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Limit on the $B^0 \to \rho^0\rho^0$ Branching Fraction and Implications for the Cabibbo-Kobayashi-Maskawa Angle $\alpha$

We search for the decay $B^0 \rightarrow \rho^0 \rho^0$ in a data sample of about $227 \times 10^6 \, Y(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II asymmetric-energy $e^+ e^-$ collider at SLAC. We find no significant signal and set an upper limit of $1.1 \times 10^{-6}$ at 90% C.L. on the branching fraction. As a result, the uncertainty due to penguin contributions on the Cabibbo-Kobayashi-Maskawa unitarity angle $\alpha$ measured in $B \rightarrow \rho \rho$ decays is decreased to 11$^\circ$ at 68% C.L.

Measurements of CP-violating asymmetries in the $B^0\bar{B}^0$ system provide tests of the standard model by over-constraining the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] through the measurement of the unitarity angles. Measuring the time-dependent CP asymmetry in a neutral-B-meson decay to a CP eigenstate dominated by the tree-level amplitude $b \rightarrow u\bar{u}d$ gives an approximation $\alpha_{\text{eff}}$ to the CKM unitarity angle $\alpha = \arg[-V_{td}V_{tb}^* / V_{ud}V_{ub}^*]$. The correction $\Delta \alpha = \alpha - \alpha_{\text{eff}}$, which accounts for the effects of penguin-amplitude contributions as an additional decay mechanism, can be extracted from an isospin analysis of the branching fractions of the $B$ decays into the full set of isospin-related channels [2].

Measurements of branching fractions and time-dependent CP asymmetries in $B \rightarrow \pi \pi$, $\rho \pi$, and $\rho \rho$ have already provided information on $\alpha$. Because the branching fraction for $B^0 \rightarrow \pi^0 \pi^0$ is comparable to that for $B^+ \rightarrow \pi^+ \pi^0$ and $B^0 \rightarrow \pi^- \pi^+$, the limit on the correction is weak: $|\Delta \alpha_{\pi\pi}| < 35^\circ$ at 90% confidence level (C.L.) [3]. (Charm conjugate B decay modes are implied in this Letter.) In contrast, the $\rho^0 \rho^0$ channel has a much smaller branching fraction than the channels with charged $\rho$'s [4-7]. As a consequence, it is possible to set a tighter limit on $\Delta \alpha_{\rho\rho}$ [2,6,8]. This makes the $\rho \rho$ system particularly effective for measuring $\alpha$ in a model-independent way.

In $B \rightarrow \rho \rho$ decays the final state is a superposition of CP-odd and CP-even states, and an isospin-triangle relation [2] holds for each of the three helicity amplitudes, which can be separated through an angular analysis. The measured polarizations in $B^+ \rightarrow \rho^+ \rho^0$ [4,5] and $B^0 \rightarrow \rho^+ \rho^-$ [6,7] modes indicate that the $\rho$'s are nearly entirely longitudinally polarized. The current best limit on the $B^0 \rightarrow \rho^0 \rho^0$ branching fraction was obtained by BABAR with a sample of $89 \times 10^6 \, Y(4S) \rightarrow B\bar{B}$ decays [4].

In this Letter we present improved constraints on the $B^0 \rightarrow \rho^0 \rho^0$ branching fraction and the penguin contribution to the measurement of the unitarity angle $\alpha$. These results are based on data collected with the BABAR detector [9] at the PEP-II asymmetric-energy $e^+ e^-$ collider [10] located at the Stanford Linear Accelerator Center. A sample of $226.6 \pm 2.5$ million $B\bar{B}$ pairs, corresponding to an integrated luminosity of approximately 205 fb$^{-1}$, was recorded at the $Y(4S)$ resonance with the center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV. We use a sample of 16 fb$^{-1}$ taken 40 MeV below the $Y(4S)$ resonance to study background contributions from $e^+ e^- \rightarrow q\bar{q}$ ($q = u, d, s, \text{ or } c$) continuum events.

