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CP and T Violation at *BABAR* and BELLE

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The most recent results on *CP* and *T* violation from the *BABAR* and Belle Collaborations are reported in the following. Time reversal symmetry violation in weak decays is measured by the *BABAR* experiment for the first time in the *B* meson system with great precision, providing an independent verification of the *CP* symmetry violation as well. The Belle experiment provides a constraint on the *CPT* symmetry. Both Collaborations show their results in the measurement of the Unitary Triangle angles. The angle β (or ϕ_1) is measured using the $B \to D^* D^*$ decays. The measurement of the angle α (or ϕ_2) is obtained by *BABAR* from $B \to \rho\pi$ decays and by Belle from $B \to \rho\rho$ and $B \to \pi\pi$. The Collaborations also present the combined value of the angle γ (or ϕ_3) based on previous measurements and a new technique to extract ϕ_3 via Dalitz analysis. *BABAR* shows a measurement of *CP* violation in B^0 meson mixing. The results shown, unless stated otherwise, are obtained on the full datasets of the *B*-factories.

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1. Introduction to *CP* and *T* violation in the *B* meson system.

In the Standard Model with three generations of quarks and leptons [1], arranged in $SU(2)_L$ left-handed doublets, and assuming *CPT* invariance [6], the weak interaction can be described through the unitary 3×3 Cabibbo-Kobayashi-Maskawa (*CKM*) matrix [2, 3] connecting the weak eigenstates (d', s', b') and the corresponding mass eigenstates (d, s, b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \hat{V}_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1.1}$$

.

The *CKM* matrix contains one irreducible complex phase responsible for the *CP*-violating asymmetries in the Standard Model.

The unitary relations of the *CKM* matrix columns can be regarded as triangles in the complex plane, whose angles and sides are related to the K, B_s, and B_d meson decays, and give the magnitude of the *CP* violation.

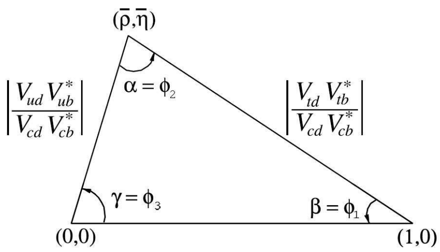

Figure 1: The normalized *CKM* triangle.

The *CP* violation effects in the phenomenology of the B mesons decays can be observed in three mechanisms:

- The *CP* violation in decay, or direct *CP* violation, occurs when $|\overline{A}/A| \neq 1$ where A and $\overline{A}$ are respectively the amplitudes of a B meson decay to a final state f, $B \to f$, and its *CP* conjugate process, $\overline{B} \to \overline{f}$;

- The mass eigenstates B_L and B_H are expressed in terms of the flavor eigenstates by

$$\begin{aligned} |B_L\rangle &= p|B^0\rangle + q|\overline{B}^0\rangle \\ |B_H\rangle &= p|B^0\rangle - q|\overline{B}^0\rangle \end{aligned} \tag{1.2}$$

  where the normalization condition is $|q|^2 + |p|^2 = 1$. A deviation from unity of the quantity $|q/p|$ would imply *CP* violation in mixing, or indirect *CP* violation. If case of *CP* violation in mixing the probability of the transition $B^0 \to \overline{B}^0$ is different from that of $\overline{B}^0 \to B^0$;

- *CP* violation can occur in the interference between mixing and decay, which is studied through the time evolution of the B mesons.

2. The B-factories.

The B-factories, *BABAR* [4] and Belle [5], operated at the asymmetric e^+e^- colliders PEP-II and KEK-B respectively, collecting data mostly at the $\Upsilon(4S)$ resonance. Overall, the B-factories have collected more than $1.1ab^{-1}$ corresponding to more than 1.2×10^9 $B\overline{B}$ events. The main goals of the physics program of the two experiments include, but is not limited to, B meson physics and *CP* violation, charm physics, τ physics, and searches for physics beyond the Standard Model.

