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CP VIOLATION
OVERVIEW OF CKM ANGLES

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The measurements of the angles of the Unitarity Triangle is an important test of the Standard Model. After an introduction to the CP violation in the Standard Model, results from the $BaBar$ collaboration will be summarized.

1 CP violation in the Standard Model

After 40 years from its discovery in K^0 system [1], the violation of the CP symmetry is one of the open problems in particle physics. In the Standard Model with three quark generations, CP violation arises from a single phase in the quarks mixing matrix (CKM matrix) [2]. The unitarity of the CKM matrix implies various relations among its elements. One of them is very useful to understand the Standard Model prediction of CP violation in the decays of B mesons:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0 \tag{1}$$

This relationship can be geometrically represented as a triangle in the complex plane and is known as the Unitarity Triangle. CP violation manifest itself as a non-zero area of the triangle. The three angles of the Unitarity Triangle are denoted by α, β and γ:

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \equiv \pi - \alpha - \beta. \tag{2}$$

These are physical quantities and can be measured by CP asymmetries in various B decays. Fig. 1 shows the geometrical representation of the Unitarity Triangle and the channels used for the measurements of the three angles. Inconsistency in the measurements of angles or sides would signal deviations from the Standard Model.

2 Measurement of angles

To measure angles of the Unitarity Triangle one needs to measure relative phases of decay amplitudes. This can be done studying time dependent asymmetries in neutral B meson's decays or charge asymmetries in charged B meson's decays.

The time-dependent asymmetry for B^0 and $\bar{B}^0$ decaying to a common final state f is given by

$$a_f(t) = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)} = C_f \cos \Delta m t + S_f \sin \Delta m t \tag{3}$$

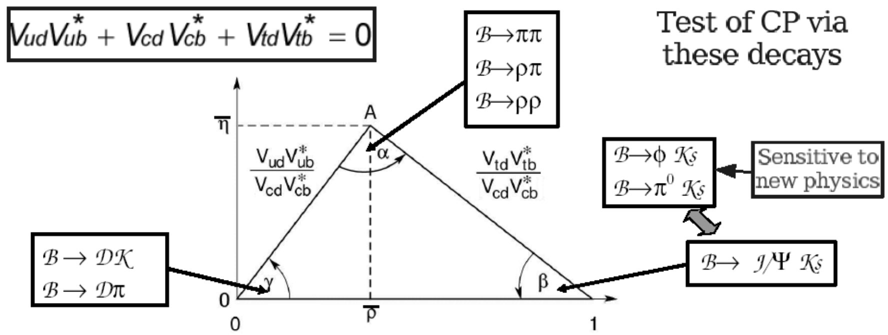

Figure 1. The rescaled Unitarity Triangle. The boxes show the channels used for the measurements of the three angles.

where

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = -\frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}. \tag{4}$$

$\lambda_f = \frac{q}{p}\,\frac{\bar{A}(f)}{A(f)}$, and $A(f)$, $\bar{A}(f)$ are the amplitudes of the decays $B^0_d \to f$, $\bar{B^0}_d \to f$. Considering particular final states f: if $f = J/\Psi K_s$, $C = 0$ and $S = sin(2\beta)$, if $f = \pi\pi, \rho\rho$, $C \neq 0$ and $S \propto sin(2\alpha + \Delta\alpha)$, $f = D\pi$, $C \approx 0$ and $S \propto sin(2\beta+\gamma) \ll 1$.

Considering the conjugates charged B decay channels $B^+ \to f^+$ and $B^- \to f^-$, the charge asymmetries in charged B meson's decays is given by:

$$A_{CP} = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)} \tag{5}$$

and it is sensitive to the direct CP violation.

The $BaBar$ detector [3] is a multipurpose detector at the $PEPII$ e^+e^- $B-$factory at $SLAC$. The results showed here are based on more than $100M$ $Y(4S) \to B\bar{B}$ decays. The non-zero center of mass boost ($\beta\gamma = 0.56$) and the high luminosity allow the study of time dependent asymmetries in B meson decays.

3 Measurements of β

Two kinds of channels are useful for the measurements of β. In charmonium modes ($J/\Psi K_s$,$\Psi(2S)K_s$ [4]) the tree and penguin contributions have the same weak phase. These modes give a precision measure of $\sin(2\beta)$. The charmless B meson decays (e.g. ϕK_s [5]) have only penguin contributions and can, in principle, measure $\sin(2\beta)$, but they are sensitive to new physics. Comparison of the value of $\sin(2\beta)$ obtained from these modes with that from charmonium modes probe new physics in penguin loops [6,7]. Fig. 2 shows the possible contribution to new physics in charmless modes and the value of $\eta_f S_f$ (η_f is the CP eigenvalue of the final state) for both charmonium and charmless modes. There starts to be some hint of difference between the two sets of modes.