To reconstruct $B^0 \rightarrow \rho^0 \rho^0 \rightarrow (\pi^+ \pi^-)(\pi^+ \pi^-)$ candidates, we select four charged tracks that are consistent with originating from a single vertex near the $e^+ e^-$ interaction point. Particle identification is provided by measurements of the energy loss in the silicon vertex tracker and the drift chamber and by the Cherenkov angle in an internally reflecting ring-imaging Cherenkov detector [9].

The angular distribution of the $B^0 \rightarrow \rho^0 \rho^0$ decay products can be expressed as a function of the helicity angles $(\theta_1, \theta_2, \phi)$, which are defined by the directions of the two-body $\rho^0 \rho^0$ decay axes and the direction opposite the $B$ in the $\rho^0$ rest systems, as shown in Fig. 1. Since the detector acceptance does not depend on $\phi$, the resulting angular distribution $d^2\Gamma / (d\cos\theta_1 d\cos\theta_2)$ is

$$\frac{9}{4} \left( 1 - f_L \right) \sin^2 \theta_1 \sin^2 \theta_2 + f_L \cos^2 \theta_1 \cos^2 \theta_2,$$

where $f_L = |A_0|^2 / (|\Sigma| |A_\perp|^2)$ is the longitudinal polarization fraction and $A_\perp$ are the helicity amplitudes.

The identification of signal $B$ candidates is based on two kinematic variables: the beam-energy-substituted mass, $m_{ES} = \left[ (s/2 + p_B \cdot p_B)/E_i^2 - p_B^2 \right]^{1/2}$, where the initial total $e^+ e^-$ four momentum ($E_i, p_B$) and the $B$ momentum $p_B$ are defined in the laboratory frame; and the difference between the reconstructed $B$ energy in the c.m. frame and its known value $\Delta E = E_B - \sqrt{s}/2$. The signal $m_{ES}$ and $\Delta E$ resolutions are 2.6 MeV/$c^2$ and 20 MeV, respectively. The selection requirements for $m_{ES}$, $\Delta E$, the two $\pi^+ \pi^-$ invariant masses $m_{1,2}$, and the helicity angles are the following: $5.24 < m_{ES} < 5.29$ GeV/$c^2$, $|\Delta E| < 85$ MeV, $0.55 < m_{1,2} < 1.00$ GeV/$c^2$, and $|\cos\theta_{1,2}| < 0.99$. The last requirement removes a region with low reconstruction efficiency.

![FIG. 1. Definition of helicity angles $\theta_1$, $\theta_2$, and $\phi$ for the decay $B^0 \rightarrow \rho^0 \rho^0$. The $\rho^0$ final states are shown in the $\rho^0$ rest frames.](image-url)
To reject the dominant continuum background we require $|\cos \theta_j| < 0.8$, where $\theta_j$ is the angle between the $B$-candidate thrust axis and that of the remaining tracks and neutral clusters in the event, calculated in the c.m. frame. We also use as discriminating variables the polar angles of the $B$ momentum vector and the $B$-candidate thrust axis with respect to the beam axis in the c.m. frame, and the two Legendre moments $L_0$ and $L_2$ of the energy flow around the $B$-candidate thrust axis [11]. These variables are combined in a neural network, the output of which is transposed into a variable $\mathcal{E}$ for which the signal and background distributions are approximately Gaussian.

We veto the background mode $B^0 \rightarrow D^- \pi^+ \rightarrow h^+ \pi^- \pi^- \pi^+$, where $h^+$ refers to a pion or kaon. We require the invariant mass of the three-particle combination that excludes the highest-momentum track in the candidate $B$ rest frame to be inconsistent with being the $D$-meson mass $(m_{b\pi\pi} - m_D) > 13 \text{ MeV}/c^2$. After application of all selection criteria, $N_{\text{cand}} = 35740$ events are retained, most of which are background events. On average each selected event has 1.05 candidates. When more than one candidate is present in the same event, one candidate is selected randomly.

The signal selection efficiency determined from Monte Carlo (MC) [12] simulation is 27% or 32% for longitudinally or transversely polarized events, respectively. MC simulation shows that 22% of longitudinally and 8% of transversely polarized signal events are misconstructed with one or more tracks not originating from the $B^0 \rightarrow \rho^0 \rho^0$ decay. These are mostly due to combinatorial background from low-momentum tracks from the other $B$. We treat these as part of the signal.

