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Constraints on ϕ_2 (α) from $B \to \rho\rho$ Decays at Belle

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We present a time dependent analysis of CP violation in $B^0 \to \rho^+\rho^-$ decays based on a data sample containing 275 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We measure the branching fraction $B = \left[22.8 \pm 3.8\,(\mathrm{stat})\,^{+2.3}_{-2.4}\,(\mathrm{syst})\right] \times 10^{-6}$, longitudinal polarization fraction $f_L = 0.951\,^{+0.033}_{-0.039}\,(\mathrm{stat})\,^{+0.029}_{-0.031}\,(\mathrm{syst})$, and the CPviolating parameters $A = 0.00 \pm 0.30\,(\mathrm{stat})\,^{+0.10}_{-0.09}\,(\mathrm{syst})$, and $S = 0.08 \pm 0.42\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$. These values are used to determine the CKM phase angle ϕ_2 via an isospin analysis; the central value and 1σ error are $(88 \pm 17)^\circ$, and $59^\circ < \phi_2 < 115^\circ$ at 90% CL.

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1. Introduction

The angle ϕ_2 can be determined using a time dependent analysis in charmless decays such as $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^+\pi^-$ and $B^0 \to \rho^+\rho^-$. Due to the small branching fraction for $B^0\to\rho^0\rho^0$ [1], the penguin contribution in $B^0\to\rho\rho$ decays is expected to be small. It allows to determine the CKM angle ϕ_2 using $B^0 \to \rho^+\rho^-$ decays with relatively little theoretical uncertainty. Extraction of ϕ_2 requires the knowledge of the polarization of the ρ mesons. The longitudinal polarization corresponds to *CP*-even state, while two transverse polarizations correspond to an admixture of *CP*-even and *CP*-odd states.

Here we present the measurements of the branching fraction, polarization, and a time dependent analysis of $B^0 \to \rho^+\rho^-$ decays. Using an isospin analysis we determine the CKM angle ϕ_2.

2. Analysis overview

To identify $\rho^\pm \to \pi^\pm\pi^0$ decays, we require that $m_{\pi^\pm\pi^0}$ be in the range 0.62–0.92 GeV/c^2. Neutral pion candidates are reconstructed from photon pairs with invariant masses in the range $0.1178\,\mathrm{GeV}/c^2 < M_{\gamma\gamma} < 0.1502\,\mathrm{GeV}/c^2$. π^0 candidates are required to have $p > 0.35$ GeV/c in the e^+e^- center-of-mass (CM) frame. Photon candidates must have a minimum energy of 50 MeV in the barrel region of the electromagnetic calorimeter and 90 MeV in the endcap regions. We require that each ρ candidate satisfy $-0.80 < \cos\theta < 0.98$, where θ is the angle between the direction of the π^0 and the negative of the B^0 momentum in the $\rho^\pm$ rest frame.

B meson candidates are identified using two kinematic variables: the beam energy constrained mass $M_{bc} \equiv \sqrt{E^2_{beam} - p^2_B}$, and the energy difference $\Delta E \equiv E_B - E_{beam}$, where E_{beam} is the center-of-mass (CM) beam energy, and E_B and p_B are the reconstructed energy and momentum of the B candidate in the CM frame. We accept events in the region $M_{\mathrm{bc}} > 5.21\,\mathrm{GeV}/c^2$ and $-0.2\,\mathrm{GeV} < \Delta E < 0.3\,\mathrm{GeV}$ and define a signal region as $M_{\mathrm{bc}} > 5.27\,\mathrm{GeV}/c^2$ and $-0.12\,\mathrm{GeV} < \Delta E < 0.08\,\mathrm{GeV}$.

The b-flavor tagging information is represented by two parameters, $q = \pm 1$, the flavor, and a quality factor r that ranges from $r = 0$ for no flavor discriminant to $r = 1$ for unambiguous flavor assignment. The dominant background to $B^0 \to \rho^+\rho^-$ is $e^+e^- \to q\bar{q}$ $(q = u,d,s,c)$ continuum events. To discriminate the signal from the background we combine a Fisher discriminant[2] based on 16 modified Fox-Wolfram moments with the cosine of the angle between the flight direction of the B in the CM frame and the electron beam direction to form the likelihood ratio $R = L_{B\bar{B}}/L_{B\bar{B}} + L_{q\bar{q}}$. As the tagging parameter r also discriminates against $q\bar{q}$ background, we divide the data into six r intervals (denoted by $\ell = 1-6$) and apply the R threshold separately for each. The R requirement removes about 97% of continuum events while retaining about 62% of signal.