3. T and CPT violation.

3.1 Measurement of T violation at *BABAR*.

The *CP* symmetry breaking is now well established in all the meson sectors and is in very good agreement with the Standard Model mechanism of the *CKM* matrix irreducible phase being the sole source of *CP* violation. The CPT invariance theorem therefore implies that also time reversal symmetry breaking must occur. If it were possible to identify a pair of T-conjugate processes that can be experimentally distinguished, then it would be possible to exploit the time asymmetry, $A_T = (P(i \to f) - P(f \to i))/(P(i \to f) + P(f \to i))$.

In the process $\Upsilon(4S) \to B\overline{B}$, the two B mesons are produced in an entangled antisymmetric state (a P-wave system), usually written in terms of flavor eigenstates, such as B^0 and $\overline{B}^0$, but can be expressed in terms of any linear combinations of B^0 and $\overline{B}^0$. One such linear combination are the B_+ and B_- states defined as the neutral B states selected to decay to the even *CP*-eigenstate $J/\psi K_L$ and odd *CP*-eigenstate $J/\psi K_S\,(K_S \to \pi\pi)$ respectively. The B_+ and B_- states are orthogonal if there is only one weak phase in the decay (as happens in $J/\psi K^0$ final states) and if *CP* violation in the K system is neglected. While the B_+ and B_- states are selected through $J/\psi K_L$ and $J/\psi K_S$ states, the flavor eigenstates, B^0 and $\overline{B}^0$, are identified through decays to semileptonic final states ℓ^+X and ℓ^-X ($\ell = e, \mu$) respectively.

The selected events have one B identified as a B_+ or B_- and the other B identified as a flavor eigenstate. When the first B meson decay occurs at time t_1, $B \to f_1$, the other B flavor or *CP* state is identified by the entanglement and will decay at time t_2 to a final state f_2. Time ordered final states, (f_1, f_2) will identify the T conjugate processes. For example, if we have identified $(\ell^+X, J/\psi K_S)$, it means the second decay involves $\overline{B}^0 \to B_-$. To find the T conjugate process, $B_- \to \overline{B}^0$, then we have to look for $(J/\psi K_L, \ell^-X)$. The difference in the rates is an indication of T symmetry breaking. There are four different (f_1, f_2) combinations that can be studied. Analogous four combinations can be defined for *CP* transformed states (like $\overline{B}^0 \to B_-$ and $B^0 \to B_-$) and CPT transformed states (like $\overline{B}^0 \to B_-$ and $B_- \to B^0$). These independent comparisons will give independent estimates of T, *CP* and CPT violation. The four independent T-violating raw asymmetries are shown in Figure 2.

The main T-violating parameters are measured at *BABAR* as $\Delta S_T^+ = -1.37 \pm 0.14$ (stat.) $\pm$ 0.06 (syst.) and $\Delta S_T^- = 1.17 \pm 0.18$ (stat.) $\pm\, 0.11$ (syst.), where $\Delta S_T^{\pm} = 0$ would indicate no T-violation. We observe a deviation from T invariance, independent of *CP* and CPT, equivalent to 14 standard deviations [7]. The confidence level contour plot with the central values are shown in Figure 3.

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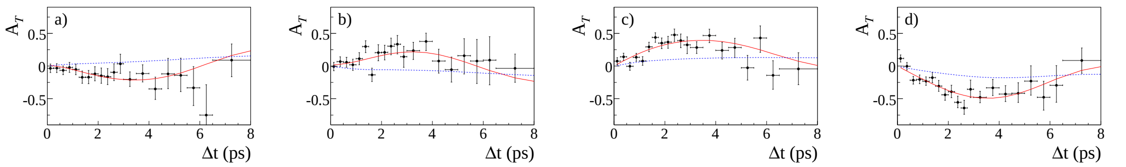

Figure 2: The four independent raw T-violating asymmetries for the reference transitions a) $\overline{B}^0 \to B_-$ $(\ell^+X, c\bar{c}K_S)$, b) $B_+ \to B^0$ $(c\bar{c}K_S, \ell^+X)$, c) $\overline{B}^0 \to B^+$ $(\ell^+X, J/\psi K_L)$, d) $B_- \to B^0$ $(J/\psi K_L, \ell^+X)$, in the signal regions. The points with error bars represent the data, the red solid and dashed blue curves represent the projections of the best fit results with and without T violation, respectively.

