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Authors
Aubert, B
Karyotakis, Y
Lees, JP
et al.

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Improved Measurement of $B^+ \to \rho^+ \rho^0$ and Determination of the Quark-Mixing Phase Angle $\alpha$


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1 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2 Universitat de Barcelona, Facultat de Fisica, Department ECM, E-08028 Barcelona, Spain
3a INFN Sezione di Bari, I-70126 Bari, Italy
3b Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
4 University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5 Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6 University of Birmingham, Birmingham, B15 2TT, United Kingdom
7 Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8 University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
9 Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
10 Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
11 University of California at Irvine, Irvine, California 92697, USA
12 University of California at Los Angeles, Los Angeles, California 90024, USA
13 University of California at Riverside, Riverside, California 92521, USA
14 University of California at San Diego, La Jolla, California 92093, USA
15 University of California at Santa Barbara, Santa Barbara, California 93106, USA
16 University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
17 California Institute of Technology, Pasadena, California 91125, USA
18 University of Cincinnati, Cincinnati, Ohio 45221, USA
19 University of Colorado, Boulder, Colorado 80309, USA
20 Colorado State University, Fort Collins, Colorado 80523, USA
21 Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
22 Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
23 Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
24 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
25a INFN Sezione di Ferrara, I-44100 Ferrara, Italy
25b Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
26 INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
27a INFN Sezione di Genova, I-16146 Genova, Italy
27b Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
28 Harvard University, Cambridge, Massachusetts 02138, USA
29 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
30 Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, D-12489 Berlin, Germany
31 Imperial College London, London, SW7 2AZ, United Kingdom
32 University of Iowa, Iowa City, Iowa 52242, USA
33 Iowa State University, Ames, Iowa 50011-3160, USA
34 Johns Hopkins University, Baltimore, Maryland 21218, USA

(BABAR Collaboration)
We present improved measurements of the branching fraction $\mathcal{B}$, the longitudinal polarization fraction $f_L$, and the direct $CP$ asymmetry $\mathcal{A}_{CP}$ in the $B^+ \to \rho^+ \rho^0$ decay channel. The data sample was collected with the BABAR detector at SLAC. The results are $\mathcal{B}(B^+ \to \rho^+ \rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$, $f_L = 0.950 \pm 0.015 \pm 0.006$, and $\mathcal{A}_{CP} = -0.054 \pm 0.055 \pm 0.010$, where the uncertainties are...
In the standard model (SM), the weak interaction couplings of quarks are described by elements $V_{ij}$ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], where $i = u, c, t$ and $j = d, s, b$ are quark indices. The CKM elements are complex, introducing violation of charge-parity $(C P)$ symmetry. Unitarity of the CKM matrix yields a relationship between the $V_{ij}$ that can be represented as a triangle in the complex plane. The SM mechanism for $C P$ violations can be tested through measurement of the sides and angles of this unitarity triangle (UT) [2].

An approximate result $\alpha_{\text{eff}}$ for the UT angle $\alpha = \text{arg}(-V_{ud}V_{ub}^*/V_{ud}V_{ub})$ can be obtained from $B$ meson decays to $C P$ eigenstates dominated by tree-level $b \rightarrow u \bar{d}d$ amplitudes, such as $B \rightarrow \rho \rho$ decays (see, e.g., Refs. [2,3]).

The correction $\Delta \alpha = \alpha - \alpha_{\text{eff}}$, which accounts for loop amplitudes, can be extracted from an analysis of the branching fractions and $C P$ asymmetries of the full set of isospin-related $b \rightarrow u \bar{d}d$ channels [4]. One of the most favorable methods to determine $\alpha$ is through an isospin analysis of the $B \rightarrow \rho \rho$ system [2,3].

Here we present updated results for the $B^+ \rightarrow \rho^+ \rho^0$ channel, with $\rho^+ \rightarrow \pi^+ \pi^0$ and $\rho^0 \rightarrow \pi^+ \pi^-$, leading to an improved determination of $\alpha$. Previous studies are presented in Refs. [5,6]. We measure the branching fraction $B$, the longitudinal polarization fraction $f_L$, and the direct $C P$ asymmetry $A_{C P} \equiv (\Gamma_\rho^- - \Gamma_\rho^+)/\Gamma_{\rho^0}$, with $\Gamma_{\rho^0}$ the $B^0$ decay width. Significant deviation of $A_{C P}$ from the SM prediction of zero could indicate new physics. We also search for the as-yet-unobserved decay $B^+ \rightarrow \rho^+ f_0(980)$, with $f_0 \rightarrow \pi^+ \pi^-$. The use of charge conjugate reactions is implied throughout.