3. Measurement of the branching fraction and polarization fraction

We determine the signal yield in two steps: we first fit the $M_{\mathrm{bc}} - \Delta E$ distribution to obtain the fraction of $B^0\to\rho^+\rho^- + B^0\to\rho^\pm\pi^\mp\pi^0$ non-resonant decays; we then fit the $m_{\pi^\pm\pi^0}$ distribution to determine the non-resonant fraction and hence the $\rho^+\rho^-$ signal yield.

The first fit is an unbinned maximum likelihood (ML) fit to the two-dimensional $M_{\mathrm{bc}} - \Delta E$ distribution in the range 5.21 GeV$/c^2 < M_{\mathrm{bc}} < 5.29$ GeV/c^2 and -0.20 GeV $< \Delta E < 0.30$ GeV. The data sample contains 7120 events: the signal, continuum events ($\sim$ 83%), $b\to c$ decays ($\sim$ 12%), and $b\to u$ decays. The PDFs for signal and $b\to u$ background are modeled by smoothed two-dimensional histograms obtained from MC samples. The PDF for $b\to c$ background is the product of a threshold ("ARGUS" [3]) function for $M_{\rm bc}$ and a quadratic polynomial for ΔE, also obtained from MC simulation. The PDF for continuum background is an ARGUS function for $M_{\rm bc}$ and a linear function for ΔE; the slope of the linear function depends on the tag quality (r) bin ℓ. The $b\to u$ background is dominated by $B^{(0,+)}\to\rho\,\pi$, $B\to a_1\pi$, and $B\to a_1\,\rho$ decays. For $B^+\to a_1^+\pi^0$ and $B\to a_1\,\rho$ we use the branching fractions 3×10^{-5} and 2×10^{-5}, respectively.

To distinguish $B^0\to\rho^+\rho^-$ decays from non-resonant $B^0\to\rho^\pm\pi^\mp\pi^0$ and $B^0\to\pi^+\pi^0\pi^-\pi^0$ decays, we do an unbinned ML fit to the $\pi^\pm\pi^0$ mass distribution. We select candidates from a $M_{\rm bc}-\Delta E$ signal region and fit the $m_{\pi^\pm\pi^0}$ distribution in the range 0.3–1.8 GeV/c^2. Only one ρ candidate is required to satisfy 0.62 GeV/$c^2 < m_{\pi^\pm\pi^0} < 0.92$ GeV/c^2; the mass of the other ρ candidate is then fit. The PDFs for signal and non-resonant $B\to\rho\pi\pi$ components are obtained from MC simulation. The PDFs for continuum and $b\to c$ backgrounds are grouped together and taken from the data sideband. We impose the constraint that the fraction of signal + non-resonant events in the $m_{\pi^\pm\pi^0}$ range 0.62–0.92 GeV/c^2 equals that which we obtained from the $M_{\rm bc}-\Delta E$ fit.

The main systematic uncertainties come from track reconstruction efficiency, π^0 reconstruction efficiency, the $\pi^\pm$ identification efficiency, the continuum suppression requirement, the $M_{\rm bc}-\Delta E$ shapes for $B^0\to\rho^+\rho^-$and $b\to c$ background, and the fraction of $b\to u$ background. The final result for the branching fraction is

$$B(B^0\to\rho^+\rho^-) = \left[22.8\pm3.8\,({\rm stat})\,^{+2.3}_{-2.4}\,({\rm syst})\right]\times10^{-6}\,. \tag{3.1}$$

The polarization of $B^0\to\rho^+\rho^-$ decays is obtained from an unbinned ML fit to the helicity angle distribution $F(\cos\theta_1,\cos\theta_2)$, where $\theta_{1,2}$ is the angle between the π^0 momentum and the direction opposite the B^0 in the ρ rest frame. For a longitudinal polarization fraction f_L, this distribution is $\frac{9}{4}\left[\,f_L\cos^2\theta_1\cos^2\theta_2+\frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2\right]$. This PDF is multiplied by a two-dimensional acceptance function $A(\cos\theta_1)\cdot A(\cos\theta_2)$ determined from MC simulation. The PDF for non-resonant decays is taken to be constant, the PDF for $b\to u$ background is taken from MC simulation, and the PDFs for continuum and $b\to c$ backgrounds are combined and determined from the data sideband. The fraction of signal + non-resonant decays is taken from the previous $M_{\rm bc}-\Delta E$ fit; the component $f_{\rho\pi\pi}$ is taken from the previous $m_{\pi^\pm\pi^0}$ fit. The small fraction of $b\to u$ background is fixed according to MC simulation. A fit to 656 candidates in the signal region yields

$$f_L = 0.951\,^{+0.033}_{-0.039}\,({\rm stat})\,^{+0.029}_{-0.031}\,({\rm syst})\,. \tag{3.2}$$