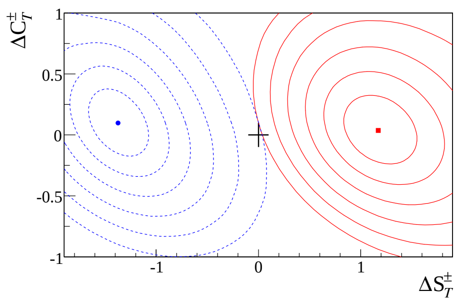

Figure 3: The central values (blue point and red square) and two-dimensional confidence level contours for the pairs of T-asymmetry parameters $(\Delta S_T^+, \Delta C_T^+)$ (blue dashed curves) and $(\Delta S_T^-, \Delta C_T^-)$ (red solid curves). Systematic uncertainties are included. The T-invariance point is shown as a $+$ sign.

3.2 Search for time-dependent *CPT* violation at Belle.

The *CPT* invariance theorem as implied by local Lorentz invariant quantum field theories is one of the most fundamental concepts in modern physics. In the presence of *CPT* violation in the mixing, Equations 1.2 would become $|B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\overline{B}^0\rangle$ and $|B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\overline{B}^0\rangle$ where z is a complex parameter such that if $z \neq 0$ then *CPT* is violated. The decay of $B^0\overline{B}^0 \to f_{rec} f_{tag}$ can be studied, where one of the B mesons decays at time t_{rec} to a reconstructed final state f_{rec} and the other B decays at time t_{tag} to a final state f_{tag} that distinguishes between B^0 and $\overline{B}^0$. In this decay, the general time-dependent decay rate with *CPT* violation allowed ($z \neq 0$) is studied through the normalized total decay width difference $\Delta\Gamma_d/\Gamma_d$ between B^0 and $\overline{B}^0$, for $B^0 \to J/\psi K^0$ $(K^0 = K_S, K_L)$, $B^0 \to D^{(*)-}h^+$ $(h^+ = \pi^+$ for D^- and π^+, ρ^+ for $D^{*-})$ and $B^0 \to D^{*-}\ell^+\nu_\ell$ $(\ell = e, \mu)$. The measured values with a dataset of 535×10^6 $B\overline{B}$ events (about 70% of the Belle final dataset) are [8]:

$$\begin{aligned} \Re(z) &= [+1.9 \pm 3.7(stat) \pm 3.3(syst)] \times 10^{-2}, \\ \Im(z) &= [-5.7 \pm 3.3(stat) \pm 3.3(syst)] \times 10^{-3}, \\ \Delta\Gamma_d/\Gamma_d &= [-1.7 \pm 1.8(stat) \pm 1.1(syst)] \times 10^{-2}, \end{aligned} \quad (3.1)$$

all consistent with zero, as expected for no *CPT* violation.

4. Unitary Triangle angles.

4.1 Measure of $\sin(2\beta)$ from $B \to D^* D^*$ decays.

The *CP* violating parameter $\sin(2\beta)$ (or $\sin(2\phi_1)$) defined as $\beta \equiv arg[-V_{cd}V_{cb}^*/-V_{td}V_{tb}^*]$, has been measured by both the *BABAR* and Belle Collaborations with high precision in the $b \to c\bar{c}s$ processes. Measurement from $B^0 \to D^{*+}D^{*-}$ decays should lead to the same value of $\sin(2\beta)$ provided that the contribution from penguin diagrams can be neglected.

