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CP violation and CKM parameters determination in BaBar

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Introduction

CP violation (CPV), first detected in $K_L \to \pi^+\pi^-$ decays in 1964 [1], is accomodated in the Standard Model (SM) by a CP-violating phase in the CKM matrix, the matrix which describes the mixing of the quarks (under the weak interaction) [2]. From the unitarity constraints of the CKM matrix, we have $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, the so-called Unitarity Triangle relation, represented in Fig. 1. CPV is proportional to the area of the triangle and

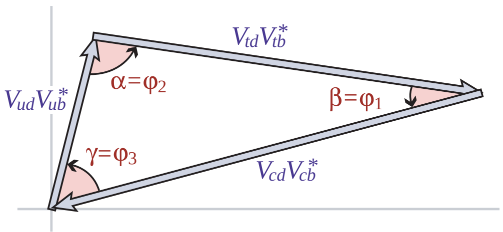

Fig. 1. Graphical representation of the unitarity constraint $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ as a triangle in the complex plane.

requires the angles and sides to be different from zero. The main goal of the BaBar experiment [3] is to overconstrain the Unitarity Triangle parameters, measuring the sides and the angles directly from the data of B_u and B_d meson decays, in order to test the consistency of the SM.

1 CP violation in decay and the angle γ

Direct CPV occurs in both charged and neutral B meson decays when the amplitude for a decay and its CP-conjugate process have different magni-

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tudes. BaBar provided the first evidence of direct CPV in $B^0 \to K^-\pi^+$ decays [4], which was then confirmed by Belle [5]. The measured asymmetry is $A_{K\pi} = \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} = -0.133 \pm 0.030 \pm 0.009$. CPV in decay arises from the interference of tree and penguin diagrams with non-vanishing CP-even and CP-odd relative phases. It is not possible to extract any CKM parameter from this measurement due to large theorethical uncertainties in the hadronic parameterization of the decay amplitude. BaBar was able to measure the CKM angle $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ studying the $B^- \to D^{(*)}K^{(*)-}$ decay chain, reconstructing the D in a final state f accessible by both the D^0 and $\bar{D}^0$. The sensitivity to γ comes from the interference between $b \to c\bar{u}s$ and the $b \to u\bar{c}s$ amplitudes. The state f can be a CP eigeinstate (GLW method) [6, 7], or a Double-Cabibbo-Suppressed state (ADS method) [8], or a three-body final state (Dalitz plot method) [9]. The Dalitz plot method has the highest sensitivity to the angle γ and requires the analysis of the distribution of the $B^- \to D^{(*)}K^{(*)-}$ events in the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plane. This analysis measures $\gamma = (92 \pm 41 \pm 11 \pm 12)$ degrees, where the first error is statistical, the second is experimental and the third is due to the D^0 decay model [10]. The combination of all the different methods yields $\gamma = (73 \pm 29)$ degrees [11].

2 *CP* violation in mixing

CPV in mixing occurs when the two neutral mass eigenstates cannot be chosen to be CP eigenstates. We define the mass eigeinstates B_H and B_L,

$$|B_H\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle \qquad |B_L\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle.$$

CPT invariance requires the complex parameter z to be zero. Similarly, T invariance leads to $\frac{|q|}{|p|} = 1$, while CP invariance requires both $\frac{|q|}{|p|} = 1$ and $z = 0$. While CPV in mixing has been observed in the neutral kaon system, there is currently no experimental evidence of CPV in mixing (or T or CPT violation) in the neutral B meson system. Reconstructing the inclusive decays of $B^0 \to Xl\nu$ it is possible to measure $A_{T/CP}(\Delta t) = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)} \simeq \frac{1-|q/p|^4}{1+|q/p|^4}$, where $N(l^\pm l^\pm)$ are the events with same lepton charge from the B decays. The sign of the lepton charge is correlated with the flavor of the neutral B meson and it is sensitive to the mixing probability. Another observable, is sensitive to CP/CPT violation $A_{CP/CPT}(|\Delta t|) = \frac{N(l^+l^-,\Delta t>0) - N(l^+l^-,\Delta t<0)}{N(l^+l^+,\Delta t>0) + N(l^-l^-,\Delta t<0)} \simeq 2\frac{\mathrm{Im}(z)\sin(\Delta m \Delta t) - \mathrm{Re}(z)\sinh(\Delta\Gamma\Delta t/2)}{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)}$. BaBar measures $|q/p| = 1.008 \pm 0.027 \pm 0.019$, $\mathrm{Im}(z) = 0.0139 \pm 0.0073 \pm 0.0032$ and $\Delta\Gamma \times \mathrm{Re}(z) = -0.0071 \pm 0.0039 \pm 0.0020\ \mathrm{ps}^{-1}$ [12]. These measurements help to constrain possible models of New Physics.

