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CP VIOLATION IN B DECAYS

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FOR THE BABAR COLLABORATION

We present recent results on CP violation in the B meson system from the BABAR experiment at the PEP II asymmetric e^+e^- collider. We discuss the study of CP violation in B-mixing and present measurements of unitarity-triangle angles α, β, and constraints on γ.

Keywords: CP Violation; B mesons, B factory.

1. Introduction

The BABAR detector[1] is located at the e^+e^- asymmetric B-factory at SLAC. The main physics goal of BABAR is to study CP-violation in the B system and provide a quantitative test of the CP sector of the Standard Model. All measurements presented in this article are based on a dataset of 232×10^6 $B\overline{B}$ events.

In the Standard Model, CP violation in the quark sector is due to the complex matrix V_{CKM} relating the quark weak eigenstates to their mass eigenstates. One unitarity condition can be written as the Unitarity Triangle: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. Over-constraining this triangle allows one to search for inconsistencies in the Standard Model. Its angles are generally measured in CP-violating processes. The angle β is the phase of V_{td} accessible in $B^0\bar{B}^0$ mixing, and has already been measured precisely at the B factories. The angle γ is the phase of V_{ub} found in transitions like $B \to D^{(*)}K^{(*)}$. The angle $\alpha = \pi - \beta - \gamma$ can be extracted in processes that involve both $B^0\bar{B}^0$ mixing and $b \to u$ transitions.

2. Experimental Technique

At the B-factories, CP violation is studied through the measurement of the time dependent CP asymmetry, $A_{CP}(t)$. This quantity is defined as

$$A_{CP}(t) \equiv \frac{N(\overline{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\overline{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})}, \tag{1}$$

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where $N(\overline{B}^0(t) \to f_{CP})$ is the number of $\overline{B}^0$ that decay into the CP-eigenstate f_{CP} after a time t. In general, this asymmetry can be expressed as the sum of two components:

$$A_{CP}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t), \quad (2)$$

where Δm is the difference in mass between B mass eigenstates. When only one diagram contributes to the final state, the cosine term vanishes. For decays such as $B \to J/\psi K^0$, $S_f = -\eta_f \times sin2\beta$, where η_f is the CP eigenvalue of the final state, negative for charmonium + K_S and positive for charmonium + K_L. It follows that $A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m t)$, which shows how the angle β is directly and simply measured by the amplitude of the time dependent CP asymmetry.

$B\bar{B}$ pairs resulting from the Υ(4S) decays are produced in a coherent state. The CP asymmetry is measured as a function of the difference $\Delta t = \Delta z/(\gamma\beta)$ between the two B-mesons decay times which is proportional to Δz, the difference between their flight distances due to a boost of $\gamma\beta \approx 0.56$ given to the Υ(4S). The average Δz is around 250 μm, with a resolution of about 170 μm. One of the B mesons is fully reconstructed into the B decay of interest (B_{CP}), while the other B meson ($B_{\rm tag}$) is used to tag its flavor at production time. Tagging combines different techniques including the use of semileptonic decays and secondary kaons. The B-flavor tagging power $Q = \Sigma_i \epsilon_i (1 - 2\omega_i)^2$ is close to 30%, when summed over the different tagging categories i, with efficiencies ϵ_i and mistag rates ω_i. In order to select the signal, the beam energy (E_{beam}) substituted mass $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$, and the energy difference $\Delta E = E^*_B - E^*_{beam}$ are powerful kinematic discriminating variables, peaking respectively for the signal at the B-meson mass and at zero. The symbol $*$ refers to the Υ(4S) rest frame.

3. Measurements of β

The determination of the angle β through the study of B^0 decays plays a key role in the test of Unitarity Triangle. The measurement of β from decays mediated by $b \to c\bar{c}s$ tree level diagrams allows for a precise test of CP violation in the Standard Model and provides the most precise constraint in the determination of the parameters ρ and η. In addition, the measurement of the same angle in final

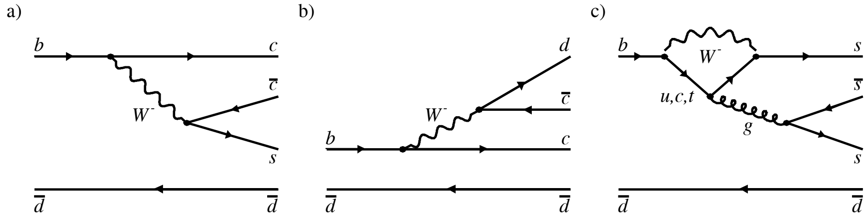

Fig. 1. Feynman diagrams that mediate the B^0 decays used to measure the angle β: **a)** $B^0 \to$ charmonium $+ K^0$, **b)** $b \to c\bar{c}s$, **c)** penguin dominated B decays.

