Improved Measurement of the Cabibbo-Kobayashi-Maskawa Angle α Using $B^0(\bar{B}) \to \rho^+\rho^-$ Decays

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We present results from an analysis of $B^0(\bar{B}^0) \rightarrow \rho^+\rho^-$ using 232×10^6 $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory at SLAC. We measure the longitudinal polarization fraction $f_L = 0.978 \pm 0.014(\text{stat})\,^{+0.021}_{-0.029}(\text{syst})$ and the CP-violating parameters $S_L = -0.33 \pm 0.24(\text{stat})\,^{+0.08}_{-0.14}(\text{syst})$ and $C_L = -0.03 \pm 0.18(\text{stat}) \pm 0.09(\text{syst})$. Using an isospin analysis of $B \rightarrow \rho\rho$ decays, we determine the unitarity triangle parameter α. The solution compatible with the standard model is $\alpha = (100 \pm 13)^\circ$.

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In the standard model, CP-violating effects in the B-meson system arise from a single phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Interference between direct decay and decay after $B^0\bar{B}^0$ mixing in $B^0(\bar{B}^0) \rightarrow \rho^+\rho^-$ results in a time-dependent decay-rate asymmetry that is sensitive to the angle $\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$ in the unitarity triangle of the CKM matrix. This decay proceeds mainly through a $b \rightarrow u\bar{u}d$ tree diagram. The presence of penguin loop contributions introduces additional phases that shift the experimentally measurable parameter α_{eff} away from the value of α. However, measurements of the $B^+ \rightarrow \rho^+\rho^0$ branching fraction and the upper limit for $B^0 \rightarrow \rho^0\rho^0$ [2,3] show that the penguin contribution in $B \rightarrow \rho\rho$ is small with respect to the leading tree diagram, and $\delta\alpha_{\rho\rho} = \alpha_{\text{eff}} - \alpha$ is constrained at ±11° at 1σ [3]. This Letter presents an update of the time-dependent analysis of $B^0(\bar{B}^0) \rightarrow \rho^+\rho^-$ and measurement of the CKM angle α reported in [4].

The CP analysis of B decays to $\rho^+\rho^-$ is complicated by the presence of a mode with longitudinal polarization and two with transverse polarizations. The longitudinal mode is CP even, while the transverse modes contain CP-even and CP-odd states. Empirically, the decay is observed to be dominated by the longitudinal polarization [4], with a fraction f_L defined by the fraction of the helicity zero state in the decay. The angular distribution is

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L\cos^2\theta_1\cos^2\theta_2 + \frac{1}{4}(1 - f_L)\sin^2\theta_1\sin^2\theta_2\right], \quad (1)$$

where $\theta_{i=1,2}$ is the angle between the π^0 momentum and the direction opposite the B^0 in the ρ rest frame, and we have integrated over the angle between the ρ decay planes.

The analysis reported here is improved over our earlier publication [4] by a change in selection requirements resulting in an increased signal efficiency, introduction of a signal time dependence that accounts for possible misreconstruction, and use of a more detailed background model. This measurement uses 232×10^6 $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the *BABAR* [5] detector at the PEP-II asymmetric-energy B factory at SLAC.

We reconstruct $B^0(\bar{B}^0) \rightarrow \rho^+\rho^-$ candidates (B_{rec}) from combinations of two charged tracks and two π^0 candidates. We require that both tracks have particle identification information inconsistent with the electron, kaon, and proton hypotheses. The π^0 candidates are formed from pairs of photons, each of which has a measured energy greater than 50 MeV. The reconstructed π^0 mass must satisfy $0.10 < m_{\gamma\gamma} < 0.16\ \text{GeV}/c^2$. The mass of the ρ candidates must satisfy $0.5 < m_{\pi^\pm\pi^0} < 1.0\ \text{GeV}/c^2$. When multiple B candidates can be formed, we select the one that minimizes the sum of $(m_{\gamma\gamma} - m_{\pi^0})^2$ where m_{π^0} is the true π^0 mass. If more than one candidate has the same π^0 mesons, we select one at random.