The *BABAR* experiment has adopted a partial reconstruction method where one D^* is fully reconstructed in $D^* \to D^0\pi, D^0 \to K\pi, K\pi\pi^0, K\pi\pi\pi, K^0_S\pi\pi$ modes and the other D^* is only constrained using the accompanying slow π [9]. Only an angular analysis with fully reconstructed final states can separate the *CP* eigenstates. In a partial reconstruction analysis, the *CP* asymmetry parameters C and S are a weighted average of the *CP*-even and *CP*-odd wave function components. If the penguin amplitudes can be neglected then the *CP*-even and *CP*-odd symmetry parameters become $S_+ = -S_-$ and $C_+ = -C_-$ and the value of the *CP*-even components S_+ and C_+, can be obtained as $C = C_+$ and $S = S_+(1-2R_\perp)$ where the factor $(1-2R_\perp)$ represents the dilution introduced by the *CP*-odd component $R_\perp$ in the signal. We obtain $C_+ = +0.15 \pm 0.09(stat) \pm 0.04(syst)$ and $S_+ = -0.49 \pm 0.18(stat) \pm 0.07(syst) \pm 0.04(R_\perp)$, where the last uncertainty is the contribution from $R_\perp$ previously measured by *BABAR* [10]. This independent determination of the CP-violating parameters is in agreement with the previous measurements from *BABAR* and Belle with fully reconstructed events and with the Standard Model expectation of $S_+ = -\sin(2\beta)$ given negligible contributions to the decay amplitude from penguin diagrams.

The Belle experiment performed a full reconstruction of the $B^0 \to D^{*+}D^{*-}$ decay in $K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, and $K^+K^-\pi^+$ final states for charged D mesons from $D^{*+} \to D^+\pi^0$, and $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$, and K^+K^- final states for neutral D mesons from $D^{*+} \to D^0\pi^+$. Given that the final states are a mixture of *CP*-even and *CP*-odd states depending on the relative angular momentum of the two D^* mesons also a full angular analysis has been performed. The measurements reported in [11] are $R_\perp = 0.138 \pm 0.024(stat.) \pm 0.006(syst.)$, $S = -0.79 \pm 0.13(stat.) \pm 0.03(syst.)$, and the asymmetry $A = 0.15 \pm 0.08(stat.) \pm 0.04(syst.)$, in agreement with previous measurements and exhibiting *CP* violation at 5.4σ.

4.2 Measure of α,or ϕ_2, from $B \to \rho\pi, \pi\pi, \rho\rho$ decays.

BABAR reports a preliminary study of $B^0 \to (\pi^+\pi^-)_{\rho^0}\pi^0$ that would allow a measurement of $\sin(2\alpha)$ from the interference between mixing and decay. A complete time-dependent Dalitz plot analysis is sensitive to the interference between the strong and weak amplitudes and allows the unambiguous extraction of the strong and weak relative phases, and of the CP-violating parameter $\alpha \equiv arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$. The CP-violation parameters are measured: $A^{+-}_{\rho\pi} = +0.09^{+0.05}_{-0.06} \pm 0.04$ and $A^{-+}_{\rho\pi} = -0.12 \pm 0.08^{+0.04}_{-0.05}$. A scan of the values of α between 0° and 180° and a χ^2 test with and without isospin constraints is performed. The scan shows that it is not robust enough and cannot be interpreted in terms of Gaussian statistics.

Belle reports a preliminary measurement of the time-dependent CP violation parameters in $B^0 \to \pi^+\pi^-$ decays [12]. The penguin contribution to this decay can shift the value of ϕ_2 into $\phi_2^{eff} = \phi_2 + \Delta\phi_2$ where $\Delta\phi_2$ can be measured with an isospin analysis. The CP-violation parameters obtained are: $A_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06(stat) \pm 0.03(syst)$, and $S_{CP}(B^0 \to \pi^+\pi^-) =$

$-0.64 \pm 0.08(stat) \pm 0.03(syst)$. The region $23.8^\circ < \phi_2 < 66.8^\circ$ is ruled out and the constraint on the shift in ϕ_2 caused by the penguin contribution is $|\Delta\phi_2| < 44.8^\circ$ at the 1σ level including systematic uncertainties.