Further background separation is achieved by the use of multivariate $B$-flavor-tagging algorithms trained to identify primary leptons, kaons, soft pions and high-momentum charged particles from the other $B$ in the event [13]. The discrimination power arises from the difference between the tagging efficiencies for signal and background in five tagging categories $c_{\text{tag}}$.

We use an unbinned extended maximum likelihood fit to extract the $B^0 \rightarrow \rho^0 \rho^0$ event yield. The likelihood function is

$$
\mathcal{L} = \exp \left( -\sum_k n_k \prod_j \left( \sum_i n_{ij} \mathcal{P}_j(\hat{x}_{ij}) \right) \right),
$$

where $n_j$ is the number of events for each hypothesis $j$ (signal, continuum, and six $B$-background classes), and $\mathcal{P}_j(\hat{x}_{ij})$ is the corresponding probability density function (PDF), evaluated with the variables $\hat{x}_{ij} = \{ \delta_{\text{ES}}, \Delta E, \mathcal{E}, m_1, m_2, \cos \theta_1, \cos \theta_2, c_{\text{tag}} \}$ of the $i$th event.

We use MC-simulated events to study the background from other $B$ decays. The charmless modes are grouped into five classes with similar kinematic and topological properties: $B^0 \rightarrow a_1^+ \pi^+$; $B^0 \rightarrow \rho^+ \rho^0$; $B^+ \rightarrow \rho^+ \rho^0$; a combination of $B \rightarrow \rho \pi$ and $B^0 \rightarrow \rho^0 \rho^0$; and $B$ decays to other charmless modes not included explicitly. One additional class accounts for the remaining neutral and charged $B$ decays to charm modes. The number of events in each class $n_j$ is left free in the fit with the exception of three classes where $n_j$ is fixed either to the expectations from independent measurements ($78 \pm 20$ events of $B^+ \rightarrow \rho^+ \rho^0$, and $48 \pm 8$ events of $B \rightarrow \rho \pi$ and $B^0 \rightarrow \rho^+ \rho^0$) or to the extrapolation from the flavor-SU(3)-related $B$-decay modes [4] ($25 \pm 18$ events of $B^0 \rightarrow \rho^0 K^{(*)\pi}$).

Since the correlations among the variables are found to be small, we take each $\mathcal{P}_j$ as the product of the PDFs for the separate variables. Exceptions are the correlation between the two helicity angles in signal, and mass-helicity correlations in backgrounds and misreconstructed signal, taken into account as discussed below.

We use double-Gaussian functions to parameterize the $m_{\text{ES}}$ and $\Delta E$ PDFs for the signal, and a relativistic $P$-wave Breit-Wigner (BW) formula convoluted with a Gaussian resolution function for the resonance masses. The angular distribution for signal, expressed as a function of the longitudinal polarization in Eq. (1), is multiplied by a detector acceptance function $G(\cos \theta_1, \cos \theta_2)$, obtained with MC simulation. The distributions of misreconstructed signal events are parameterized with empirical shapes in a fashion similar to that used for $B$ background, as described below. The $\mathcal{E}$ variable is described by two asymmetric Gaussian functions with different parameters for signal and background distributions.

The $m_{\text{ES}}$ distribution of the continuum background is described with the ARGUS parameterization [14]. The $\Delta E$ and resonance mass $m_{1,2}$ PDFs are parameterized with low-degree polynomials. The parameterization of the $m_1$ and $m_2$ distributions includes a BW resonant component to account for the real $\rho^0$ resonances in the continuum background, which are assumed to be unpolarized and thus to have a flat distribution in $\cos \theta_2$. The $\cos \theta_2$ distribution of the continuum background excluding the real resonances is parameterized with a second-degree polynomial and an exponential function to allow for the increased fraction of combinatorial $\pi^+ \pi^-$ candidates with low-momentum pions near $|\cos \theta_{1,2}| = 1$. This parameterization depends on the $\rho$ candidate’s mass.

