BABAR-CONF-06/027
SLAC-PUB-11961
hep-ex/0607097
July 2006

Evidence for the $B^0 \rightarrow \rho^0\rho^0$ Decay and Implications for the CKM Angle α

The *BABAR* Collaboration

July 28, 2006

Abstract

We search for the decays $B^0 \rightarrow \rho^0\rho^0$, $B^0 \rightarrow \rho^0 f_0(980)$, and $B^0 \rightarrow f_0(980)f_0(980)$ in a sample of about 348 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. We find evidence for $B^0 \rightarrow \rho^0\rho^0$ with 3.0σ significance and measure the branching fraction $\mathcal{B} = (1.16^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6}$ and longitudinal polarization fraction $f_L = 0.86^{+0.11}_{-0.13} \pm 0.05$. As a consequence, the uncertainty on the CKM unitarity angle α due to penguin contributions in $B \rightarrow \rho\rho$ decays is estimated to be 18° at 1σ level. We also set upper limits on the $B^0 \rightarrow \rho^0 f_0(980)$ and $B^0 \rightarrow f_0(980)f_0(980)$ decay rates. All results are preliminary.

Submitted to the 33$^{\mathrm{rd}}$ International Conference on High-Energy Physics, ICHEP 06,
26 July—2 August 2006, Moscow, Russia.

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Work supported in part by Department of Energy contract DE-AC02-76SF00515.

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1 INTRODUCTION

Measurements of *CP*-violating asymmetries in the $B^0\overline{B}^0$ 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 $b \to u\bar{u}d$ gives an approximation $\alpha_{\rm eff}$ to the CKM unitarity angle $\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$. The correction $\Delta\alpha = \alpha - \alpha_{\rm eff}$ accounts for the additional contributions from loop (penguin) amplitudes. The value of $\Delta\alpha$ can be extracted from an 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 $B \to \pi\pi$, $\rho\pi$, and $\rho\rho$ have already provided information on α. Because the branching fraction[5] for $B^0 \to \pi^0\pi^0$ is comparable to that for $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^+\pi^-$, the limit on the correction is weak: $|\Delta\alpha_{\pi\pi}| < 41^\circ$ at 90% confidence level (C.L.) [3]. On the contrary, the $B^0 \to \rho^0\rho^0$ decay has a much smaller branching fraction than $B^0 \to \rho^+\rho^-$ and $B^+ \to \rho^+\rho^0$ channels [4–10]. As a consequence, it is possible to set a tighter limit on $\Delta\alpha_{\rho\rho}$ [2, 7, 11]. This makes the $\rho\rho$ system particularly effective for measuring α.

In $B \to \rho\rho$ decays the final state is a superposition of *CP*-odd and *CP*-even states. 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 $B^+ \to \rho^+\rho^0$ [4, 6, 10] and $B^0 \to \rho^+\rho^-$ [7–9] modes indicate that the ρ's are nearly entirely longitudinally polarized. In this paper we present evidence for the $B^0 \to \rho^0\rho^0$ decay, the first measurement of the longitudinal polarization fraction in this decay, and updated constraints on the penguin contribution to the measurement of the unitarity angle α. These results supersede our previous limits on this decay [4, 5].

2 THE *BABAR* DETECTOR AND DATASET

These results are based on data collected with the *BABAR* detector [12] at the PEP-II asymmetric-energy e^+e^- collider [13] located at the Stanford Linear Accelerator Center. A sample of 347.5 ± 1.9 million $B\overline{B}$ pairs, corresponding to an integrated luminosity of approximately 316 $\rm fb^{-1}$, was recorded at the $\Upsilon(4S)$ resonance with the center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV. We use a sample of 28 $\rm fb^{-1}$ taken 40 MeV below the $\Upsilon(4S)$ resonance to study background contributions from $e^+e^- \to q\bar{q}$ ($q = u, d, s, \text{or } c$) continuum events. Charged-particle momenta and trajectories are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber, both within a 1.5-T solenoidal magnetic field. Charged-particle identification is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector.

