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Constraints upon the CKM angle ϕ_2 (α) from Belle

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The Belle experiment has measured branching fractions and CP asymmetries for the charmless decays $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^\pm\pi^\mp$. From these measurements, constraints upon the CKM angle ϕ_2 can be obtained. These constraints indicate that ϕ_2 is around 100°.

1. Overview

The Standard Model predicts CP violation to occur in B^0 meson decays owing to a complex phase in the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. This phase is illustrated by plotting the unitarity condition $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$ as vectors in the complex plane: the phase results in a triangle of nonzero height. One interior angle of the triangle, denoted ϕ_1 or β, is determined from $B^0 \to J/\psi\, K^0$ decays.[a] Another interior angle, ϕ_2 or α, is determined from charmless decays such as $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^\pm\pi^\mp$. Here we present measurements of these charmless decays from Belle,[1] and the resulting constraints upon ϕ_2.

To select $B^0 \to \pi^+\pi^-/\rho^\pm\pi^\mp$ decays, we require two opposite-charge pion-candidate tracks originating from the interaction region. For $B^0 \to \rho^\pm\pi^\mp$, one of these tracks is combined with a π^0 candidate. The charged pion identification criteria are based on information from time-of-flight counters, aerogel cherenkov counters, and dE/dx information from the central tracker.[2] B decays are identified via the "beam-constrained" mass $m_{\rm bc} \equiv \sqrt{E_b^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_b$, where p_B is the reconstructed B momentum, E_B is the reconstructed B energy, and E_b is the beam energy, all evaluated in the e^+e^- center-of-mass (CM) frame. The $m_{\rm bc}$ and ΔE distributions are jointly fit for the signal event yields.

A tagging algorithm is used to identify the flavor of the B decay, i.e., B^0 or $\overline{B}{}^0$. This algorithm examines tracks not associated with the signal decay to identify the flavor of the non-signal B. The signal-side tracks are fit for a decay vertex, and the tag-side tracks are fit for a separate decay vertex; the distance Δz between vertices is (to good approximation) proportional to the time difference between the B decays: $\Delta z \approx (\beta\gamma c)\Delta t$, where $\beta\gamma$ is the Lorentz boost of the e^+e^- system.

[a] Charge-conjugate modes are included throughout this paper unless noted otherwise.

The dominant background for both modes is $e^+e^- \to q\bar{q}$ continuum events, where $q = u, d, s, c$. In the CM frame such events tend to be collimated along the beam directions, whereas $B\overline{B}$ events tend to be spherical. The "shape" of an event is quantified via Fox-Wolfram moments[3] of the form $h_\ell = \sum_{i,j} p_i\, p_j\, P_\ell(\cos\theta_{ij})$, where i runs over all tracks on the tagging side and j runs over all tracks on either the tagging side or the signal side. The function P_ℓ is the ℓth Legendre polynomial and θ_{ij} is the angle between momenta $\vec{p_i}$ and $\vec{p_j}$ in the CM frame. These moments are combined into a Fisher discriminant, and this is combined with the probability density function for the cosine of the angle between the B direction and the electron beam direction. This yields an overall likelihood $\mathcal{L}$. Continuum events are rejected by requiring that the ratio $\mathcal{L}_{B\overline{B}}/(\mathcal{L}_{B\overline{B}} + \mathcal{L}_{q\bar{q}})$ be greater than a minimum value.

2. $B^0 \to \pi^+\pi^-$

The decay time dependence of $B^0/\overline{B}{}^0 \to \pi^+\pi^-$ decays is given by[4]

$$\frac{dN}{d\Delta t} \;\propto\; e^{-\Delta t/\tau}\Big[1 - q\,\mathcal{C}_{\pi\pi}\cos(\Delta m\Delta t) + q\,\mathcal{S}_{\pi\pi}\sin(\Delta m\Delta t)\Big], \tag{1}$$

where $q = +1$ (-1) corresponds to B^0 $(\overline{B}{}^0)$ tags, and Δm is the B^0-$\overline{B}{}^0$ mass difference. The parameters $\mathcal{C}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ are CP-violating and related to ϕ_2 via[5]

$$\mathcal{C}_{\pi\pi} \;=\; \frac{1}{R}\cdot\left(2\left|\frac{P}{T}\right|\sin(\phi_1-\phi_2)\sin\delta\right) \tag{2}$$

$$\mathcal{S}_{\pi\pi} \;=\; \frac{1}{R}\cdot\left(2\left|\frac{P}{T}\right|\sin(\phi_1-\phi_2)\cos\delta + \sin 2\phi_2 - \left|\frac{P}{T}\right|^2\sin 2\phi_1\right) \tag{3}$$

$$R \;=\; 1 - 2\left|\frac{P}{T}\right|\cos(\phi_1+\phi_2)\cos\delta + \left|\frac{P}{T}\right|^2 , \tag{4}$$

where $\phi_1 = (23.2^{+1.6}_{-1.5})^\circ$,[6] $|P/T|$ is the magnitude of a possible penguin amplitude relative to that of the tree-level amplitude, and δ is the strong phase difference between the two amplitudes. If there were no penguin contribution, $\mathcal{C}_{\pi\pi} = 0$ and $\mathcal{S}_{\pi\pi} = \sin 2\phi_2$. Since Eqs. (2) and (3) have three unknown parameters, measuring $\mathcal{C}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ determines a volume in ϕ_2 - δ - $|P/T|$ space.