Combinatorial backgrounds dominate near $|\cos\theta_i| = 1$, and backgrounds from B decays tend to concentrate at negative values of $\cos\theta_i$. We reduce these backgrounds with the requirement $-0.90 < \cos\theta_i < 0.98$.

Continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events are the dominant background. This background is reduced by requiring that $|\cos B_{TR}| < 0.8$, where B_{TR} is the angle between the B thrust axis and that of the rest of the event, ROE. The thrust axis of the B is the direction that maximizes the longitudinal momenta of the particles in the B candidate. To distinguish signal from continuum we use a neural network ($\mathcal{N}$) to combine ten discriminating variables: the event shape variables that are used in the Fisher discriminant in Ref. [6], the cosine of the angle between the direction of the B and the collision axis (z) in the e^+e^- center-of-mass (c.m.) frame, the cosine of the angle between the B thrust axis and the z axis, $|\cos B_{TR}|$, the decay angle of each π^0 (defined in analogy to the ρ decay angle, θ_i), and the sum of transverse momenta in the ROE relative to the z axis.

Signal events are identified kinematically using two variables, the difference ΔE between the c.m. energy of the B candidate and $\sqrt{s}/2$, and the beam-energy-substituted mass $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where $\sqrt{s}$ is the total c.m. energy. The B momentum $\mathbf{p}_B$ and four-momentum of the initial state (E_i, $\mathbf{p}_i$) are defined in the laboratory frame. We accept candidates that satisfy $5.23 < m_{\text{ES}} < 5.29\ \text{GeV}/c^2$ and $-0.12 < \Delta E < 0.15$ GeV. The asymmetric ΔE selection reduces background from higher-multiplicity B decays.

To study the time-dependent asymmetry, one needs to measure the proper-time difference, Δt, between the two B decays in the event, and to determine the flavor of the other B meson (B_{tag}). We calculate Δt from the measured separation Δz between the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices [7]. We determine the $B_{\rm rec}$ vertex from the two charged-pion tracks in its decay. The $B_{\rm tag}$ decay vertex is obtained by fitting the other tracks in the event, with constraints from the $B_{\rm rec}$ momentum and the beam-spot location. The rms resolution on Δt is 1.1 ps. We use only events that satisfy $|\Delta t| <$ 20 ps and for which the error on Δt less than 2.5 ps. The flavor of the $B_{\rm tag}$ meson is determined with a multivariate technique [6] that has a total effective tagging efficiency of $(29.9 \pm 0.5)\%$.

Signal candidates may pass the selection requirement even if one or more of the pions assigned to the $\rho^+\rho^-$ state belongs to the other B in the event. These self-cross-feed (SCF) candidates constitute 50% (26%) of the accepted signal for $f_L = 1$ ($f_L = 0$). The majority of SCF events have both charged pions from the $\rho^+\rho^-$ final state, and unbiased CP information (correct-track SCF). There is a SCF component (14% of the signal) where at least one track in $B_{\rm rec}$ is from the rest of the event. These wrong-track events have biased CP information, and are treated separately for the CP result. The probability density function (PDF) describing wrong-track events is used only in determining the signal yield and polarization. A systematic error is assigned to the CP results from this type of signal event.

We obtain a sample of 68703 events that enter a maximum-likelihood fit. These events are dominated by backgrounds: roughly 92% from $q\bar{q}$ and 7% from $B\bar{B}$ events. The remaining 1% of events is signal. We distinguish the following candidate types: (i) correctly reconstructed signal; (ii) SCF signal, split into correct and wrong-track parts; (iii) charm $B^\pm$ background ($b \to c$); (iv) charm B^0 background ($b \to c$); (v) charmless B backgrounds; and (vi) continuum background. The dominant charmless backgrounds are B decays to $\rho\pi$, $(a_1\pi)^\pm$, $(a_1\pi)^0$, and longitudinally polarized $a_1\rho$ final states. For these decays we use the inclusive branching fractions (in units of 10^{-6}), 34 ± 4 [8], 42 ± 42, 42 ± 6 [9], and 100 ± 100, respectively. The corresponding expected number of events in the sample are 82 ± 13, 87 ± 87, 65 ± 9, and 202 ± 202. We also account for contributions from higher kaon resonances (112 ± 112 events) and $\rho^+\rho^0$ (82 ± 19 events). In addition, we expect 2551 ± 510 (1316 ± 263) charged (neutral) B decays to final states containing charm mesons. The B-background decays are included as separate components in the fit.

