi^+ \) 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 \( \rho \) and \( K^* \) mesons in an analogous manner using the direction of the daughter pions [for the \( \rho^{\pm} (\rho^0) \) we use the (positively) charged pion]. Finally, the helicity angle of the \( \omega \) is taken as the angle between the normal to the \( 3\pi \) decay plane and the direction of the boost to the \( \omega \) rest frame. To suppress backgrounds originating from low-momentum particles, we apply the selection criteria summarized in Table [1]. 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 \( \rho / K^* \) helicity angles \( \theta_A \) and \( \theta_V \):

\[
F(\theta_A, \theta_V) = f_L \left[ \frac{2}{3} \cos^2 \theta_A + \frac{1}{3} \frac{C_1}{C_0} \sin^2 \theta_A \right] \cos^2 \theta_V + \frac{1}{3} \left( 1 - f_L \right) \left[ \frac{2}{3} \frac{C_1}{C_0} \frac{1}{3} (1 + \cos^2 \theta_A) \right] \sin^2 \theta_V.
\]  

(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 \( D/S = 0.277 \pm 0.027 \) [11]. From this we obtain the ratio of helicity amplitudes in Eq. [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 mass \( m_{ES} \equiv \sqrt{s/4 - \mathbf{p_B}^2} \) 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 mass and the helicity angle of meson observables: \( \Delta E \) and combinatorial background. Continuum events peak near 1.0 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 \( b_1^0 \rho^0 \) for which we require \( |\cos \theta_T| < 0.55 \), because of substantially higher backgrounds. To further reduce continuum background we define a Fisher discriminant \((F)\) 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 \( Y(4S) \) rest frame. The moments are defined by \( L_j = \sum_i p_i \times |\cos \theta_i|^j \), where \( \theta_i \) 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 one 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: \( \Delta E \), \( m_{ES} \), \( F \), \( m_k \), and \( \cos \theta_k \); \( m_k \) and \( \theta_k \) are the mass and the helicity angle of meson \( k \) (\( k = b_1^0, \rho, \) and either \( \rho \) 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) \( P_j(x) \) for the variable \( x \), with the associated likelihood

\[
L = \frac{e^{-(\sum_j Y_j)}}{N!} \prod_{i=1}^{N} \sum_j Y_j \times P_j(\Delta E^i)P_j(m_{ES}^i)P_j(F^i) \prod_k \left( P_j(m_k^i)P_j(\cos \theta^i_k) \right),
\]

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-crossfeed (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 \( b_1 \rho \) \((b_1 K^*)\), measured in our data by fitting the central regions of the \( b_1 \pi \pi \) \((b_1 K \pi )\) and \( \omega \pi \rho \) 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 \( K_1(1430) \) 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 \( \Delta E \) 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 parameterize most of the
PDFs. For $q\bar{q}$ background, we adopt a parameterization 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 $b^0 K^{*0}$ mode, where the (statistical only) signal significance exceeds three 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 $B$ for each mode by subtracting $Y_0$ from the fitted signal yield $Y$ and dividing by the efficiency $\varepsilon$ and the number of $B$ mesons in our data sample. We assume the branching fractions of the $Y(4s)$ to $B^{+}B^{-}$ and $B^{+}B^{0}$ to be each 50%, consistent with measurements [11]. We evaluate $\varepsilon$ 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 sub-modes by adding their $-2\ln L$ curves. The significance $S$ is computed from the difference between the value of $-2\ln L$ at zero signal and its minimum value. The results are summarized in Table I 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 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 ±50% (the resulting uncertainty is 0.1-8.5 events) and the yield of the $S$-wave $K\pi$ component by the larger of ±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 $B$ 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

![FIG. 1: Projections onto $m_{ES}$ for the modes (a) $b_1^- \rho^0$, (b) $b_0^+ \rho^0$, (c) $b_1^- \rho^0$, (d) $b_0^+ \rho^0$, (e) $b_1^- K^{*+} K^{*0}$, (f) $b_0^+ K^{*+} K^{*0}$, (g) $b_1^- K^{*+} K^{*0} +$, (h) $b_0^+ K^{*+} K^{*0} +$, (i) $b_1^- K^{*0}$, (j) $b_0^+ K^{*0}$. 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 $\ln L$, optimized separately for each final state.](attachment://fig1.png)
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 π⁰ in the final state. Other uncertainties arise from the reconstruction of charged particles (0.4% per track), K⁰ (1.5%), and π⁰ mesons (3% for π⁰); the uncertainty in the number of B mesons is 1.1%.

In summary, we present a search for decays of B mesons to b₁ρ and b₁K⁺ 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 naïve factorization calculations [3], 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 [3] is surprising given that the opposite is expected based on the ratio of the vector and pseudoscalar decay constants.

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TABLE II: Signal yield Y and its statistical uncertainty, bias Y₀, detection efficiency ε, significance S (including systematic uncertainties) and central value of the branching fraction 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 (evts) | Y₀ (evts) | ε (σ) | S (10⁻⁶) | B (10⁻⁶) | B U.L. (10⁻⁶) |
|-----------|----------|-----------|-------|----------|----------|--------------|
| b₁⁺ρ⁺     | —33 ± 10 | 4 ± 2     | 3.0   | —1.8 ± 0.5 | 1.0 | 1.4 |
| b₁⁻ρ⁻     | —18 ± 5  | —4 ± 2    | 1.1   | —3.0 ± 0.9 | 1.8 | 3.3 |
| b₁⁺ρ⁰     | 37 ± 25  | 8 ± 4     | 3.6   | 1.5 ± 1.5 | 2.2 | 5.2 |
| b₁⁻ρ⁰     | —8 ± 19  | 5 ± 3     | 2.4   | —1.1 ± 1.1 | 0.9 | 3.4 |
| b₁⁺K⁺     |         |           | 1.7   | 2.4 ± 1.5 | 1.0 | 5.0 |
| b₁⁻K⁺     | 3 ± 8    | —5 ± 3    | 0.8   | 1.8 ± 1.9 | 1.4 |       |
| b₁⁺K⁰     | 17 ± 9   | 4 ± 2     | 0.9   | 3.2 ± 2.1 | 1.5 |       |
| b₁⁻K⁰     |         |           | 0.1   | 0.4 ± 2.9 | 0.9 | 6.7 |
| b₁⁺K⁺π⁰   | —8 ± 7   | —3 ± 2    | 0.5   | —2.2 ± 3.0 | 1.5 |       |
| b₁⁻K⁺π⁰   | 3 ± 4    | 0 ± 0     | 0.4   | 1.6 ± 2.5 | 3.3 |       |
| b₁⁺K⁰π⁰   | 55 ± 21  | 15 ± 8    | 2.8   | 2.9 ± 1.5 | 1.5 | 5.9 |
| b₁⁻K⁰π⁰   | 30 ± 15  | —6 ± 3    | 1.7   | 4.8 ± 1.9 | 2.2 | 8.0 |

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