The PDFs for exclusive nonsignal $B$ decay modes are generally modeled with empirical nonparametric distributions [15]. However, analytical distributions are used for the variables that have distributions identical to those for signal, such as $m_{\text{ES}}$ when all four tracks come from the same $B$, or $\pi^+ \pi^-$ invariant mass $m_{1,2}$ when both tracks come from a $\rho^0$ meson. The two $\rho^0$ candidates of some exclusive nonsignal modes can have very different mass and helicity distributions. This occurs when one of the two $\rho^0$ candidates is real (e.g., $\rho^+ \rho^0, \rho^0 K^{(*)\pi}$) or when one of the two $\rho^0$ candidates contains a high-momentum pion ($a_1, \pi$). In such cases, we use a four-variable correlated mass-helicity PDF.
The signal and B-background PDF parameters are extracted from MC simulation while the continuum background PDF parameters are obtained from data in $m_{ES}$ and $\Delta E$ sidebands. The MC parameters of $m_{ES}$, $\Delta E$, and $\mathcal{E}$ are adjusted by comparing data and MC in calibration channels with similar kinematics and topology, such as $B^0 \rightarrow D^- \pi^+$ with $D^- \rightarrow K^+ \pi^- \pi^-$. Finally, the B-flavor tagging PDFs for all decay modes are the normalized discrete $c_\text{tag}$ distributions of tagging categories. Large samples of fully reconstructed B-meson decays are used to obtain the B-tagging efficiencies for signal $B$ decays and to study systematic uncertainties in the MC values of B-tagging efficiencies for the $B$ backgrounds.

Table I shows the results of the fit. No significant signal yield is observed. We obtain an upper limit by integrating the normalized likelihood distribution over the positive values of the branching fraction. The value of $f_{L}$ is fixed to 1 in the fit, as this assumption has been shown to give the most conservative upper limit and it approximates the values obtained in the $B \rightarrow \rho \rho$ decays dominated by the tree-level amplitude. The statistical significance is taken as the square root of the change in the likelihood fit. The statistical significance is taken as the square root of the change in the likelihood fit.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$n_{\text{sig}}$ (events)</td>
<td>$33^{+39}_{-20} \pm 12$</td>
</tr>
<tr>
<td>Eff (%)</td>
<td>$27.1 \pm 1.3$</td>
</tr>
<tr>
<td>$\mathcal{B}$ ($\times 10^{-6}$)</td>
<td>$0.54^{+0.36}_{-0.32} \pm 0.19$</td>
</tr>
<tr>
<td>UL ($\times 10^{-6}$)</td>
<td>$1.1$</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>$1.6$</td>
</tr>
</tbody>
</table>

TABLE I. Summary of results: signal yield ($n_{\text{sig}}$), selection efficiency (Eff), branching fraction ($\mathcal{B}$), branching fraction upper limit (UL) at 90% C.L., and significance (including systematic uncertainties). The assumption $f_{L} = 1$ is used. The systematic errors are quoted last.

Uncertainties in the reconstruction efficiency arise from track finding (3%), particle identification (2%), and other selection requirements, such as on vertex probability (2%), track multiplicity (1%), and thrust angle (1%).

Our measurement confirms the small value of the $B^0 \rightarrow \rho^0 \rho^0$ branching fraction with the statistical uncertainty improved by approximately a factor of 2 over our previous result [4]. Since the tree contribution to the $B^0 \rightarrow \rho^0 \rho^0$ decay is color suppressed, the decay rate is sensitive to the penguin amplitude. Thus, this mode has important implications for constraining the uncertainty due to penguin contributions in the measurement of the CKM unitarity angle $\alpha$ with $B \rightarrow \rho \rho$ decays.

In the isospin analysis [2], we minimize a $\chi^2$ that includes the measured quantities expressed as the lengths of the sides of the isospin triangles. We use the measured branching fractions and fractions of longitudinal polarization of the $B^+ \rightarrow \rho^+ \rho^0$ [4,5] and $B^0 \rightarrow \rho^+ \rho^- [6,7]$ decays, the CP-violating parameters $S_L^{+}$ and $C_L^{-}$ obtained from the time evolution of the longitudinally polarized $B^0 \rightarrow \rho^+ \rho^-$ decay [7], and the branching fraction of $B^0 \rightarrow \rho^0 \rho^0$ from this analysis. We neglect isospin-breaking effects, nonresonant, and $I = 1$ isospin contributions [8].