3 ANALYSIS METHOD

We select $B^0 \to \rho^0\rho^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ candidates from combinations of four charged tracks that are consistent with originating from a single vertex near the e^+e^- interaction point. The identification of signal B candidates is based on several kinematic variables. The beam-energy-substituted mass, $m_{\rm ES} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}$, where the initial total e^+e^- four-momentum

[5] Charge conjugate B decay modes are implied in this paper.

$(E_i, \mathbf{p_i})$ and the B momentum $\mathbf{p_B}$ are defined in the laboratory frame, is centered near B mass with a resolution of 2.6 MeV for signal candidates. The difference between the reconstructed B energy in the c.m. frame and its known value $\Delta E = E_B^{\rm cm} - \sqrt{s}/2$ has a maximum near zero with a resolution of 20 MeV for signal events. Four other kinematic variables describe two possible $\pi^+\pi^-$ pairs: they are invariant masses $m_1(\pi\pi) \equiv m_1$ and $m_2(\pi\pi) \equiv m_2$, and helicity angles θ_1, θ_2.

The angular distribution of the $B^0 \to \rho^0\rho^0$ decay products can be expressed as a function of the helicity angles θ_1 and θ_2, which are defined as the angles between the direction of π^+ and the direction of the B in the rest system of each ρ^0. The resulting angular distribution $d^2\Gamma/(\Gamma\, d\cos\theta_1\, d\cos\theta_2)$ is

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

where $f_L = |A_0|^2/(\Sigma|A_\lambda|^2)$ is the longitudinal polarization fraction and $A_{\lambda=-1,0,+1}$ are the helicity amplitudes.

The selection requirements for signal candidates are the following: $5.240 < m_{\rm ES} < 5.290$ GeV/c^2, $|\Delta E| < 85$ MeV, $550 < m_{1,2} < 1050$ MeV, and $|\cos\theta_{1,2}| < 0.98$. The latter requirement removes a region with low reconstruction efficiency. In addition, we veto the copious decays $B^0 \to D^{(*)-}\pi^+ \to (h^+\pi^-\pi^-)\pi^+$, where h^+ refers to a pion or kaon, by requiring the invariant mass of the three-particle combination to differ from the D-meson mass by more than 13.2 MeV, or 40 MeV if the kaon is positively identified.

We reject the dominant continuum background by requiring $|\cos\theta_T| < 0.8$, where θ_T 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 suppress continuum background further using 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. Other discriminating variables calculated in the c.m. frame include the two Legendre moments L_0 and L_2 of the energy flow around the B-candidate thrust axis [14] and the sum of the transverse momenta of all particles in the rest of the event, calculated with respect to the B direction. These variables are combined in a neural network, whose output is transformed into the approximately Gaussian-distributed variable $\mathcal{E}$.

After application of all selection criteria, $N_{\rm cand} = 65180$ events are retained, most of which are background events, well separated in the kinematic observables from $B^0 \to \rho^0\rho^0$, $B^0 \to \rho^0 f_0(980)$, and $B^0 \to f_0(980)f_0(980)$ signal candidates. On average, each selected background event has 1.05 candidates, while in Monte Carlo (MC) samples we find 1.15 and 1.03 candidates for longitudinally and transversely polarized $B^0 \to \rho^0\rho^0$ decays, respectively. When more than one candidate is present in the same event, the candidate having the best χ^2 consistency with a single four-pion vertex is selected.

The signal selection efficiency determined from Monte Carlo [15] simulation is 23.5% or 28.9% for longitudinally or transversely polarized events, respectively. MC simulation shows that 18% of longitudinally and 4% of transversely polarized signal events are misreconstructed with one or more tracks not originating from the $B^0 \to \rho^0\rho^0$ decay. These are mostly due to combinatorial background from low-momentum tracks from the other B meson in the event.

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 [16]. The discrimination power arises from the difference between the tagging efficiencies for signal and background in seven tagging categories ($c_{\rm tag} = 1-7$).

