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Observation of $B^+ \to \rho^+ K^0$ and Measurement of its Branching Fraction and Charge Asymmetry

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We present the first observation of the decay $B^+ \to \rho^+ K^0$, using a data sample of 348 fb^{-1} collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector. The branching fraction and charge asymmetry are measured to be $(8.0^{+1.4}_{-1.3} \pm 0.5) \times 10^{-6}$ and $(-12.2 \pm 16.6 \pm 2.0)\%$, respectively, where the first uncertainty is statistical and the second is systematic. The significance of the observed branching fraction, including systematic uncertainties, is 7.9 standard deviations.

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In the Standard Model (SM) of particle physics, the weak-current couplings of quarks are described by elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. Charmless decays of B mesons provide important information about these couplings. These decays, which have branching fractions of the order of 10^{-6}, are generally expected to occur via $b \to s$ or $b \to d$ virtual loop ("penguin") amplitudes, tree-level $b \to u$ decays, or a combination of the two. Phenomenological fits to the branching fractions and charge asymmetries of charmless B decays can be used to understand the relative importance of tree and penguin amplitudes and to extract measurements of the CKM phase angles.

We present the first observation of the charmless $b \to s$ process $B^+ \to \rho^+ K^0$. Throughout this Letter, the charge conjugate channel is implied unless otherwise stated. We measure the branching fraction and charge asymmetry. The latter is defined as $\mathcal{A}_{\rm ch} = (\Gamma_{B^-} - \Gamma_{B^+})/(\Gamma_{B^-} + \Gamma_{B^+})$ with $\Gamma_{B^\pm}$ the $B^\pm$ decay rate. Data were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider at the Stanford Linear Accelerator Center. The data sample used in the analysis consists of an integrated luminosity of 348 fb^{-1}, corresponding to 383 ± 4 million $B\overline{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance [center-of-mass energy (CM) $\sqrt{s} = 10.58$ GeV].

The $B^+ \to \rho^+ K^0$ decay is expected to be a pure penguin decay [2], making it particularly helpful to separate the contributions of tree and penguin amplitudes in other channels. Phenomenological studes [2–4] of charmless $B \to VP$ decays, with V a vector and P a pseudoscalar meson, assume that the penguin amplitudes p'_V and p'_P are related by $p'_V = -p'_P$, where p'_V (p'_P) is the amplitude for the spectator quark to appear in the V (P) meson. Measurement of the $B^+ \to \rho^+ K^0$ branching fraction can provide a direct test of this assumption [5]. Exploiting U-spin symmetry, Soni and Suprun [6] recently introduced a technique to determine the CKM phase angle γ with precision comparable to the best current measurements, using charmless $B^\pm \to M^\pm M^0$ decays, where $M^\pm$ and M^0 are charged and neutral mesons. Of the eight $M^\pm M^0$ channels necessary to apply this technique to $B^\pm \to V^\pm P^0$ decays, experimental results exist for all but two channels: $B^+ \to \rho^+ K^0$, the topic of this study, and $K^{*+}\overline{K}^0$.

Theoretical predictions of the branching fraction for $B^+ \to \rho^+ K^0$, based on QCD factorization [7, 8], heavy quark effective theory [9], and flavor SU(3) symmetry [2, 10], vary from 10^{-5} to 10^{-6}. The only current experimental result is $\mathcal{B}(B^+ \to \rho^+ K^0) < 4.8 \times 10^{-5}$ at 90% confidence level (CL) [11]. The charge asymmetry for this decay is expected to be zero. Any significant deviation from this expectation would provide evidence for the creation of non-SM particles produced in the loops.

The *BABAR* detector is described elsewhere [12]. In brief, charged particle tracks are detected and their momenta measured by a combination of a five-layer double-sided silicon microstrip detector (SVT) and a 40-layer drift chamber (DCH), both operating in the 1.5 T magnetic field of a superconducting solenoid. Tracks are identified as charged kaons or pions using specific energy loss measurements in the SVT and DCH as well as radiation angles measured in a ring imaging Cherenkov detector. Photons are reconstructed from energy clusters deposited in a CsI(Tl) electromagnetic calorimeter.