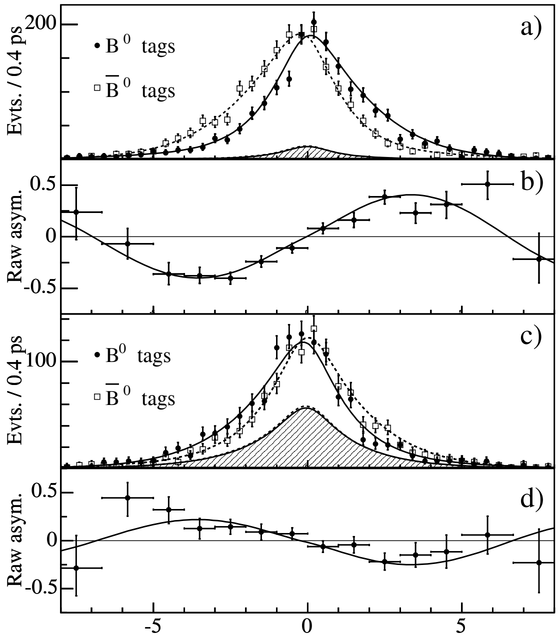

Fig. 2. Measurement of $\sin 2\beta$ in the "golden modes" by BABAR. **a)** Time distributions for events tagged as B^0 (full dots) or $\overline{B}^0$ (open squares) in CP odd (charmonium K_S) final states. **b)** The corresponding raw CP asymmetry with the projection of the unbinned maximum likelihood fit superimposed. **c)**, **d)** The corresponding distributions for CP even ($J/\psi K_L$) final states.

states mediated by penguin decays and $b \to c\bar{c}d$ diagrams can be used to look for new physics. The angle β can be independently measured through the three types of B^0 decays illustrated in Fig. 1.

The decays $B^0 \to \text{charmonium} + K^0$, known as "golden modes", are dominated by a tree level diagram $b \to c\bar{c}s$ with internal W boson emission (Fig. 1a). The leading penguin diagram contribution to the final state has the same weak phase as the tree diagram, and the largest term with different weak phase is a penguin diagram contribution suppressed by $O(\lambda^2)$. This makes $C_f = 0$ in equation (2) a very good approximation. Besides the theoretical simplicity, these modes also offer experimental advantages because of their relatively large branching fractions ($\sim 10^{-4}$) and the presence of the narrow J/ψ resonance in the final state, which provides a powerful rejection of combinatorial background. The CP eigenstates considered for this analysis are $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$ and $J/\psi K_L$. The asymmetry between the two Δt distributions, clearly visible in Fig. 2, is a striking manifestation of CP violation in the B system. The same figures also display the corresponding raw CP asymmetry with the projection of the unbinned maximum likelihood fit superimposed. The results of the fit is $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$[2]. The main sources of systematic errors are uncertainties in the background level and characteristics, in

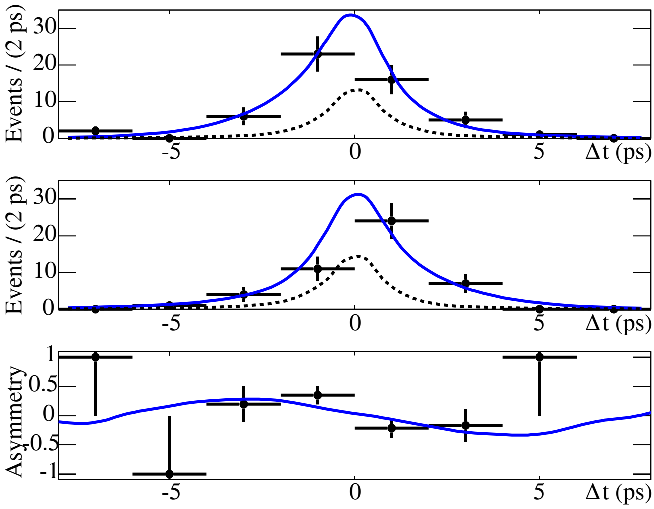

Fig. 3. Measurement of CP asymmetries for the channel $B \to J/\psi\pi^0$ by BaBar. The time distribution is shown for events tagged as B^0 (*top*) or $\overline{B}^0$ (*middle*). The dotted lines are the sum of backgrounds and the solid lines are the sum of signal and backgrounds. The time-dependent CP asymmetry is also shown (*bottom*), where the curve is the measured asymmetry.