4 MAXIMUM LIKELIHOOD FIT

We use an unbinned extended maximum likelihood fit to extract the $B^0 \to \rho^0\rho^0$ event yield and fraction of longitudinal polarization f_L. We also fit for the event yield of $B^0 \to \rho^0 f_0$ and $B^0 \to f_0 f_0$ decays, as well as several background categories. The likelihood function is

$$\mathcal{L} = \exp\left(-\sum_k n_k\right) \prod_{i=1}^{N_{\rm cand}} \left(\sum_j \; n_j \, \mathcal{P}_j(\vec{x}_i)\right), \quad (2)$$

where n_j is the number of events for each hypothesis j (signal $B^0 \to \rho^0\rho^0$, five other B-decay classes, and continuum), and $\mathcal{P}_j(\vec{x}_i)$ is the corresponding probability density function (PDF), evaluated with the variables $\vec{x}_i = \{m_{\rm ES}, \Delta E, \mathcal{E}, m_1, m_2, \cos\theta_1, \cos\theta_2, c_{\rm tag}\}$ of the ith event.

We use MC-simulated events to parameterize contributions from other B decays. The charmless modes are grouped into several classes with similar kinematic and topological properties: $B^0 \to \rho^0 f_0(990)$; $B^0 \to f_0(980) f_0(980)$; $B^0 \to a_1^{\pm}\pi^{\mp}$; and a combination of other charmless modes, including $B^0 \to \rho^0 K^{*0}$, $B^+ \to \rho^+\rho^0$, $B \to \rho\pi$, and $B^0 \to \rho^+\rho^-$. 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. We ignore any other four-pion final states in our invariant mass window whose contributions are expected to be small.

Since the statistical 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 kinematic correlation between the two helicity angles in signal, and mass-helicity correlations in other B-decay classes and misreconstructed signal. They are taken into account as discussed below.

We use double-Gaussian functions to parameterize the $m_{\rm ES}$ and ΔE PDFs for signal, and a relativistic Breit-Wigner (BW) for the resonance masses of ρ^0 [18] and $f_0(980)$ [19]. The angular distribution at production for $B^0 \to \rho^0\rho^0$, $B^0 \to \rho^0 f_0$, and $B^0 \to f_0 f_0$ modes (expressed as a function of the longitudinal polarization in Eq. (1) for $B^0 \to \rho^0\rho^0$) is multiplied by a detector acceptance function $\mathcal{G}(\cos\theta_1, \cos\theta_2)$, determined from MC. The distributions of misreconstructed signal events are parameterized with empirical shapes in a way similar to that used for B background, as described below. The $\mathcal{E}$ variable is described by three asymmetric Gaussian functions with different parameters for signal and background distributions.

The PDFs for exclusive non-signal B decay modes are generally modeled with empirical analytical distributions. Several variables have distributions identical to those for signal, such as $m_{\rm ES}$ when all four tracks come from the same B, or $\pi^+\pi^-$ invariant mass $m_{1,2}$ when both tracks come from a ρ^0 meson. In certain exclusive modes the two ρ^0 candidates can have very different mass and helicity distributions, *e.g.* when only one of the two ρ^0 candidates is a genuine ρ^0 meson or when one of the two ρ^0 candidates contains a high-momentum pion (as in $B \to a_1\pi$). In such cases, we use a four-variable correlated mass-helicity PDF.

The signal and B-background PDF parameters are extracted from MC simulation. The initial continuum background PDF parameters are obtained from data in $m_{\rm ES}$ and ΔE sidebands and are then left free in the fit. The MC parameters for $m_{\rm ES}$, ΔE, and $\mathcal{E}$ PDFs are adjusted by comparing data and MC in control channels with similar kinematics and topology, such as $B^0 \to D^-\pi^+$ with $D^- \to K^+\pi^-\pi^-$. Finally, the B-flavor tagging PDFs for all decay modes are the normalized discrete $c_{\rm tag}$ 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.