Each candidate is described with the eight $B_{\rm rec}$ kinematic variables: $m_{\rm ES}$, ΔE, the $m_{\pi^\pm\pi^0}$ and $\cos\theta_i$ values of the two ρ mesons, Δt, and $\mathcal{N}$. For each fit component, we construct a PDF that is the product of PDFs for these variables, neglecting correlations. This introduces a fit bias that is corrected with the use of Monte Carlo (MC) simulation. The continuum-background yield and its PDF parameters for $m_{\rm ES}$, ΔE, $\cos\theta_i$, and $\mathcal{N}$ are floated in the fit to data. The continuum $m_{\pi^\pm\pi^0}$ distribution is described by a Breit-Wigner and polynomial shape, and is derived from $m_{\rm ES}$ and ΔE data sidebands. For all other fit components the PDFs are extracted from high-statistics MC samples. The $\cos\theta_i$ distributions for the background are described by a nonparametric (NP) PDF derived from the MC samples, as the detector acceptance and selection modify the known vector-meson decay distribution. The true signal distribution is given by Eq. (1) multiplied by an acceptance function determined from signal MC samples, whereas SCF signal is modeled using NP PDFs.

The signal decay-rate distribution for both polarizations $f_+(f_-)$ for $B_{\rm tag} = B^0(\bar{B}^0)$ is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)],$$

where τ is the mean B^0 lifetime, Δm_d is the $B^0\bar{B}^0$ mixing frequency, and $S = S_L$ or S_T and $C = C_L$ or C_T are the CP-asymmetry parameters for the longitudinally and transversely polarized signal. The parameters S and C describe B-mixing-induced and direct CP violation, respectively. S and C for the longitudinally polarized wrong-track signal are fixed to zero. The Δt PDF takes into account incorrect tags and is convolved with the resolution function described below. Since f_L is approximately 1, the fit has no sensitivity to either S_T or C_T. We set these parameters to zero and vary them in the evaluation of systematic uncertainties.

The signal Δt resolution function consists of three Gaussians (~90% core, ~9% tail, ~1% outliers), and takes into account the per-event error on Δt from the vertex fit. The resolution is parametrized using a large sample of fully reconstructed hadronic B decays [7]. For wrong-track SCF we replace the B-meson lifetime by an effective lifetime obtained from MC simulation to account for the difference in the resolution. The nominal Δt distribution for the B backgrounds is a NP representation of the MC samples; in the study of systematic errors we replace this model with the one used for signal. The resolution for continuum background is described by the sum of three Gaussian distributions whose parameters are determined from data.

We perform an unbinned extended maximum-likelihood fit. The results of the fit are 617 ± 52 signal events, after correction of a 68 event fit bias, with $f_L = 0.978 \pm 0.014$, $S_L = -0.33 \pm 0.24$, and $C_L = -0.03 \pm 0.18$. The measured signal yield, polarization, and CP parameters are in agreement with our earlier publication [4], with significantly improved precision. Figure 1 shows distributions of $m_{\rm ES}$, ΔE, $\cos\theta_i$, and $m_{\pi^\pm\pi^0}$ for the highest purity tagged events with a loose requirement on $\mathcal{N}$. The plot of $m_{\rm ES}$ contains 14% of the signal and 1.5% of the background. For the other plots there is an added constraint that $m_{\rm ES} > 5.27$ GeV/c^2; these requirements retain 11.5% of the signal and 0.4% of the background. Figure 2 shows the Δt distribution for B^0 and $\bar{B}^0$ tagged events. The time-