the parameterization of the time resolution, and in the measurement of the mis-tag fractions. Most of these uncertainties will decrease with additional statistics. The world average value for $\sin 2\beta$, heavily dominated by the results from BaBar[2] and Belle[3], is $\sin 2\beta = 0.687 \pm 0.032$. This value can be compared with the indirect constraints on the apex of the Unitarity Triangle originating from measurements of ϵ_K, $|V_{ub}|$, $|V_{cb}|$, B^0 and B_S mixing, $\sin 2\beta = 0.793 \pm 0.033$ as described, for example, in Ref. 4. The comparison shows good agreement between the measurements, indicating that the observed CP asymmetry in $B^0 \to \text{charmonium} + K^0$ is consistent with the predictions of the CKM mechanism.

For what concerns $b \to c\bar{c}d$ channels, a new measurement has been obtained with the decay $B \to J/\psi\pi^0$, which can proceed with a color-suppressed tree level diagram with internal W boson emission and a penguin diagram contribution. New physics could enhance the penguin contribution and would lead to a measurement of time dependent CP asymmetry substantially different from that measured in $B^0 \to$ charmonium$+K^0$ decays. The two $Delta$t distributions are shown in Fig. 3, together with the corresponding raw CP asymmetry. We obtain a branching fraction $\mathcal{B}(B \to J/\psi\pi^0) = (1.94 \pm 0.22(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-5}$ and the CP asymmetry parameters $C = -0.21 \pm 0.26(\text{stat}) \pm 0.06(\text{syst})$ and $S = -0.68 \pm 0.30(\text{stat}) \pm 0.04(\text{syst})$[5].

In the Standard Model, final states dominated by penguin $b \to s\bar{s}s$ or $b \to s\bar{d}d$ decays offer a clean and independent way of measuring $sin 2\beta$[6]. Examples of these final states are ϕK^0, $\eta' K^0$, $f_0 K^0$, $\pi^0 K^0$, ωK^0, $K^+K^-K_S$ and $K_S K_S K_S$. These decays are mediated by the gluonic penguin diagram illustrated in Fig. 1c. In presence of physics beyond the Standard Model, new particles such as squarks and gluinos,

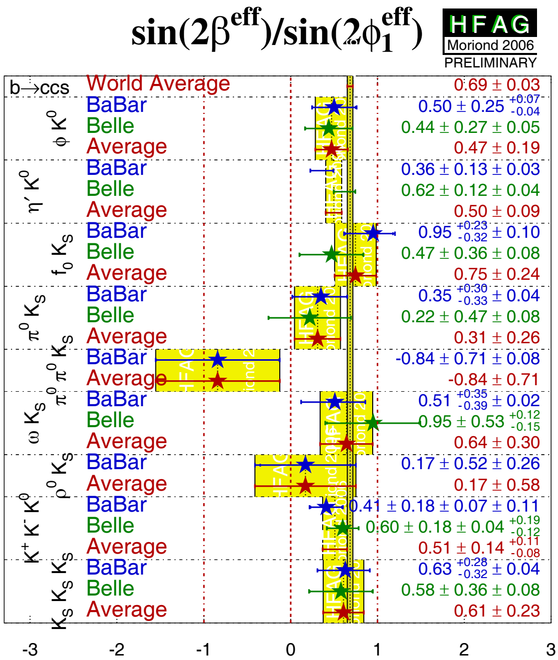

Fig. 4. BaBar measurements of "$\sin 2\beta$" in the penguin dominated channels. The right band indicates the world average of the charmonium + K^0 final states $\pm 1\sigma$; the left band is the average of the s-penguin modes $\pm 1\sigma$.

could participate in the loop and affect the time dependent asymmetries[7]. The decays $B^0 \to \phi K_S$ are ideal for these studies. In the Standard Model, these decays are almost pure $b \to s\bar{s}s$ penguin decays, and their CP asymmetry is expected to coincide with the one measured in charmonium + K^0 decays within a few percent[7]. Experimentally, this channel is also very clean, thanks to the powerful background suppression due to the narrow ϕ resonance. Unfortunately, the branching fraction for this mode is quite small ($\approx 8 \times 10^{-6}$), therefore the measurement is affected by a large statistical error. The decays $B^0 \to \eta' K_S$ are favored by a larger branching fraction ($\approx 6 \times 10^{-5}$). In the Standard Model, these decays are also dominated by penguin diagrams; other contributions are expected to be small[8].