The analysis is based on $(465 \pm 5) \times 10^6 B \bar{B}$ events (424 fb$^{-1}$) collected on the $\Upsilon$(4S) resonance [center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV] with the BABAR detector [7] at the PEP-II asymmetric energy $e^+ e^-$ collider at SLAC. Compared to our previous study [5], the analysis incorporates higher signal efficiency and background rejection, twice as much data, and improved procedures to reconstruct charged particles and to account for correlations in the backgrounds. Simulated event samples based on Monte Carlo (MC) event generation are used to determine signal and background characteristics, optimize selection criteria, and evaluate efficiencies.

$B^+ \rightarrow \rho^+ \rho^0$ decays are described by a superposition of two transversely (elicity $\pm 1$) and one longitudinally (elicity 0) polarized amplitudes. Our acceptance is independent of the angle between the two $\rho$ decay planes in the $B$ rest frame. We integrate over this angle to obtain an expression for $(1/\Gamma)(d\Gamma/d\cos\theta_\rho d\cos\theta_{\rho^+})$:

$$2 \pi f_L \cos^2\theta_{\rho^+}\cos^2\theta_{\rho^+} + (1 - f_L)\sin^2\theta_{\rho^+}\sin^2\theta_{\rho^+}. \quad (1)$$

with $f_L \equiv \Gamma_L/\Gamma$, where $\Gamma$ is the total decay width, $\Gamma_L$ is the partial width to the longitudinally polarized mode, and the $\rho^0 (\rho^+)$ helicity angle $\theta_{\rho^0} (\theta_{\rho^+})$ is the angle between the daughter $\pi^+$ in the $\rho^0 (\rho^+)$ rest frame and the direction of the boost from the $B^+$ rest frame.

A $B$ meson candidate is kinematically characterized by the beam-energy-substituted mass $m_{E S} = \sqrt{s/4 - (p_E^2/c^2)}$ and energy difference $\Delta E = E_{\rho^0} - \sqrt{s}/2$, where $E_{\rho^0}$ and $p_E^2$ are the c.m. energy and momentum of the $B$ candidate, respectively. Signal events peak at the nominal $B$ mass for $m_{E S}$ and at zero for $\Delta E$, with resolutions of 3 MeV/c$^2$ and 30 MeV, respectively.

The $\pi^0$ mesons are reconstructed through $\pi^0 \rightarrow \gamma\gamma$. The $\gamma$ is required to be consistent with a single electromagnetic shower. The $\gamma$ and $\pi^0$ laboratory energies must be larger than 30 MeV and 0.2 GeV, respectively. The mass of a $\pi^0$ candidate (resolution 6 MeV/c$^2$) is required to lie within [0.115, 0.150] GeV/c$^2$ and is subsequently constrained to its nominal value [2].

The $\pi^0 (\pi^-)$ candidate is combined with a $\pi^+$ to form a $\rho^+ (\rho^0)$. The $\pi^\pm$ are identified with measurements of specific energy loss in the tracking chambers and radiation angles and photon multiplicity in a ring-imaging Cherenkov detector [7]. The $\rho^+$ ($\rho^0$) candidate mass $m_{\pi^+ \rho^+}$ ($m_{\pi^- \rho^0}$) must lie within [0.52, 1.06] GeV/c$^2$. $\rho^+$ candidates with misreconstructed $\pi^0$ mesons tend to cluster near $\cos\theta_{\rho^+} = \frac{1}{3}$, so we require $\cos\theta_{\rho^0} \leq 0.8$. The $B^+$ candidates must satisfy $5.26 < m_{E S} < 5.29$ GeV/c$^2$ and $|\Delta E| < 0.15$ GeV. In cases of multiple $B^+$ candidates (about 10% of events), the candidate with the largest $B^+$ vertex [8] fit probability is retained.