3 CP violation in the interference between decays with and without mixing

A third type of CPV occurs in decays into final states that are common to B^0 and $\bar{B}^0$, for example neutral B decays into CP eigenstates, f_{CP}. The physically meaningful quantity of interest, independent of phase conventions is $\lambda \equiv \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} \equiv \eta_{f_{CP}}\frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$, with $\eta_{f_{CP}}$ the CP eigenvalue of the final state f. When CP is conserved, $|q/p| = 1$, $|\bar{A}_{\bar{f}_{CP}}/A_{f_{CP}}| = 1$, and the relative phase between (q/p) and $(\bar{A}_{\bar{f}_{CP}}/A_{f_{CP}})$ vanishes. Therefore, $\lambda \neq \pm 1$ implies CPV. It is possible to define a time-dependent asymmetry, $a_{f_{CP}} = \frac{\Gamma(B^0_{\text{phys}}(t)\to f_{CP})-\Gamma(\bar{B}^0_{\text{phys}}(t)\to f_{CP})}{\Gamma(B^0_{\text{phys}}(t)\to f_{CP})+\Gamma(\bar{B}^0_{\text{phys}}(t)\to f_{CP})}$, where $B^0_{\text{phys}}(t)$ is the state vector of a B^0 meson at time $t = t_{f_{CP}} - t_{tag}$. The flavor of the B_{CP} meson at time $t = 0$ is determined from the other B of the event (B_{tag}). The BaBar detector is able to measure the time difference t of the two B decays reconstructing their decay vertex positions, separated by the boost of the center of mass system ($\beta\gamma = 0.56$). The silicon vertex tracker (SVT), reconstructs the decay vertices of the B mesons achieving a resolution on the spatial separation ($\sim 100\mu m$), which is fundamental for these measurements. The time-dependent asymmetry is given by $a_{f_{CP}} = \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta m_B t)-2\text{Im}(\lambda_{f_{CP}})\sin(\Delta m_B t)}{1+|\lambda_{f_{CP}}|^2}$ and is sensitive to the physics parameter λ.

3.1 The angle β

In the decay modes which proceed via $b \to c\bar{c}s$ transitions, we have $\text{Im}(\lambda) = \eta_{f_{CP}} \sin 2\beta$. BaBar has measured $\sin 2\beta = 0.710 \pm 0.034 \pm 0.019$ and $\lambda = 0.932 \pm 0.026 \pm 0.017$ [13] reconstructing CP eigeinstates containing a charmonium meson. Decay modes which proceed via $b \to d\bar{d}s$ or $b \to s\bar{s}s$ penguin diagrams, could have contributions from particles not predicted in the SM. The precise measurement of time dependent CP asymmetries for those decay modes compared with the results of the charmonium modes could reveal effects of New Physics. BaBar measured CP asymmetries in several penguin modes: $\sin 2\beta_{eff} = 0.55 \pm 0.11 \pm 0.02$ in $\eta' K^0$ [14], $\sin 2\beta_{eff} = 0.50 \pm 0.25^{+0.07}_{-0.04}$ in ϕK^0 [15], and $\sin 2\beta_{eff} = -0.66 \pm 0.26 \pm 0.08$ in $K^0_S K^0_S K^0_S$ [16]. Results are compatible with SM expectations within the errors.

3.2 The angle α

The angle α can be measured in $B^0 \to \rho^-\rho^+$ and $B^0 \to \pi^-\pi^+$ time-dependent CP-asymmetries. The decay amplitude has penguing contributions which make the extraction of the weak phase from the CP-asymmetry measurement difficult. An isospin analysys, which requires also the measurement of the branching ratios of isospin related modes, could in principle extract the value of α [17]. This is currently not possible with the available statistics, instead we can evaluate the penguin pollution measuring the ratio of the branching ratios $r = \frac{BR(B^0 \to h^0 h^0)}{BR(B^\pm \to h^\pm h^0)}$ $(h = \pi, \rho)$ and bound effect on the measured value of α [19]. In the case of $B \to \pi^+\pi^-$ BaBar constrain $\alpha \in [0, 27] \cup [63, 180]$ degrees [18] while the case of $B^0 \to \rho^+\rho^-$ BaBar measures $\alpha \in [74, 117]$ degrees [20, 21]. A time-dependent Dalitz plot analysis of the $B \to \pi^+\pi^-\pi^0$ decay, which takes advantage of the interference between the ρ resonances in the Dalitz plot, is also sensitive to the angle α and measures $\alpha \in [75, 152]$ degrees [22].

4 Perspectives and conclusions

CPV has been estabilished in the B meson system. Measurement of the angle β has reached a good precision, while the measurements of the angles α and γ require more statistics. Several approaches have been explored and with 1 ab^{-1} data BaBar can reach $\simeq 10 - 15$ degree precision on both α and γ. The present BaBar results are fully compatible with the SM predictions. New Physics searches require much larger statistics, $\mathcal{O}(50)$ ab^{-1}, achievable with a SuperB Factory [23].

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