The systematic errors include the uncertainties in the signal + non-resonant and non-resonant fractions, acceptance, misreconstructed $B^0\to\rho^+\rho^-$ decays, the continuum suppression requirement, possible interference with an $L=0$ $\pi^\pm\pi^0$ system produced in non-resonant $\rho^\pm\pi^\mp\pi^0$ decays, and uncertainty in the continuum $+(b\to c)$ background shape. The obtained branching fraction and f_L are consistent with previously published measurements[4].

4. Measurement of the *CP*-violating parameters and constraint on ϕ_2

The *CP* parameters A and S are obtained from an unbinned ML fit to the Δt distribution. The likelihood function for event i is

$$L_i = f^{(i)}_{\rho\rho} P_{\rho\rho} + f^{(i)}_{\rm SCF} P_{\rm SCF} + f^{(i)}_{\rho\pi\pi} P_{\rho\pi\pi} + f^{(i)}_{b\to c} P_{b\to c} + f^{(i)}_{b\to u} P_{b\to u} + f^{(i)}_{q\bar{q}} P_{q\bar{q}}$$

where $f^{(i)}$ is the fraction of events determined on an event-by-event basis as a function of the $M_{\rm bc}$ and ΔE for each flavor tagging r interval. The PDFs $P(\Delta t)$ for $b\to c$ and $b\to u$ backgrounds are determined from MC simulation, and the PDF for continuum $q\bar{q}$ background is determined from a $M_{\rm bc}$ sideband. We include an additional PDF for SCF background in which a $\pi^{\pm}$ daughter is swapped with a track from the rest of the event; this function is determined from MC simulation and is found to be exponential with an effective lifetime of about 1 ps. $f_{\rm SCF}$ is also determined from MC simulation; its normalization is 5.7% of all $\rho^+\rho^-$ candidates. The PDF $P_{\rho\rho}(\Delta t)$ is given by

$$\int_{-\infty}^{+\infty} \frac{e^{-|\Delta t'|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 - q\Delta\omega_{\ell(i)} + q(1-2\omega_{\ell(i)}) \left[A\cos(\Delta m \Delta t') + S\sin(\Delta m\Delta t')\right]\right\} R(\Delta t^{(i)}, \Delta t')\, d\Delta t',$$

where $R(\Delta t, \Delta t')$ is a resolution function determined from data, ω_ℓ is the mistag probability for the ℓth bin of the tagging parameter r, and $\Delta\omega_\ell$ is a possible difference in ω_ℓ between $q=+1$ and $q=-1$ tags. The PDF $P_{\rho\pi\pi}$ is taken to be exponential with $\tau=\tau_B$ and is smeared by the same resolution function R. A fit to the 656 candidates in the signal region yields

$$\begin{aligned} A &= 0.00 \pm 0.30\,({\rm stat})\,^{+0.10}_{-0.09}\,({\rm syst}) \\ S &= 0.08 \pm 0.42\,({\rm stat}) \pm 0.08\,({\rm syst})\,. \end{aligned} \qquad (4.1)$$

These values are consistent with the no-*CP*-violation case $A=S=0$, and the errors are consistent with expectations based on MC studies. The systematic errors include the uncertainties in the wrong-tag fractions, component fractions, background asymmetry, fitting bias, vertex reconstruction, Δt resolution function, background Δt PDF, tag-side interference [5], and the systematic error due to the transversity amplitudes $A_\perp$ and $A_\parallel$ (which may have different values of A and S).

We use these values along with the measured branching fraction for $B^0\to\rho^+\rho^-$ and previously-measured branching fractions for $B^+\to\rho^+\rho^0$ [6] and $B^0\to\rho^0\rho^0$ [1] to constrain the angle ϕ_2. We use the isospin relations of Ref. [7] (originally applied to the $B\to\pi\pi$ system), neglecting a possible $I=1$ contribution to the $B^0\to\rho^+\rho^-$ amplitude [8]. We obtain a central value and 1σ error $\phi_2=(88\pm17)^\circ$; the 90% CL interval around the central value is $59^\circ<\phi_2<115^\circ$.

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