Monte Carlo (MC) events are used to determine signal and background characteristics, optimize selection criteria, and evaluate efficiencies. Samples of $e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0$ and B^+B^- events, generated by the `EvtGen` [13] event generator, are passed through the `GEANT`-based [14] *BABAR* detector simulation. The corresponding integrated luminosity of the MC samples is about three times larger than that of the data. We follow a blind procedure: the optimization and systematic study of selection criteria are completed before the data are examined in the region where signal is expected.

A B meson candidate is kinematically characterized by the energy-substituted mass $m_{\rm ES} \equiv \sqrt{s/4 - (p^*_B)^2}$ and the energy difference $\Delta E \equiv E^*_B - \sqrt{s}/2$, where E^*_B and p^*_B are the CM energy and 3-momentum of the B candidate, respectively. Signal events peak at the nominal B mass for $m_{\rm ES}$ and at zero for ΔE.

We reconstruct $B^+ \to \rho^+ K^0$ candidates through the decays $K^0 \to K^0_S \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$, with $\pi^0 \to \gamma\gamma$. The γ energy in the laboratory frame is required to exceed 30 MeV. The π^0 candidates are required to have a mass in the interval [0.115, 0.150] GeV/c^2 and a laboratory energy larger than 0.2 GeV. The π^0 mass resolution is about 6 MeV/c^2. To improve the resolution of $m_{\rm ES}$ and ΔE, the π^0 candidate's mass is constrained to its nominal value. The π^0 candidate is combined with an identified charged pion to form a ρ^+ candidate. We require ρ^+ candidates to have a mass $m_{\pi^+\pi^0}$ in the interval [0.5, 1.0] GeV/c^2. The helicity angle θ_ρ, defined as the angle in the ρ^+ rest frame between the direction of the boost from the B^+ rest frame and the 3-momentum of the π^+ from the ρ^+ decay, is required to satisfy $|\cos\theta_\rho| < 0.9$, since mis-reconstructed π^0 mesons are concentrated near $|\cos(\theta_\rho)| \approx 1$. We form K^0_S candidates by combining all oppositely charged pairs of tracks, by fitting the two tracks to a common vertex, and by requiring the mass to lie in the interval [0.490, 0.506] GeV/c^2 assuming the two tracks to be pions. The K^0_S mass resolution is about 3 MeV/c^2. The angle α between the K^0_S flight direction and its momentum vector is required to satisfy $\cos\alpha > 0.995$, where the flight direction is the direction between the primary and secondary vertices. The K^0_S candidate is combined with the ρ^+ candidate to form a B^+ candidate with a vertex constrained to the beam spot. The K^0_S decay length significance, defined by the distance between the K^0_S and B^+ decay vertices divided by the uncertainty on that quantity, is required to be larger than 5. The χ^2 probabilities of the fitted K^0_S and B^+ vertices are each required to exceed 0.5%. B^+ candidates are required to satisfy $5.25 < m_{\rm ES} < 5.29$ GeV/c^2 and $|\Delta E| < 0.20$ GeV. The typical resolution for ΔE ($m_{\rm ES}$) is approximately 30 MeV (3.0 MeV/c^2). We find that 9.8% of the events contain two or more $B^+ \to \rho^+ K^0$ candidates. For these events, the candidate with the largest B vertex fit probability is retained.

Backgrounds arise primarily from random combinations of tracks and clusters in $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum events. To suppress these events, we use the angle θ_T between the thrust axis of the B candidate's decay products and the thrust axis determined using the remaining charged tracks and neutral clusters in the event, evaluated in the CM frame. The distribution of $|\cos\theta_T|$ is nearly uniform for the almost-isotropic $B\overline{B}$ events and sharply peaked near 1 for the jetlike continuum events. We require $|\cos\theta_T| < 0.9$. Additional use of the event topology is made by employing a Fisher discriminant $\mathcal{F}$, constructed from the angles with respect to the beam axis of the B momentum and the B thrust axis, and the energy flow around the B thrust axis (see Ref. [15]).