With the $B^0 \rightarrow \rho^0 \rho^0$ measurement we improve the constraint on $\alpha$ due to the penguin contribution and obtain a 68% (90%) C.L. limit on $\Delta \alpha_{\rho \rho} = \alpha - \alpha_{\text{eff}}$ of $\pm 11^{+14}_{-11}$ ($\pm 14^+$). Figure 3 shows the $\Delta \chi^2$ on $\Delta \alpha_{\rho \rho}$. Since the central value from Fig. 3 is $\Delta \alpha_{\rho \rho} = 0$, the central value of $\alpha$ obtained from the isospin analysis is the same as $\alpha_{\text{eff}}$, which is constrained by the relation $\sin(2\alpha_{\text{eff}}) = S_L^{+} / (1 - C_L^{-})^{1/2}$ and is measured with the $B^0 \rightarrow \rho^+ \rho^-$...
to measure the served, time-dependent and angular analyses will allow us to determine the dominant uncertainty in the measurement of the ratio. where the corresponding CKM factors are included in the C convention defined in Ref. [17], and where we adopt the tree amplitude includes the to-tree [19] B⁰ → ρ⁺ρ⁻ amplitude ratio r⁺⁻ = 0.07±0.14, where we adopt the C convention defined in Ref. [17], and where the corresponding CKM factors are included in the ratio.

The error due to the penguin contribution may become the dominant uncertainty in the measurement of the α using B → ρρ decays. However, if B⁰ → ρ⁺ρ⁻ decays are observed, time-dependent and angular analyses will allow us to resolve the ambiguities inherent to isospin-triangle orientations.

In summary, we have improved the precision on the measurement of the B⁰ → ρ⁺ρ⁻ branching fraction by approximately a factor of 2. The limit on this branching fraction relative to those for B⁺ → ρ⁺ρ⁻ and B⁰ → ρ⁺ρ⁻ provides a tight constraint on the penguin uncertainty in the determination of the CKM unitarity angle α. The results summarized in Table I supersede our previous measurement [4].

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

Fig. 3 (color online). Δχ² on Δαₚρ obtained from the isospin analysis discussed in the text. The dashed lines at Δχ² = 1 and Δχ² = 2.7 are taken for the 1σ (68%) and 1.64σ (90%) interval estimates.

The decay [7] to be α_eff = [102⁺⁻¹₂(stat)⁺⁻²⁻¹(syst)]° at 68% C.L., where the solution closest to the CKM best fit central value [17,18] is chosen. For this solution we obtain the penguin-to-tree [19] B⁰ → ρ⁺ρ⁻ amplitude ratio r⁺⁻ = 0.07±0.14, where we adopt the C convention defined in Ref. [17], and where the corresponding CKM factors are included in the ratio.

The error due to the penguin contribution may become the dominant uncertainty in the measurement of the α using B → ρρ decays. However, if B⁰ → ρ⁺ρ⁻ decays are observed, time-dependent and angular analyses will allow us to resolve the CP parameters S_L⁰ and C_L⁰, analogous to S_L⁺⁻ and C_L⁺⁻, resolving ambiguities inherent to isospin-triangle orientations.

In summary, we have improved the precision on the measurement of the B⁰ → ρ⁺ρ⁻ branching fraction by approximately a factor of 2. The limit on this branching fraction relative to those for B⁺ → ρ⁺ρ⁻ and B⁰ → ρ⁺ρ⁻ provides a tight constraint on the penguin uncertainty in the determination of the CKM unitarity angle α. The results summarized in Table I supersede our previous measurement [4].

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*Also at Università della Basilicata, Potenza, Italy
†Deceased
[19] In the C convention [17], the tree amplitude includes the contribution from the difference of the u and the c penguin-type amplitudes, while the penguin amplitude is the difference between the t and c penguin amplitudes. 