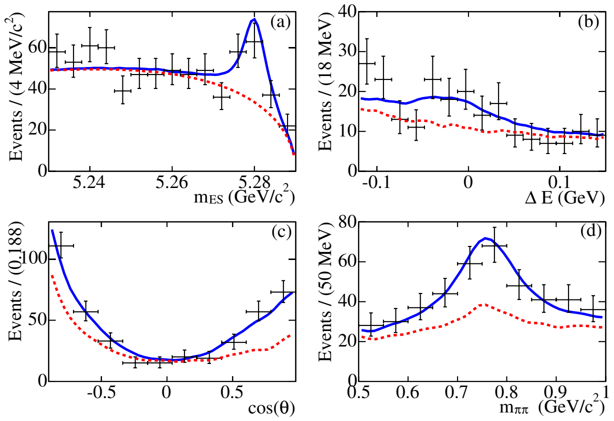

FIG. 1 (color online). The distributions for the highest purity tagged events for the variables (a) m_{ES}, (b) ΔE, (c) cosine of the ρ helicity angle, and (d) $m_{\pi^\pm\pi^0}$. The dotted lines are the sum of backgrounds, and the solid lines are the full PDF.

dependent decay-rate asymmetry $[N(\Delta t) - \bar{N}(\Delta t)]/[N(\Delta t) + \bar{N}(\Delta t)]$ is also shown, where $N(\bar{N})$ is the decay rate for $B^0(\bar{B}^0)$ tagged events.

We have studied possible sources of systematic uncertainties on f_L, S_L, and C_L. The dominant uncertainties for f_L come from floating the B background yields $\left({}^{+0.00}_{-0.02}\right)$, nonresonant events (0.015), and fit bias (0.01). The dominant systematic uncertainty on the CP results comes from the uncertainty in the B-background branching ratios. This results in a shift on $S_L(C_L)$, as large as ${}^{+0.00}_{-0.12}\left({}^{+0.008}_{-0.003}\right)$. Additional uncertainties on the CP results come from possible CP violation in the B background, calculated as in Ref. [4]. We allow for a CP asymmetry up to 20% in B decays to final states with charm, resulting in an uncertainty of 0.027 (0.045) on $S_L(C_L)$. Allowing for possible CP violation in the transverse polarization results in an uncertainty of $0.02\left({}^{+0.002}_{-0.016}\right)$ on $S_L(C_L)$. We estimate the systematic error on our CP results from neglecting the interference between $B^0(\bar{B}^0) \to \rho^+\rho^-$ and other 4π final states: $B \to a_1\pi$, $\rho\pi\pi^0$, and $B \to \pi\pi\pi^0\pi^0$. Strong phases and CP content of the interfering states are varied between zero and maximum using uniform prior distributions, and the rms deviation of the parameters from the nominal fit is taken as the systematic error; this is found to be 0.02 on S_L and C_L. Other contributions that are large include knowledge of the vertex detector alignment 0.034 (0.005) on $S_L(C_L)$, and possible CP violation in the doubly Cabibbo-suppressed decays on the tag side of the event [10]. We allow CP violation in the wrong-track SCF to vary between -1 and $+1$, which results in changes of 0.007 (0.012) in $S_L(C_L)$. The nominal fit does not account for nonresonant background. If we add a nonresonant component of $B \to \rho\pi\pi^0$ events to the likelihood, we fit 83 ± 59 nonresonant events and observe only a $(6 \pm 4)\%$ drop in signal yield. This effect is included in our total systematic uncertainty. Possible contributions from $\sigma(400)\pi^0\pi^0$ decays are neglected due to the small reconstruction efficiency (0.4%). Our results are

$$
\begin{aligned}
f_L &= 0.978 \pm 0.014(\mathrm{stat})\,{}^{+0.021}_{-0.029}(\mathrm{syst}),\\
S_L &= -0.33 \pm 0.24(\mathrm{stat})\,{}^{+0.08}_{-0.14}(\mathrm{syst}),\\
C_L &= -0.03 \pm 0.18(\mathrm{stat}) \pm 0.09(\mathrm{syst}),
\end{aligned}
$$

where the correlation between S_L and C_L is -0.042.