Potential backgrounds from B^+B^- and $B^0\overline{B}^0$ events arise from $\overline{B} \to \overline{D}\pi$, $K^*(892)\pi$ and $K^*_0(1430)\pi$ decays that have the same $\pi^+\pi^0 K^0_S$ final state and similar peaking structure in $m_{\rm ES}$ and ΔE as the signal events. The selection requirement applied to $m_{\pi^+\pi^0}$, given above, rejects most of these backgrounds. To further reduce the $B\overline{B}$ background, we apply a D^0 veto ($1.78 \le m_{K^0_S\pi^0} \le 1.94$) GeV/$c^2$, a D^+ veto ($1.83 \le m_{K^0_S\pi^+} \le 1.91$) GeV/$c^2$, a K^{*0} veto ($0.8 \le m_{K^0_S\pi^0} \le 1.0$) GeV/$c^2$, a K^{*+} veto ($0.8 \le m_{K^0_S\pi^+} \le 1.0$) GeV/$c^2$, a $K^{*0}(1430)$ veto ($1.3 \le m_{K^0_S\pi^0} \le 1.6$) GeV/$c^2$, and a $K^{*+}(1430)$ veto ($1.3 \le m_{K^0_S\pi^+} \le 1.6$) GeV/$c^2$, where a veto indicates that an event is rejected if the two-particle invariant mass lies in the specified mass window. These veto criteria are determined as follows: 4 standard deviations of the experimental resolution around the mass peaks for D^+ and D^0, and 2 (1) resonance widths [16] around the mass peak for K^* [$K^*(1430)$]. The decay $B^+ \to K^0_S\pi^+$ ($B^0 \to K^0_S\pi^0$) can contribute to background when the decay products are combined with a low momentum π^0 (π^+). We therefore require the $K^0_S\pi^0$ and $K^0_S\pi^+$ invariant masses to be less than 5.2 GeV/c^2.

These criteria reject more than 99% of the $B\overline{B}$ background channels discussed above and about 30% of the signal. The remaining $B\overline{B}$ background is combinatoric and does not peak in ΔE and $m_{\rm ES}$.

From MC simulation, the signal efficiency is determined to be $(14.78 \pm 0.10)\%$ where the uncertainty is statistical. This efficiency has been corrected to account for small differences in track and neutral particle reconstruction efficiencies between the data and MC, including differences in the identification efficiency of the π^+ used to reconstruct the ρ^+. As an example, the latter correction is determined using a $D^{*+} \to D^0\pi^+$ data control sample with $D^0 \to K^-\pi^+$.

The signal yield and charge asymmetry are determined from an extended unbinned maximum likelihood (ML) fit with the following variables: $m_{\rm ES}$, ΔE, $\mathcal{F}$, $m_{\pi^+\pi^0}$, $\cos\theta_\rho$, and the B flight time significance, with the latter variable defined as the proper time difference Δt between the produced B and $\overline{B}$ candidates divided by its uncertainty $\sigma_{\Delta t}$ [17]. The $\overline{B}$ vertex is determined by fitting all tracks except the daughters of the signal B candidate to a common vertex, employing constraints from the beam spot. The likelihood function has the form

$$\mathcal{L} = \frac{1}{N!}\exp\Big(-\sum_{j=1}^{3} n_j\Big)\prod_{i=1}^{N}\left[\sum_{j=1}^{3} n_j \mathcal{P}_j(\mathbf{x}_i)\right], \qquad (1)$$

where N is the total number of input events, n_j is the fitted yield of component j (signal, continuum, and $B\overline{B}$ background), and $\mathcal{P}_j(\mathbf{x}_i)$ is the corresponding overall probability density function (PDF), given by

$$\begin{aligned}\mathcal{P}_j &= \mathcal{P}_j(m_{\rm ES})\,\mathcal{P}_j(\Delta E)\,\mathcal{P}_j(\mathcal{F})\,\mathcal{P}_j(m_{\pi^+\pi^0}) \\ &\quad\times \mathcal{P}_j(\cos\theta_\rho)\,\mathcal{P}_j(\Delta t/\sigma_{\Delta t}). \qquad (2)\end{aligned}$$