5 RESULTS

Table 1 shows the results of the fit. The $B^0 \to \rho^0\rho^0$ decay is observed with a significance of 3.0σ, as determined by the quantity $\sqrt{-2\log(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ is the maximum likelihood value, and $\mathcal{L}_0$ is the likelihood for a fit with the signal contribution set to zero. It corresponds to a probability of background fluctuation to the observed signal yield of 0.1%, including systematic uncertainties, which are assumed to be Gaussian-distributed. We do not observe significant event yields for $B^0 \to \rho^0 f_0(980)$ and $B^0 \to f_0(980) f_0(980)$ decays. Background yields are found to be consistent with expectations. In Fig. 1 we show the projections of the fit results onto $m_{\rm ES}$ and ΔE.

Table 1: Summary of results: signal yield ($n_{\rm sig}$, events), fraction of longitudinal polarization (f_L), selection efficiency (Eff), branching fraction ($\mathcal{B}_{\rm sig}$), branching fraction upper limit (UL) at 90% CL, and significance (including systematic uncertainties). The systematic errors are quoted last. We also show the background yields for $a_1\pi$, $B\overline{B}$, and $q\overline{q}$ components (events, with only statistical uncertainties quoted).

Quantity	Value
$n_{\rm sig}$ ($B^0 \to \rho^0\rho^0$)	$98^{+32}_{-31} \pm 22$
f_L	$0.86^{+0.11}_{-0.13} \pm 0.05$
Eff (%)	24.2 ± 1.0
$\mathcal{B}_{\rm sig}$ ($\times 10^{-6}$)	$1.16^{+0.37}_{-0.36} \pm 0.27$
Significance (σ)	3.0 (3.4 statistics only)
$n_{\rm sig}$ ($B^0 \to \rho^0 f_0$)	$12^{+18}_{-17} \pm 13$
Eff (%)	20.7 ± 0.8
$\mathcal{B}_{\rm sig} \times \mathcal{B}(f_0 \to \pi^+\pi^-)$ ($\times 10^{-6}$)	$0.17^{+0.25}_{-0.23} \pm 0.18$
UL$\times\mathcal{B}(f_0 \to \pi^+\pi^-)$ ($\times 10^{-6}$)	0.68
$n_{\rm sig}$ ($B^0 \to f_0 f_0$)	$-5^{+7}_{-6} \pm 12$
Eff (%)	23.5 ± 0.9
$\mathcal{B}_{\rm sig} \times \mathcal{B}^2(f_0 \to \pi^+\pi^-)$ ($\times 10^{-6}$)	$-0.06^{+0.08}_{-0.07} \pm 0.15$
UL$\times\mathcal{B}^2(f_0 \to \pi^+\pi^-)$ ($\times 10^{-6}$)	0.33
$n_{a_1\pi}$	90^{+26}_{-25}
$n_{\rm charmless}$	-17^{+113}_{-99}
$n_{B\overline{B}}$	3280^{+187}_{-194}
$n_{q\overline{q}}$	61719^{+286}_{-289}