Background from $B \rightarrow D^{(*)}X$ decays, due to $D \rightarrow \pi \pi^+$ or kaon misidentification and $D \rightarrow \pi^- \pi^0$, is suppressed by requiring the $K^+\pi^- (\pi^0)$ or $K^+\pi^{-}\pi^0$ invariant mass to lie outside $\pm 4\sigma$ of the nominal $D^0$ mass [2], with $\sigma = 9$ MeV/c$^2$ the $D^0$ mass resolution.

The dominant background, from random combinations of particles in continuum events ($e^+ e^- \rightarrow q\bar{q}$, with $q = u, d, s, c$), is suppressed by requiring $|\cos\theta_\Gamma| < 0.8$ [9], with $\theta_\Gamma$ the angle between the thrust axis of the $B$ candidate’s decay products and the thrust axis of the remaining particles in the event (ROE), evaluated in the c.m. frame, and by employing a neural network algorithm based on 11 variables calculated in the c.m.: $|\cos\theta_\Gamma|$; the cosines of the angles with respect to the beam axis of the $B$ momentum and $B$ thrust axis (we use the absolute value for the latter variable); the momentum-weighted sums $L_0$ and $L_2$ [9], determined with charged and neutral particles separately; the sum of transverse momenta of the ROE particles with respect to the beam axis; the ratio of the second to...
The neural network output $NN$ peaks near 0 and 1 for continuum and signal events, respectively. We require $NN > 0.2$, which rejects about 5% of the signal and 60% of the continuum events.

We examine the remaining $B$ backgrounds and identify nine channels with peaking structures in $m_{ES}$ or $\Delta E$ that can potentially mimic signal events: $B^+ \rightarrow \pi^0 a_1^{(*)} (1260)$, $\pi^+ a_1^0, \rho^+ \pi^0, \rho^+ \pi^+ \pi^0, \rho^+ \pi^0 \pi^0, \rho^0 \pi^+ \pi^-, \rho^0 \pi^0 \pi^0, \gamma \rho^0, f_0 \pi^+ \pi^0, \gamma \rho^0$. All other $B$ backgrounds are combined into a “nonpeaking” $B\bar{B}$ background component.

An extended unbinned maximum likelihood (ML) fit is applied to the selected events. The fit has 14 components: signal $\rho^+ \rho^0$ events, taken to be $B^+ \rightarrow \rho^+ \rho^0$ events that are correctly reconstructed; self-cross-feed (SXf) events, defined as misreconstructed $B^+ \rightarrow \rho^+ \rho^0$ events (29% of the $B^+ \rightarrow \rho^+ \rho^0$ sample); signal $B^+ \rightarrow \rho^+ f_0$ events, including both correctly and incorrectly reconstructed events to increase efficiency; nonpeaking $B\bar{B}$ background; continuum background; and the nine peaking $B\bar{B}$ background channels listed above. The $\rho^+ \rho^0$ signal and SXf components are further divided into categories with either longitudinal or transverse polarization.

The likelihood function is $L = (1/N!) \exp (-\sum n_i) \times \prod_{j=1}^{12} \sum n_j P_j(x_j)$, with $N$ the number of events, $n_j$ the yield of component $j$, $P_j(x_j)$ the probability density function (PDF) for event $i$ to be associated with component $j$, and $x_j$ the seven experimental observables specified in Eq. (2) below. The signal $\rho^+ \rho^0, \rho^+ f_0$, continuum, and nonpeaking $B\bar{B}$ background yields are allowed to vary in the fit. The $\rho^+ \rho^0$ SXf yield is fixed to its expected value based on the MC prediction for the SXf rate and the $B^+ \rightarrow \rho^+ \rho^0$ branching fraction determined here (we iterate the fit to find this result). The relative contributions of the $\rho^+ \rho^0$ longitudinal and transverse polarization components are determined by allowing $f_L$ to vary, with $f_L$ common to the signal and SXf events. The three $\rho \pi \pi$ yields are varied under the requirement that they have the same branching fraction. The $\pi^0 a_1^+, \pi^+ a_1^0, \omega \rho^+$, and $\eta' \rho^+$ yields are fixed according to their known branching fractions [2]. The $\rho^0 \pi^+ \pi^- \pi^0$ and $f_0 \pi^0 \pi^0 \pi^0$ yields are fixed assuming their branching fractions to be $10^{-5}$, consistent with or larger than the limits [11,12] for $B^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $f_0 \pi^+ \pi^- \pi^0$ decays.