A first measurement of the CP violation parameters has been obtained for the channel $B^0 \to \rho K_S$ by BaBar. We obtain the following CP asymmetry parameters $C = 0.64 \pm 0.41(\text{stat}) \pm 0.25(\text{syst})$ and $S = 0.17 \pm 0.52(\text{stat}) \pm 0.26(\text{syst})$.

The average between the Belle and BaBar measurements in each channel is illustrated in Figure 4. The band on the right indicates the world-average value of $sin2\beta$. A naive average of all the penguin modes[9] is 2.8σ away from the value of $\sin 2\beta$ measured in the golden mode. This discrepancy, however, has to be interpreted with caution since each mode is theoretically affected by new physics in different ways.

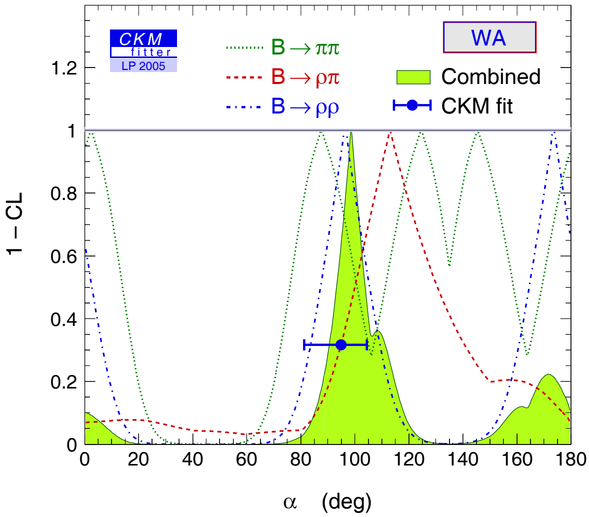

Fig. 5. Constraints on the angle α.

4. Measurements of α

$B^0 \to h^+h^-$ decays ($hh = \pi\pi, \rho\rho$) are dominated by the $b \to u$ tree amplitude T, with weak phase γ. Ignoring other contributions, one would simply get $\lambda_{h^+h^-} = \frac{p}{q} \times \frac{\bar{T}}{T} = e^{-i2\beta}e^{-i2\gamma} = e^{i2\alpha}$, $C_{h^+h^-} = 0$ and $S_{h^+h^-} = \sin(2\alpha)$. But contributions of amplitude P, from dominant gluonic penguins and with no weak phase, allow direct CP violation. If we define the amplitude T' as that dominated by tree processes but also including non-dominant penguins with a weak phase γ, and if δ is the strong phase difference between the T' and P amplitudes then: $\lambda_{h^+h^-} = e^{i2\alpha}\frac{|T'|+|P|e^{+i\gamma}e^{i\delta}}{|T'|+|P|e^{-i\gamma}e^{i\delta}}$, $C_{h^+h^-} \propto sin\delta$, and $S_{h^+h^-} = \sqrt{1-C^2} \times sin(2\alpha_{eff})$. Measuring $C_{h^+h^-}$ and $S_{h^+h^-}$ only yields an effective value of α, α_{eff}, which depends on the B-decay mode studied. Fortunately, other B-mesons decays to hh can be used to determine the difference $\alpha - \alpha_{eff}$ using isospin symmetry[10]. The $B \to \rho\rho$ branching ratio is about 6 times larger than for $B \to \pi\pi$, and the penguin pollution is much smaller. Thus this mode is better for constraining α.

A measurement of the branching fraction, polarization and CP asymmetry has been obtained by BaBar , for the channel $B^\pm \to \rho^\pm\rho^0$, $\mathcal{B}(B^\pm \to \rho^\pm\rho^0) = (16.8 \pm 2.2(\mathrm{stat}) \pm 2.3(\mathrm{syst})) \times 10^{-6}$, $f_L = 0.905 \pm 0.042(\mathrm{stat})^{+0.23}_{-0.27}(\mathrm{syst})$, $A_{CP} = -0.12 \pm 0.13(\mathrm{stat}) \pm 0.10(\mathrm{syst})$[11].

Figure 5[4] summarizes all constraints on α obtained at BaBar and Belle, yielding a combined value of $\alpha = (99^{+12}_{-9})^\circ$ in good agreement with the global CKM fit using other world measurements $\alpha = (91.9 \pm 5.5)^\circ$. The $\rho\rho$ mode gives the best single measurement, but has mirror solutions that are disfavored thanks to the Dalitz analysis results. The contribution to the constraint from the $\pi\pi$ modes is limited, mostly due to the large penguin pollution.