The most recent Belle measurement of $\mathcal{C}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ is with 140 fb^{-1} of data.[7] The event sample consists of 224 $\overline{B}{}^0 \to \pi^+\pi^-$ candidates and 149 $B^0 \to \pi^+\pi^-$ candidates after background subtraction. These events are subjected to an unbinned maximum-likelihood (ML) fit in Δt; the results are $\mathcal{C}_{\pi\pi} = -0.58 \pm 0.15\,(\text{stat}) \pm 0.07\,(\text{syst})$ and $\mathcal{S}_{\pi\pi} = -1.00 \pm 0.21\,(\text{stat}) \pm 0.07\,(\text{syst})$, which indicate large CP violation. The nonzero value for $\mathcal{C}_{\pi\pi}$ indicates *direct* CP violation. Fig. 1 shows the Δt distributions for $q = \pm 1$ tagged events; a clear difference is seen between the distributions.

These values determine a 95% C.L. volume in ϕ_2 - δ - $|P/T|$ space. Projecting this volume results in the constraints $90^\circ < \phi_2 < 146^\circ$ for $|P/T| < 0.45$ (as predicted by QCD factorization[8] and perturbative QCD[9]), and $|P/T| > 0.17$ for any value of δ.

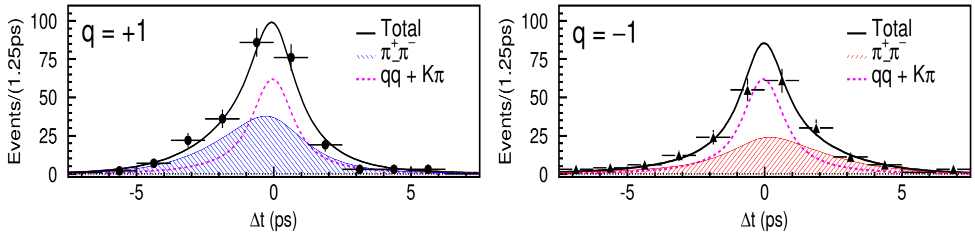

Fig. 1. The $B^0 \to \pi^+\pi^-$ Δt distribution for $q = +1$ tags (left) and $q = -1$ tags (right). The points show the data and the smooth curves are projections of the unbinned ML fit.

The dependence upon $|P/T|$ and δ can be removed by making additional theoretical assumptions. A model based on $SU(3)$ symmetry that uses the measured rates for $B^+ \to K^0\pi^+$ and $B^0 \to K^+\pi^-$ obtains $\phi_2 = (103 \pm 17)^\circ$.[10]

3. $B^0 \to \rho^\pm\pi^\mp$

For $B^0 \to \rho^\pm\pi^\mp$ the final state is not a CP eigenstate, and there are four decays to consider: $B^0 \to \rho^\pm\pi^\mp$ and $\overline{B}{}^0 \to \rho^\pm\pi^\mp$. The rates can be parametrized as[11]

$$\frac{dN(B \to \rho^\pm\pi^\mp)}{d\Delta t} \propto (1 \pm A_{CP}^{\rho\pi}) \times e^{-\Delta t/\tau}\left[1 - q\,(\mathcal{C}_{\rho\pi} \pm \Delta\mathcal{C}_{\rho\pi})\cos(\Delta m \Delta t) + q\,(\mathcal{S}_{\rho\pi} \pm \Delta\mathcal{S}_{\rho\pi})\sin(\Delta m \Delta t)\right], \quad (5)$$

where $q = +1$ (-1) corresponds to B^0 $(\overline{B}{}^0)$ tags. The parameters $\mathcal{C}_{\rho\pi}$ and $\mathcal{S}_{\rho\pi}$ are CP-violating, whereas $\Delta\mathcal{C}_{\rho\pi}$ and $\Delta\mathcal{S}_{\rho\pi}$ are CP-conserving. $\Delta\mathcal{C}_{\rho\pi}$ characterizes the difference in rates between the "$W \to \rho$" process $B^0 \to \rho^+\pi^-$ or $\overline{B}{}^0 \to \rho^-\pi^+$ and the "spectator $\to \rho$" process $B^0 \to \rho^-\pi^+$ or $\overline{B}{}^0 \to \rho^+\pi^-$. $\Delta\mathcal{S}_{\rho\pi}$ depends, in addition, on differences in phases between the $W \to \rho$ and spectator $\to \rho$ amplitudes. The parameter $A_{CP}^{\rho\pi}$ is the time and flavor integrated asymmetry $\Gamma(B^0 \to \rho^+\pi^-) + \Gamma(\overline{B}{}^0 \to \rho^+\pi^-) - \Gamma(\overline{B}{}^0 \to \rho^-\pi^+) - \Gamma(B^0 \to \rho^-\pi^+)$ divided by the sum of the four rates. We also define the asymmetries $A_{\substack{+- \\ -+}} \equiv \left[N(\overline{B}{}^0 \to \rho^\mp\pi^\pm) - N(B^0 \to \rho^\pm\pi^\mp)\right] / \left[N(\overline{B}{}^0 \to \rho^\mp\pi^\pm) + N(B^0 \to \rho^\pm\pi^\mp)\right]$. A_{+-} depends only on $W \to \rho$ processes and A_{-+} depends only on spectator $\to \rho$ processes.