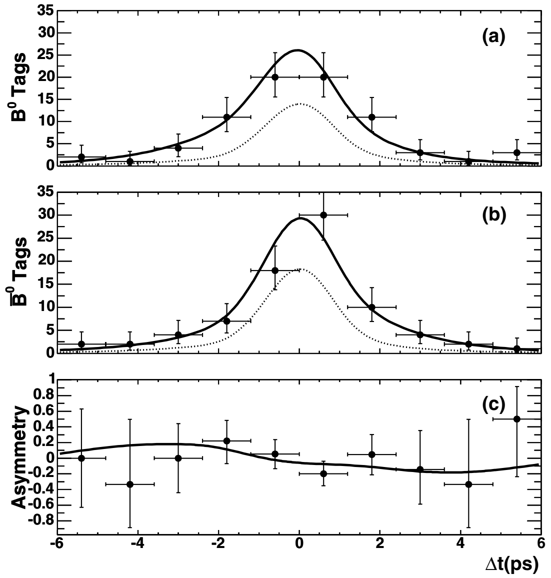

FIG. 2. The Δt distribution for a sample of events enriched in signal for (a) B^0 and (b) $\bar{B}^0$ tagged events. The dotted lines are the sum of backgrounds, and the solid lines are the sum of signal and backgrounds. The time-dependent CP asymmetry (see text) is shown in (c), where the curve is the measured asymmetry.

We constrain the CKM angle α from an isospin analysis [11] of $B \to \rho\rho$. The inputs to the isospin analysis are the amplitudes of the CP-even longitudinal polarization of the $\rho\rho$ final state, as well as the measured values of S_L and C_L for $B^0(\bar{B}^0) \to \rho^+\rho^-$. We use the measurements of f_L, S_L, and C_L presented here, the branching fraction of $B^0 \to \rho^+\rho^-$ from [4], which uses information from [12], the

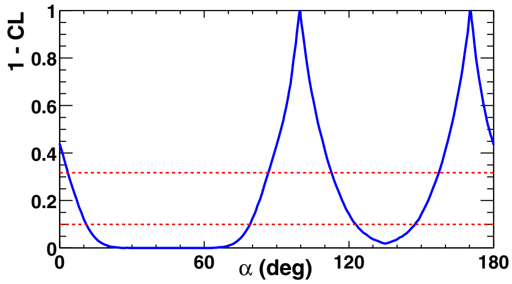

FIG. 3 (color online). C.L. on α obtained from the isospin analysis with the statistical method described in [15]. The dashed lines correspond to the 68% (top) and 90% (bottom) C.L. intervals.

combined branching fraction and f_L for $B \to \rho^+\rho^0$ from Ref. [2], and the central value corresponding to the upper limit of $\mathcal{B}(B \to \rho^0\rho^0)$ from Ref. [3]. We ignore electroweak penguins and possible $I = 1$ amplitudes [13].

To interpret our results in terms of a constraint on α from the isospin relations, we construct a χ^2 that includes the measured quantities expressed as the lengths of the sides of the isospin triangles, and we determine the minimum χ^2_0. As the isospin triangles do not close with the current central values of the branching ratios, we have adopted toy MC techniques to compute the confidence level (C.L.) on α; our method is similar to the approach proposed in Ref. [14]. For each value of α, scanned between 0° and 180°, we determine the difference $\Delta\chi^2_{\mathrm{DATA}}(\alpha)$ between the minimum of $\chi^2(\alpha)$ and χ^2_0. We then generate MC experiments around the central values obtained from the fit to data with the given value of α, and we apply the same procedure. The fraction of these experiments in which $\Delta\chi^2_{\mathrm{MC}}(\alpha)$ is smaller than $\Delta\chi^2_{\mathrm{DATA}}(\alpha)$ is interpreted as the C.L. on α. Figure 3 shows $1 - \mathrm{C.L.}$ for α obtained from this method. Selecting the solution closest to the CKM combined fit average [15,16], we find $\alpha = 100° \pm 13°$, where the error is dominated by $\delta\alpha_{\rho\rho}$ which is $\pm 11°$ at 1σ. The 90% C.L. allowed interval for α is between 79° and 123°.

In summary, we have improved the measurement of the CP-violating parameters S_L and C_L in $B^0(\bar{B}^0) \to \rho^+\rho^-$ using a data sample 2.6 times larger than that in Ref. [4]. We do not observe mixing-induced or direct CP violation. We derive a model-independent measurement of the CKM angle α, which is the most precise to date.

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