5. Measurements of γ

A theoretically clean measurement of the angle γ can be obtained from the study of $B^- \to D^{(*)0}K^{(*)-}$, exploting the interference between $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$ when the D^0 and the $\bar{D}^0$ mesons decay to the same CP eigenstate. BaBar has measured the partial-rate charge asymmetries $A_{CP\pm}$ and the ratios $R_{CP\pm}$ of the $B \to D^0K$ decay branching fractions as measured in $CP\pm$ and non-CP D^0 decays[12]: $A_{CP+} = 0.35 \pm 0.13(\mathrm{stat}) \pm 0.04(\mathrm{syst})$, $A_{CP-} = -0.06 \pm 0.13(\mathrm{stat}) \pm 0.04(\mathrm{syst})$, $R_{CP+} = 0.90 \pm 0.12(\mathrm{stat}) \pm 0.04(\mathrm{syst})$, $R_{CP-} = 0.86 \pm 0.10(\mathrm{stat}) \pm 0.05(\mathrm{syst})$, Combining results from BaBar and Belle, it is possible to obtain the following limits: $\gamma = (65 \pm 20)^\circ$ ($[27, 107]$@95% CL) or $\gamma = (-115 \pm 20)^\circ$ ($[-153, 73]$@95% CL).

Additional information on the CKM unitarity triangle can come from the time evolution of $B^0 \to D^{(*)\pm}h^\mp$, since the decay amplitudes $\bar{B}^0 \to D^{(*)+}h^-$ and $B^0 \to D^{(*)+}h^-$ interfere due to mixing, and the total weak phase difference is $2\beta + \gamma$. Using all BaBar measurements[13] we find $|\sin(2\beta+\gamma)| > 0.64(0.40)$ at 68% (90%) confidence level.

6. CP Violation in $B^0 - \bar{B}^0$ Mixing

The Standard Model predicts the size of CP asymmetry due to $B^0 - \bar{B}^0$ mixing to be at or below 10^{-3}. A large measured value would be an indication of new physics. BaBar has recently searched for T, CP and CPT violation in mixing using an inclusive dilepton sample, obtaining[14] $|q/p| - 1 = (-0.8 \pm 2.7(\mathrm{stat}) \pm 1.9(\mathrm{syst})) \times 10^{-3}$, $\mathrm{Im}\ z = (-13.9 \pm 7.3(\mathrm{stat}) \pm 3.2(\mathrm{syst})) \times 10^{-3}$ and $\Delta\Gamma \times \mathrm{Re}\ z = (-7.1 \pm 3.9(\mathrm{stat}) \pm 2.0(\mathrm{syst})) \times 10^{-3}\mathrm{ps}^{-1}$.

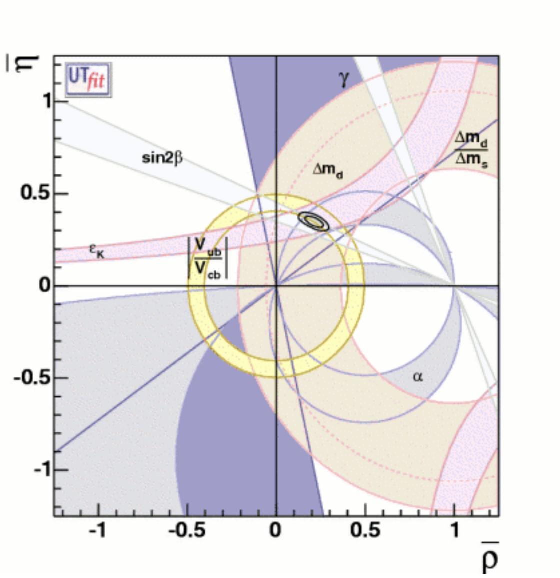

Fig. 6. Constraints on the apex of the Unitarity Triangle

7. Summary and Conclusions

The measurement of time-dependent CP asymmetry in B^0 decays have provided a crucial test of CP violation in the Standard Model. The parameter $\sin 2\beta$ is now measured in $b \to c\bar{c}s$ decays by BaBar with a precision of 5%. Measurements of time-dependent CP violation asymmetries in $b \to c\bar{c}d$ and in penguin-dominated modes are sensitive to contributions from physics beyond the Standard Model. The angle α is now measured with 10% precision, and interesting limits have been obtained for the angle γ. Figure 6 shows the combined constraints on the unitarity triangle, coming from all experimental measurements. Most of these measurements are still heavily dominated by statistical errors and will benefit greatly from additional data. BaBar has now (September 2006) collected a total integrated luminosity of 390.22 fb^{-1}, almost double of the one used in this article, and is planning to double it again by 2008.

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