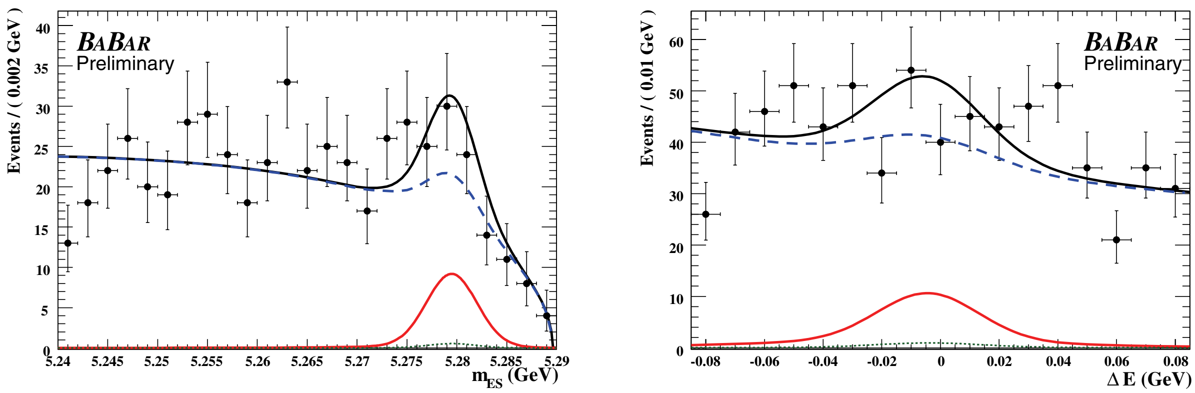

Figure 1: Projections of the multidimensional fit onto $m_{\rm ES}$ and ΔE after a requirement on the signal-to-background probability ratio with the plotted variable excluded. This requirement maximizes the fraction of signal events in the sample. The data points are overlaid by the solid (dashed) line, which shows the full (background only) PDF projection. The individual PDF components are shown for the $B^0 \to \rho^0\rho^0$ (solid red) and $B^0 \to \rho^0 f_0$ modes (dotted green).

6 SYSTEMATIC STUDIES

Dominant systematic errors in the fit originate from statistical uncertainties in the PDF parameterizations, due to the limited number of events in the control samples. The PDF parameters are varied by their respective uncertainties to derive the corresponding systematic errors (15, 11, 12 events for $\rho^0\rho^0$, $\rho^0 f_0$, and $f_0 f_0$ respectively, and 0.05 for f_L). We also assign a systematic error of 2 events for $\rho^0\rho^0$ and $f_0 f_0$ and 7 events for $\rho^0 f_0$ (0.02 for f_L) to account for a possible fit bias, evaluated with MC experiments. The above systematic uncertainties do not scale with event yield and are included in the calculation of the significance of the result. We also assign 8%, 5%, 10% multiplicative systematic error due to possible fit bias for $\rho^0\rho^0$, $\rho^0 f_0$, and $f_0 f_0$ modes, respectively.

We estimate the systematic uncertainty due to the interference between $\rho^0\rho^0$ and $a_1^{\pm}\pi^{\mp}$ final states using simulated samples in which the decay amplitudes for $B^0 \to \rho^0\rho^0$ are generated according to this measurement and those for $B^0 \to a_1^{\pm}\pi^{\mp}$ correspond to a branching fraction of $(39.7 \pm 3.7) \times 10^{-6}$ [20]. Their amplitudes are modeled with a Breit-Wigner function for all $\rho \to \pi\pi$ and $a_1 \to \rho\pi$ combinations and their relative phase is assumed to be constant across the phase space. The strong phases and *CP* content of the interfering state $a_1^{\pm}\pi^{\mp}$ are varied between zero and a maximum using uniform prior distributions. We take the RMS variation of the average signal yield (14 events for the $\rho^0\rho^0$ yield, or 0.03 for f_L) as a systematic uncertainty.

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

7 IMPLICATIONS FOR THE CKM ANGLE α

Since the tree contribution to the $B^0 \to \rho^0\rho^0$ decay is color-suppressed, the decay rate is sensitive to the penguin amplitude. Thus, this mode has important implications for constraining the uncertainty in the measurement of the CKM unitarity angle α due to penguin contributions to $B \to \rho\rho$