About 85% of continuum events, and 90% of nonpeaking $B\bar{B}$ background events, contain at least one misreconstructed $\rho$. For these events, we find correlations of order 10% between the $NN, m_{\pi\pi}$, and $\cos \theta_\rho$ variables, and—to account for these correlations—construct three-dimensional (3D) PDFs of the five variables based on conditional PDFs $P(x | y)$ of variable $x$ given the value of variable $y$: $P_{3D} = [P(m_{\pi\pi} | \cos \theta_\rho) \times P(\cos \theta_\rho | NN)] \times P(NN)$. For example, $P(m_{\pi\pi} | \cos \theta_\rho)$ is constructed by examining the $m_{\pi\pi}$ distribution in nine bins of $\cos \theta_\rho$, fitting a second-order polynomial to each bin, and parameterizing how the coefficients of the polynomial vary between bins. The fraction of events with a correctly reconstructed $\rho^+$ and $\rho^0$ is fixed to the MC prediction for the nonpeaking $B\bar{B}$ background and allowed to vary for the continuum background. For all other components, the overall PDFs are defined as the product of seven 1D PDFs, one for each observable. The PDFs of the $\rho^+ \rho^0$ signal and SXf parameters take the form of Eq. (1), with detector resolution and acceptance incorporated, by summing the longitudinal ($L$) and transverse ($T$) components with a relative fraction $f_L e_L / (f_L e_L + (1 - f_L) e_T)$, with $e_L$ and $e_T$ the respective reconstruction efficiencies, leading to an effective 2D PDF in $\cos \theta_\rho$ and $|\cos \theta_\rho|$: $P_j(x_i) = P_j(m_{ES}) P_j(\Delta E) P_j(NN) P_j(m_{i_{\pi\pi}}) \times P_j(m_{i_{\pi\pi}}) P_j(\cos \theta_{i_{\rho}}, |\cos \theta_{i_{\rho}}|)$. (2)
A possible bias, from unmodeled correlations, is evaluated by applying the ML fit to an ensemble of simulated experiments, where the numbers of signal and background events in each component correspond to those observed or fixed in the fit to data. The continuum events are drawn from the PDFs, while events for all other components are drawn from MC samples. The biases are determined to be $71 \pm 3$ and $-31 \pm 1$ events for the signal $\rho^+\rho^0$ and $\rho^+f_0$ yields and $-0.005 \pm 0.001$ for $f_L$, where the uncertainties are statistical. The signal yields and $f_L$ are then corrected by subtracting these biases.

The branching fractions are given by the bias-corrected yields divided by the reconstruction efficiencies and initial number of $B\bar{B}$ pairs $N_{B\bar{B}}$. From the simulations, the $\rho^+\rho^0$ signal efficiencies including the $\pi^0$ daughter branching fraction [2] are $\epsilon_L = [9.12 \pm 0.02\, \text{stat}]\%$ and $\epsilon_T = [17.45 \pm 0.03\, \text{stat}]\%$. The corresponding result for $\rho^+f_0$ is $[14.20 \pm 0.08\, \text{stat}]\%$. We assume that the Y(4S) decays to each of $B^+B^-$ and $B^0\bar{B}^0$ 50% of the time.

The principal systematic uncertainties associated with the ML fit are listed in Table I. Uncertainties from the fit biases are defined by the quadratic sum of half the biases themselves (for $f_L$, the full bias) and the statistical uncertainties of the biases. The uncertainties related to the signal and nonpeaking $B\bar{B}$ background PDFs are assessed by varying the PDF parameters within their uncertainties. For the signal, the uncertainties of the PDF parameters are determined from the $B^+ \to \bar{B}^0\pi^+\pi^-$ data control sample. Variations of the $\pi^0\alpha_L^1$, $\pi^0\alpha_T^1$, $\alpha p^+$, and $\eta p^+$ branching fractions within their measured uncertainties, and of the assumed $\pi^+\pi^-\pi^0\pi^0$ and $f_0\pi^+\pi^-\pi^0$ branching fractions by $\pm 100\%$, define the systematic uncertainty associated with the peaking $B\bar{B}$ background. The uncertainty associated with the SxF fraction is assessed by varying the fixed SxF yield by $\pm 10\%$. The other principal sources of systematic uncertainty are the $\pi^0$ reconstruction efficiency (3.0%), the track reconstruction efficiency (1.1%), the $\pi^\pm$ identification efficiency (1.5%), the uncertainty of $N_{B\bar{B}}$ (1.1%), and the selection requirements on $|\cos\theta_T|$ (1.0%). The individual terms are added in quadrature to define the total systematic uncertainties.