The signal and $B\overline{B}$ background PDFs are determined from MC simulation. The continuum background PDF is obtained from sideband data ($0.1 < |\Delta E| < 0.2$ GeV for $m_{\rm ES}$ and $5.25 < m_{\rm ES} < 5.27$ GeV/c^2 for other variables). For $m_{\rm ES}$, the PDFs of the signal and continuum are parameterized by a Crystal Ball [18] and an ARGUS function [19], respectively. A relativistic Breit-Wigner function with a p-wave Blatt-Weisskopf form factor [20] is used to model the signal $m_{\pi^+\pi^0}$ distribution. For the background components, the ρ mass is modeled by a combination of a polynomial and the signal function. Slowly varying distributions (ΔE for the continuum background, and $\cos\theta_\rho$) are modeled by polynomials. The remaining variables are parameterized with either a Gaussian, the sum of two or three Gaussians, or an asymmetric Gaussian. Dips occur near $|\cos\theta_\rho| = 0.81$ because of the resonance vetoes. We describe these dips by two Gaussians. We use a large data control sample of $B^+ \to \overline{D}^0\pi^+$ ($\overline{D}^0 \to K^0_S\pi^0$) events to verify the simulated resolutions and peak positions of the $m_{\rm ES}$, ΔE, $\mathcal{F}$, and $\Delta t/\sigma_{\Delta t}$ signal PDFs.

Eq. (2) is based on the assumption that the variables in the PDFs are uncorrelated. We evaluate possible bias in the signal yield that might arise from residual correlations, by fitting ensembles of simulated continuum events drawn from the PDFs, in which we embed the expected number of signal and $B\overline{B}$ background events drawn from the MC samples. The bias in the signal yield is determined to be 4.8 ± 1.2 events, where the uncertainty is statistical only.

TABLE I: Summary of results. The uncertainties on the event yields, fit bias, and efficiencies are statistical only.

Parameter	Value
Events in fit	41150
Signal yield (events)	158^{+27}_{-26}
Continuum background yield (events)	$40{,}321^{+210}_{-211}$
$B\overline{B}$ background yield (events)	673^{+71}_{-70}
Fit bias (events)	4.8±1.2
Detection efficiency (%)	14.78±0.10
Daughter branching fractions $\prod \mathcal{B}_i$ (%)	34.18±0.03
Statistical significance (σ)	8.2
Significance with systematics (σ)	7.9
Branching fraction $\mathcal{B}$ ($\times 10^{-6}$)	$8.0^{+1.4}_{-1.3} \pm 0.5$
Charge asymmetry $\mathcal{A}_{\rm ch}$ (%)	$-12.2 \pm 16.6 \pm 2.0$

Table I lists the results of the fit to the data. The fit yields a simultaneous determination of the number of B^+ and B^- signal events, which we use to obtain $\mathcal{A}_{\rm ch}$. The statistical uncertainty of the signal yield is given by the change in the central value when the quantity $-2\ln\mathcal{L}$ increases by one unit from its minimum value. The statistical significance is given by the square root of the difference between the value of $-2\ln\mathcal{L}$ for zero signal events and the value at its minimum. The corresponding significance including systematic uncertainties (discussed below) is determined by convolution of the likelihood function with a Gaussian distribution whose standard deviation equals the total systematic uncertainty. Figure 1 shows projections of the fitted variables. To enhance the visibility of the signal, events are required to satisfy $\mathcal{L}_i(S)/[\mathcal{L}_i(S) + \mathcal{L}_i(B)] > 0.9$. This retains 70.0%, 1.4%, and 14.5% of the signal, continuum, and $B\overline{B}$ background events, respectively, where $\mathcal{L}_i(S)$ is the likelihood function for signal events excluding the PDF of the plotted variable i, and $\mathcal{L}_i(B)$ is the corresponding term for all background components added together.