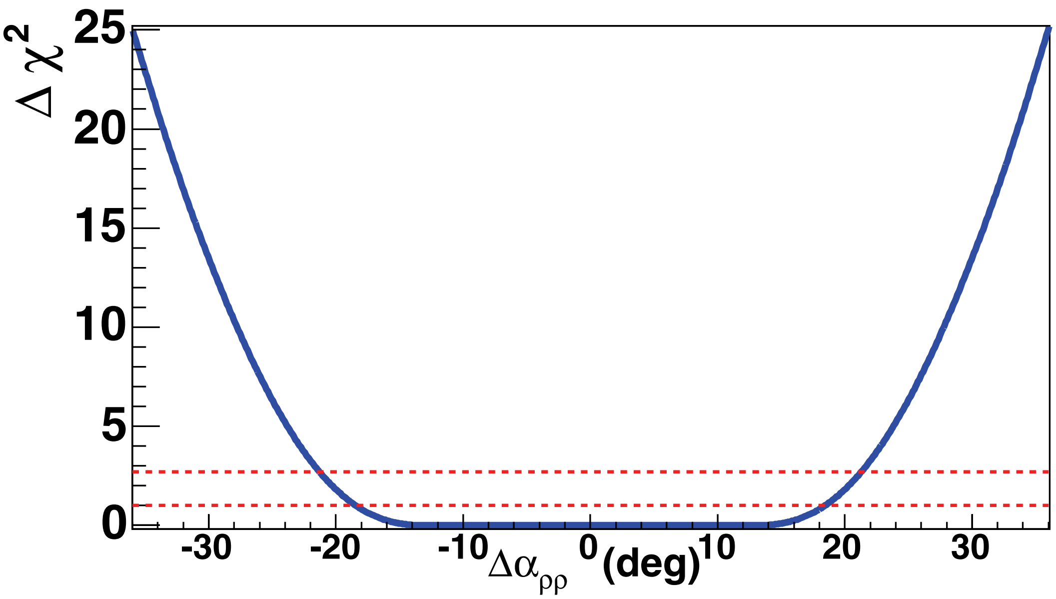

Figure 2: $\Delta\chi^2$ on $\Delta\alpha_{\rho\rho}$ obtained from the isospin analysis discussed in the text. The dashed lines at $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 2.7$ are taken for the 1σ (68%) and 1.64σ (90%) interval estimates.

decays.

In the isospin analysis [2], we minimize a χ^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 $B^+ \to \rho^+\rho^0$ [6, 10] and $B^0 \to \rho^+\rho^-$ [8, 9] decays, the CP-violating parameters S_L^{+-} and C_L^{+-} obtained from the time evolution of the longitudinally polarized $B^0 \to \rho^+\rho^-$ decay [8, 9], and the branching fraction of $B^0 \to \rho^0\rho^0$ from this analysis. We assume Gaussian behavior of the distributions. We neglect $I = 1$ isospin contributions, non-resonant and isospin-breaking effects.

With the $B^0 \to \rho^0\rho^0$ measurement we obtain the constraint on α due to the penguin contribution and obtain a 68% (90%) CL limit on $\Delta\alpha_{\rho\rho} = \alpha - \alpha_{\rm eff}$ of $\pm 18^{\rm o}$ ($\pm 21^{\rm o}$). Fig. 2 shows the $\Delta\chi^2$ on $\Delta\alpha_{\rho\rho}$. The central value of α obtained from the isospin analysis is the same as $\alpha_{\rm eff}$, which is constrained by the relation $\sin(2\alpha_{\rm eff}) = S_L^{+-}/(1 - C_L^{+-2})^{1/2}$ and is measured with the $B^0 \to \rho^+\rho^-$ decay [8, 9].

The error due to the penguin contribution becomes the dominant uncertainty in the measurement of α using $B \to \rho\rho$ decays. However, once the sample of $B^0 \to \rho^0\rho^0$ decays becomes more significant, time-dependent angular analysis will allow us to measure the CP parameters S_L^{00} and C_L^{00}, analogous to S_L^{+-} and C_L^{+-}, resolving ambiguities inherent to isospin triangle orientations.

8 SUMMARY

In summary, we have found evidence for $B^0 \to \rho^0\rho^0$ decay with 3.0σ significance. We measure

$$\mathcal{B}(B^0 \to \rho^0\rho^0) = 1.16^{+0.37}_{-0.36}\ (\text{stat.}) \pm 0.27\ (\text{syst.})$$

and we determine the longitudinal polarization fraction for these decays of

$$f_L = 0.86^{+0.11}_{-0.13}\ (\text{stat.}) \pm 0.05\ (\text{syst.})$$

The measurement of this branching fraction combined with that for $B^+ \to \rho^0\rho^+$ and $B^0 \to \rho^+\rho^-$ decays provides a constraint on the penguin uncertainty in the determination of the CKM unitarity angle α. We find no significant evidence for the decays $B^0 \to \rho^0 f_0$ and $B^0 \to f_0 f_0$. These results are preliminary, and they supersede our previous measurements [4, 5].

9 ACKNOWLEDGMENTS

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

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