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


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We present results from an analysis of $B^0(B^0) \rightarrow \rho^+ \rho^-$ using 232 \times 10^6 Y(4S) \rightarrow BB$ decays collected with the BABAR detector at the PEP-II asymmetric-energy B factory at SLAC. We measure the longitudinal polarization fraction $f_L = 0.978 \pm 0.014(\text{stat}) \pm 0.021(\text{syst})$ and the CP-violating parameters $S_L = -0.33 \pm 0.24(\text{stat}) \pm 0.04(\text{syst})$ 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 $\alpha$. 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 $B^0(B^0)$ mixing in $B^0(B^0) \rightarrow \rho^+ \rho^-$ 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 $b \rightarrow u\bar{d}d$ tree diagram. The presence of penguin loop contributions introduces additional phases that shift the experimentally measurable parameter $\alpha_{\text{eff}}$ away from the value of $\alpha$. 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 $\pm 11^\circ$ at 1$\sigma$ [3]. This Letter presents an update of the time-dependent analysis of $B^0(B^0) \rightarrow \rho^+ \rho^-$ and measurement of the CKM angle $\alpha$ 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

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

where $\theta_{1,2}$ is the angle between the $\pi^0$ momentum and the direction opposite the $B^0$ in the $B$ rest frame, and we have integrated over the angle between the $\rho$ 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 mis-reconstruction, and use of a more detailed background model. This measurement uses 232 \times 10^6 Y(4S) \rightarrow BB$ decays collected with the BABAR [5] detector at the PEP-II asymmetric-energy B factory at SLAC.

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

Combinatorial backgrounds dominate near $|\cos\theta_1| = 1$, and backgrounds from B decays tend to concentrate at negative values of $\cos\theta_1$. We reduce these backgrounds with the requirement $-0.90 < \cos\theta_1 < 0.98$.

Continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events are the dominant background. This background is reduced by requiring that $|\cos B_{\text{TR}}| < 0.8$, where $B_{\text{TR}}$ 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 analysis of [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, $|\cos B_{\text{TR}}|$, the decay angle of each $\pi^0$ (defined in analogy to the $\rho$ decay angle, $\theta_2$), and the sum of transverse momenta in the ROE relative to the z axis.

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

To study the time-dependent asymmetry, one needs to measure the proper-time difference, $\Delta t$, between the two B decays in the event, and to determine the flavor of the other B meson ($B_{\text{tag}}$). We calculate $\Delta t$ from the measured sepa-
ration $\Delta z$ between the $B_{\text{rec}}$ and $B_{\text{tag}}$ decay vertices [7]. We determine the $B_{\text{rec}}$ vertex from the two charged-pion tracks in its decay. The $B_{\text{tag}}$ decay vertex is obtained by fitting the other tracks in the event, with constraints from the $B_{\text{rec}}$ momentum and the beam-spot location. The rms resolution on $\Delta t$ is 1.1 ps. We use only events that satisfy $|\Delta t| < 20$ ps and for which the error on $\Delta t$ less than 2.5 ps. The flavor of the $B_{\text{tag}}$ 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 $B_{\text{rec}}$ 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 ($b \rightarrow c$); (iv) charm $B^0$ background ($b \rightarrow c$); (v) charmless $B$ backgrounds; and (vi) continuum background. The dominant charmless backgrounds are $B$ decays to $\rho\pi$, $(a_1\pi)^0$, $(a_1\pi)^0$, and longitudinally polarized $a_1\rho$ final states. For these decays we use the inclusive branching fractions (in units of $10^{-6}$), $34 \pm 4$ [8], $42 \pm 42$, $42 \pm 6$ [9], and $100 \pm 100$, respectively. The corresponding expected number of events in the sample are $82 \pm 13$, $87 \pm 87$, $65 \pm 9$, and $202 \pm 202$. We also account for contributions from higher kaon resonances ($112 \pm 112$ events) and $\rho^+\rho^0$ ($82 \pm 19$ events). In addition, we expect 2551 $\pm$ 510 ($1316 \pm 263$) 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 $B_{\text{rec}}$ kinematic variables: $m_{\text{ES}}, \Delta E$, the $m_{\pi^+\pi^-}$ and $\cos\theta_j$ values of the two $\rho$ mesons, $\Delta t$, and $N$. 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 $m_{\text{ES}}, \Delta E$, $\cos\theta_j$, and $N$ are floated in the fit to data. The continuum $m_{\pi^+\pi^-}$ distribution is described by a Breit-Wigner and polynomial shape, and is derived from $m_{\text{ES}}$ and $\Delta E$ data bands. For all other fit components the PDFs are extracted from high-statistics MC samples. The $\cos\theta_j$ 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 $B_{\text{tag}} = B^0(B^0)$ is given by

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

where $\tau$ is the mean $B^0$ lifetime, $\Delta m_d$ 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 $\Delta t$ 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 $\Delta t$ resolution function consists of three Gaussians ($\sim$90% core, $\sim$9% tail, $\sim$1% outliers), and takes into account the per-event error on $\Delta t$ 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 $\Delta t$ distribution for the $B$ backgrounds is a $CP$ 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 $617 \pm 52$ 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 $m_{\text{ES}}, \Delta E$, $\cos\theta_j$, and $m_{\pi^+\pi^-}$ for the highest purity tagged events with a loose requirement on $N$. The plot of $m_{\text{ES}}$ contains 14% of the signal and 1.5% of the background. For the other plots there is an added constraint that $m_{\text{ES}} > 5.27$ GeV/$c^2$; these requirements retain 11.5% of the signal and 0.4% of the background. Figure 2 shows the $\Delta t$ distribution for $B^0$ and $B^0$ tagged events. The time-
dependent decay-rate asymmetry \[ \frac{N(\Delta t) - \bar{N}(\Delta t)}{N(\Delta t) + \bar{N}(\Delta t)} \] 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 \( (+0.007, -0.02) \), nonresonant events \( (0.015) \), and fit bias \( (0.01) \). The dominant systematic uncertainty on the \( C_L \) results comes from the uncertainty in the \( B^- \)-background branching ratios. This results in a shift on \( S_L(C_L) \), as large as \( +0.007 \). Additional uncertainties on the \( C_L \) results come from possible \( CP \) violation in the \( B \) background, calculated as

\[
\begin{align*}
\frac{N(\Delta t) - \bar{N}(\Delta t)}{N(\Delta t) + \bar{N}(\Delta t)} &= \text{systematic uncertainty. Possible contributions from } \sigma(400) \pi^0 \pi^0 \text{ decays are neglected due to the small reconstruction efficiency (0.4%). Our results are} \\
f_L &= 0.978 \pm 0.014(\text{stat}) +0.021 -0.029 \text{(syst)}, \\
S_L &= -0.33 \pm 0.24(\text{stat}) +0.08 -0.14 \text{(syst)}, \\
C_L &= -0.03 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}),
\end{align*}
\]

where the correlation between \( S_L \) and \( C_L \) is \( -0.042 \).

We constrain the CKM angle \( \alpha \) 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
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 $l = 1$ amplitudes [13].

To interpret our results in terms of a constraint on $\alpha$ from the isospin relations, we construct a $\chi^2$ that includes the measured quantities expressed as the lengths of the sides of the isospin triangles, and we determine the minimum $\chi_0^2$. As the isospin triangles do not close with the current central values of the branching ratios, we have adopted the isospin triangles, and we determine the minimum $\chi_0^2$.

We derive a model-independent measurement of the CKM $\alpha$ using a data sample 2.6 times larger than that in Ref. [4]. 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.

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