The most recent Belle results are from 140 fb^{-1} of data.[12] To remove charge-ambiguous decays and possible interference between $B^0 \to \rho^+\pi^-$ and $B^0 \to \rho^-\pi^+$ amplitudes, we require both $0.57 < m_{\pi^\pm\pi^0} < 0.97$ GeV/c^2 and $m_{\pi^\mp\pi^0} > 1.22$ GeV/c^2. We define a signal region $m_{\rm bc} > 5.27$ GeV/c^2 and $-0.10 < \Delta E < 0.08$ GeV; there are 1215 events in this region and 329 $B^0 \to \rho^\pm\pi^\mp$ candidates. Fitting to Δt yields $A_{CP}^{\rho\pi} = -0.16 \pm 0.10 \pm 0.02$, $C_{\rho\pi} = 0.25 \pm 0.17\,^{+0.02}_{-0.06}$, $S_{\rho\pi} = -0.28 \pm 0.23\,^{+0.10}_{-0.08}$, $\Delta C_{\rho\pi} = 0.38 \pm 0.18\,^{+0.02}_{-0.04}$, and $\Delta S_{\rho\pi} = -0.30 \pm 0.24 \pm 0.09$. From these values we calculate $A_{+-} = -0.02 \pm 0.16\,^{+0.05}_{-0.02}$ and $A_{-+} = -0.53 \pm 0.29\,^{+0.09}_{-0.04}$. The first errors listed are statistical and the second systematic. The Δt distributions for $q = \pm 1$ tagged events and the resulting CP asymmetry are shown in Fig. 2.

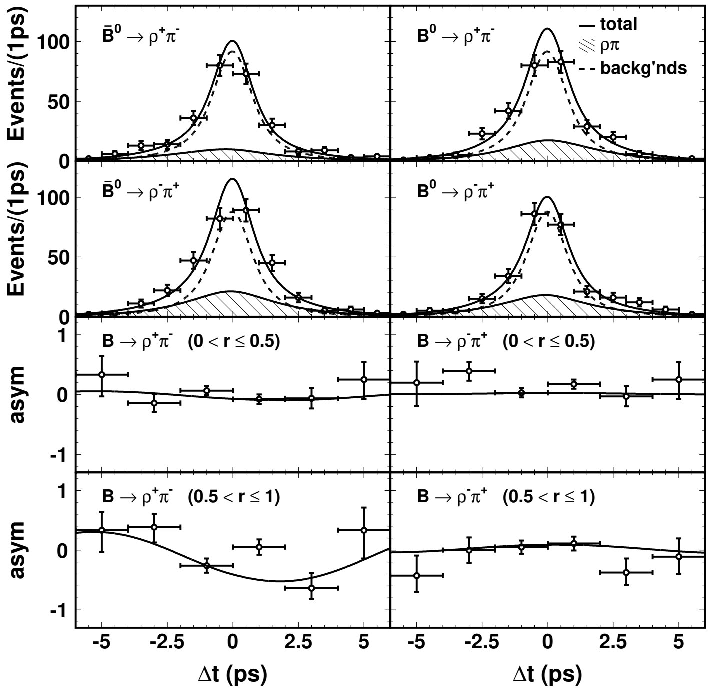

Fig. 2. The $B^0 \to \rho^\pm\pi^\mp$ Δt distribution for $q = +1$ tags (left) and $q = -1$ tags (right), and the resulting CP asymmetry (bottom). The asymmetry is shown separately for high-quality ($r > 0.5$) and low quality ($r \leq 0.5$) tags. The smooth curves are projections of the unbinned ML fit.

These values can be used to constrain ϕ_2. However, since the penguin contribution is unknown, additional information is needed. An $SU(3)$-based model that uses the measured rates or limits for $B^0 \to K^{*\pm}\pi^\mp$, $B^0 \to \rho^\mp K^\pm$, $B^\pm \to K^{*0}\pi^\pm$, and $B^\pm \to \rho^\pm K^0$ obtains $\phi_2 = 102 \pm 19°$.[13] This value is surprisingly close to that resulting from the values of $\mathcal{C}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ measured in $B^0 \to \pi^+\pi^-$ decays.

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