We find $\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$, $f_L = 0.950 \pm 0.015 \pm 0.006$, $\mathcal{A}_{CP} = -0.054 \pm 0.055 \pm 0.010$, and $\mathcal{B}(B^+ \to \rho^+f_0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = (1.21 \pm 0.44 \pm 0.40) \times 10^{-6}$, where the first (second) uncertainty is statistical (systematic). The $\mathcal{B}(\rho^+\rho^0)$ result is larger than in Ref. [5], primarily because of the improved method used here to account for correlations in the backgrounds. The significance of the $\mathcal{B}(\rho^+f_0)$ result without (with) systematics is 3.2 (2.2) standard deviations. We find $-0.15 < \mathcal{A}_{CP} < 0.04$ and $\mathcal{B}(B^+ \to \rho^+f_0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) < 2.0 \times 10^{-6}$, where these latter results correspond to the 90% confidence level (C.L.) including systematics.

We perform an isospin analysis of $B \to \rho\rho$ decays by minimizing a $\chi^2$ that includes the measured quantities expressed as the lengths of the sides of the $B$ and $\bar{B}$ isospin triangles [4]. We use the $B^+ \to \rho^+\rho^0$ branching fraction and $f_L$ results presented here, with the branching fractions, polarizations, and CP-violating parameters in $B^0 \to \rho^+\rho^0$ [15] and $B^0 \to \rho^0\rho^0$ [11] decays. We assume the uncertainties to be Gaussian-distributed and neglect potential isospin $I = 1$ and electroweak-loop amplitudes, which are expected to be small [3].

The CKM phase angle $\alpha$ and its correction $\Delta\alpha$ are found to be $\alpha = (92.4^{+4.7}_{-5.3})^\circ$ and $-1.8^\circ < \Delta\alpha < 6.7^\circ$, respectively, at 68% C.L., significant improvements [16] compared to $\alpha = (82.6^{+3.2}_{-6.3})^\circ$ and $|\Delta\alpha| < 15.7^\circ$ [11] obtained with the same $\rho^+\rho^-$ and $\rho^0\rho^0$ measurements, but the previous $B^+ \to \rho^+\rho^0$ results [5], or $\alpha = (91.7 \pm 14.9)^\circ$ from the Belle Collaboration [12]. The improvement is primarily due to the increase in $\mathcal{B}(\rho^+\rho^0)$ compared to our previous result. $\mathcal{B}(\rho^+\rho^0)$ determines the length of the common base of the isospin triangles for the $B$ and $\bar{B}$ decays. The increase in the base length flattens both triangles, making the four possible solutions [4] nearly degenerate.

In summary, we have improved the precision of the measurements of the $B^+ \to \rho^+\rho^0$ decay branching and longitudinal polarization fractions, leading to a significant improvement in the determination of the CKM phase angle $\alpha$ based on the favored $B \to \rho\rho$ isospin method. We set a
90% C.L. upper limit of $2.0 \times 10^{-6}$ on the branching fraction of $B^+ \to \rho^+ f_0(980)$, with $f_0 \to \pi^+ \pi^-$. 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 thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A.P. Sloan Foundation.

*Present address: Temple University, Philadelphia, PA 19122, USA.
†Present address: Tel Aviv University, Tel Aviv, 69978, Israel.
‡Also at Università di Perugia, Dipartimento di Fisica, Perugia, Italy.
§Also at Università di Roma La Sapienza, I-00185 Roma, Italy.
**Also at Università di Sassari, Sassari, Italy.