We calculate the branching fraction by subtracting the fit bias from the measured signal yield and dividing the result by the overall efficiency and the number of produced $B\overline{B}$ pairs $N_{B\overline{B}}$. The overall efficiency is the product of the detection efficiency and the daughter branching fractions [16] (see Table I). We assume equal decay

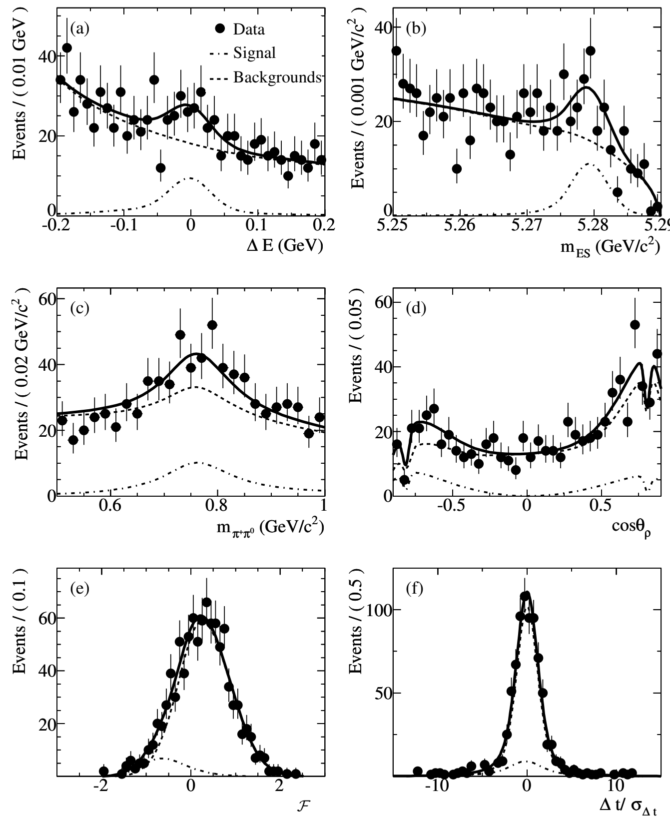

FIG. 1: Distributions of (a) ΔE, (b) $m_{\rm ES}$, (c) $m_{\pi^+\pi^0}$, (d) $\cos\theta_\rho$, (e) $\mathcal{F}$, and (f) $\Delta t/\sigma_{\Delta t}$. To improve visibility, a selection requirement on the likelihood ratio that retains 70.0% of the signal events has been applied. The points with uncertainties are the data. The curves are projections of the ML fit. The dashed curves show the sum of the continuum and $B\overline{B}$ background components. The dot-dashed curves show the signal component. The solid curves show the sum of the signal and background components.

rates of the $\Upsilon(4S)$ to B^+B^- and $B^0\overline{B}^0$. The branching fraction and charge asymmetry are determined to be $(8.0^{+1.4}_{-1.3} \pm 0.5) \times 10^{-6}$ and $(-12.2 \pm 16.6 \pm 2.0)$%, respectively, where the first uncertainty is statistical and the second is systematic. We determine $-0.40 < \mathcal{A}_{\rm ch} < 0.15$ at 90% CL, including systematic uncertainties.

The principal sources of systematic uncertainty are the π^0 reconstruction efficiency (3.0%), the signal PDF parameterization, and the fit bias. The uncertainty related to the signal PDFs is assessed by varying the fitted PDF parameters within their uncertainties as determined from the $B^+ \to \overline{D}^0\pi^+$ data control sample. This leads to an uncertainty of 3.2 events. An uncertainty in the fit bias (2.7 events) is defined by the quadratic sum of half the bias itself and the statistical uncertainty of the bias. Variations of all resonance vetoes yield an uncertainty of 3.1%. When the requirement on $\cos\theta_\rho$ is varied, the results change by less than 2.0%. Other sources of systematic uncertainty are the track reconstruction efficiency (1.6%), the $B\overline{B}$ background PDFs (2.0 events), the uncertainty on $N_{B\overline{B}}$ (1.1%), and variation of the selection criteria on $|\cos\theta_T|$ (1.0%). Uncertainties [16] in the daughter branching fractions make negligible contributions. The individual terms are added in quadrature to obtain the total systematic uncertainty.

In summary, we present the first observation of the pure penguin $b \rightarrow s$ decay process $B^+ \rightarrow \rho^+ K^0$. The significance of the measured branching fraction is 7.9 standard deviations. Using the assumption $p'_V = -p'_P$ [5], the $B^+ \rightarrow \rho^+ K^0$ branching fraction is predicted to lie between about 9 and 13×10^{-6}, consistent with our measurement within the uncertainties. The measured charge asymmetry is consistent with the SM expectation of zero.

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