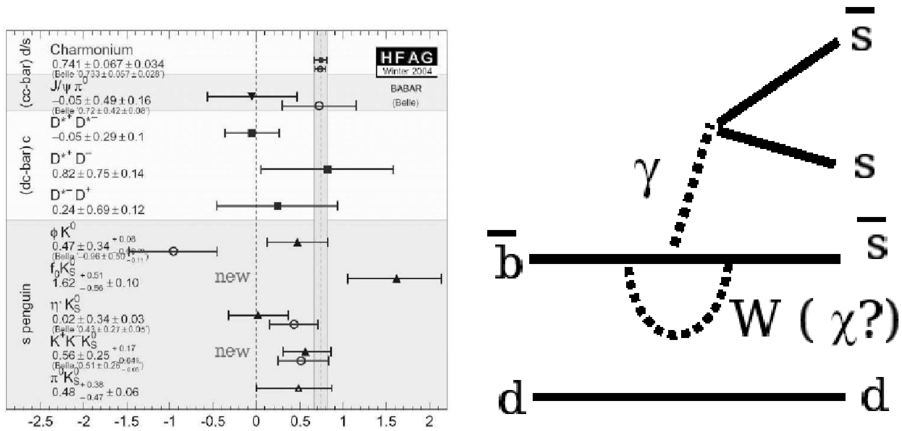

Figure 2. Left: value of $\eta_f S_f$ for both charmonium and charmless modes. Right: possible contribution to new physics in charmless modes.

4 Measurements of α

The decay $B^0 \to \rho^+\rho^-$ $(\pi^+\pi^-)$ proceeds mainly through the $b \to u\bar{u}d$ tree diagram, whose interference with $B^0 - \bar{B}^0$ mixing results in a time-dependent decay rate asymmetry between B^0 and $\bar{B}^0$ decays which is sensitive to the CKM angle $\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$. The presence of loop (penguin) contributions introduces additional phases which can shift the experimentally measurable parameter α_{eff} away from the value of α $(\Delta\alpha)$.

The $B \to \rho\rho$ decays are very well suited for the measurements of α because of several positive circumstances: the penguin pollution is small, as shown by the small $B^0 \to \rho^0\rho^0$ branching fraction ($< 2.1\ 10^{-6}$ at $90\%CL$ [8]); the $B^0 \to \rho^+\rho^-$ branching fraction is high ($(30 \pm 4\ stat \pm 5\ syst)10^{-6}$ [9]); and the longitudinal polarization of $B^0 \to \rho^+\rho^-$ is large ($0.99 \pm 0.03\ stat\ ^{+0.04}_{-0.03}\ syst$ [9]).

Neglecting $I = 1$ contributions in applying the Grossman-Quinn bound [10] and ignoring interferences with other $\pi^+\pi^-\pi^0\pi^0$ final states, one can measure $\alpha = 96 \pm 10\ stat \pm 4\ syst \pm 13\ peng$.

The limiting factor on the extraction of α comes from penguin pollution, which can be constrained using an improved measurement of the decay $B^0 \to \rho^0\rho^0$.

5 Measurements of γ

It is possible to measure γ using the interference between $b \to u$ and $b \to c$ transitions. The time evolution of $B^0 \to D^{(*)\pm}\pi^\mp$ decays is sensitive to γ because of the interference between the CKM-favored decay $\bar{B}^0 \to D^{(*)+}\pi^-$, whose amplitude is proportional to the CKM matrix elements $V_{cb}V_{ud}^*$, and the doubly-CKM-suppressed decay $B^0 \to D^{(*)+}\pi^-$, whose amplitude is proportional to $V_{cd}V_{ub}^*$. The relative weak phase between the two amplitudes is γ, which, when combined with $B^0\bar{B}^0$

mixing, yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes. Using other measurements and theoretical assumptions a time dependent analysis gives $| \sin(2\beta + \gamma) | > 0.69$ at 68% CL [12]. It is possible also to measure γ using direct CP asymmetries in B^+ decay. Various methods have been proposed for obtaining the CKM angle γ through the interference of the charged B decay channel $B^- \to D^0 K^-$ and $B^- \to \bar{D^0} K^-$ where the D^0 and $\bar{D^0}$ decay to common final state. For all of these methods is important the value of the parameter $r_B =| A(B^- \to \bar{D^0} K^-) \mid / \mid A(B^- \to \bar{D^0} K^-) |$. The larger is the value of the product of r_B and the same parameter for the D^0, the better is the precision on γ. It is possible to measure r_B using $B^- \to (K^+\pi^-)_D K^-$ decays [13]; recent results from $BaBar$ [14] give an upper limit to $r_B < 0.22$ at $90\% CL$ which seems to indicate that an accurate measurement of γ will require a lot of statistics.

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