Belle also report a preliminary study of $B^0 \to \rho^0\rho^0$ and other four pion final states in [13]. The measured branching fraction is $B(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30(stat) \pm 0.22(syst)) \times 10^{-6}$ corresponding to an upper limit $B(B^0 \to \rho^0\rho^0) < 1.5 \times 10^{-6}$ at the 90% confidence level. The measured longitudinal polarization fraction is $f_L = 0.21^{+0.18}_{-0.22}(stat) \pm 0.11(syst)$. Using the longitudinal polarization in an isospin analysis, the mixing angle $\phi_2 = (91.0 \pm 7.2)^\circ$ is measured.

4.3 Observation of the mixing angle γ with $B \to D^{(*)}K^{(*)}$ decays.

The angle $\gamma \equiv arg[-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}]$ is the only mixing parameter that can be determined purely from tree-level B mesons decays, but it is affected by large statistical uncertainties.

There are basically three methods to measure γ from $B^\pm \to D^{(*)}K^{(*)\pm}$ decays: The Giri-Grossman-Soffer-Zupan (GGSZ) method [14] is based on a Dalitz plot analysis of the three body decays of the D meson in the $D^0 \to K_s\pi^+\pi^-$ and $D^0 \to K_S K^+K^-$ final states; The Gronau-London-Wyler (GLW) method [15] uses the CP-even and CP-odd final states like K^+K^- and $K_S\pi^0$; The Atwood-Dunietz-Soni (ADS) method [16] is based on doubly-Cabibbo suppressed decays like $D^0 \to K^+\pi^-$. The GGSZ method provides the highest statistical power for measuring γ but the other two provide tighter constraints on the hadronic parameters for a more robust determination.

BABAR uses a combination of all three methods (34 observables) in order to extract γ. External inputs for the D meson hadronic parameters are needed. *BABAR* determination is $\gamma = (69^{+17}_{-16})^\circ$ (modulo 180°) [17], where the dominant contribution to the error is statistical. The statistical significance is 5.9σ, indicating the observation of direct CP violation in the measurement of γ.

Belle presents a binned Dalitz plot analysis based on Ref. [14]. The complex phase entering the Dalitz plot analysis of the $D^0 \to K_s\pi^+\pi^-$ decay brings a large model uncertainty that can surpass the 10% level. The binned Dalitz plot eliminates the model uncertainty, replacing it with a statistical error related to the precision of the strong-phase parameters obtained from the decays of quantum-correlated D^0 pairs produced in the $\psi(3770) \to D^0\overline{D}^0$ process. The measured value is $\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$, where the first error is statistical, the second is systematic and the third is related to the systematic uncertainty on CP-violating parameters that include information about the functions C and S averaged over the bin region [18].

5. Search for CP violation in $B^0\overline{B}^0$ mixing at *BABAR*.

According to the Standard Model, the CP violation asymmetry in mixing A_{CP} is predicted the $O(10^{-4})$ level, beyond the experimental sensitivity of the B-factories ($O(10^{-3})$). Here new approach is shown at *BABAR*, in which a sample of $B^0 \to D^{*+}X\ell^+\nu$ decats (charge conjugate modes implied) with a partial reconstruction method is selected and kaon tagging is used to assess the flavor of the other B meson in the event [19].

The preliminary measured asymmetry at *BABAR* is $A_{CP} = [N(B^0B^0) - N(\overline{B}^0\overline{B}^0)]/[N(B^0B^0) + N(\overline{B}^0\overline{B}^0)] = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$ and the deviation from unity of the $|q/p|$ parameter is $\Delta_{CP} = 1 - |q/p| = 0.29 \pm 0.84^{+1.88}_{-1.61} \times 10^{-3}$. No deviation from the Standard Model expectation is observed.

6. Conclusions

The *BaBar* and Belle Collaborations continue to produce high quality results with their full datasets. The phenomenology of CP, T and CPT symmetries and their breaking continues to provide new ground for more precise measurements of the violating parameters, as well as advanced searches for new physics beyond the Standard Model. A great wealth of new results has been produced in the last year and the ones discussed here are only a fraction of these. Examples are the time reversal asymmetry from the *BaBar* Collaboration and the first observation of mixing induced CP violation in $B^0 \to D^{*+}D^{*-}$ at more than 5σ from the Belle Collaboration.

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