Recent Results on $T$ and $CP$ Violation at $\text{BaBar}$

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$CP$-violation ($CPV$) and Time-reversal violation ($TRV$) are intimately related through the $CPT$ theorem: if one of these discrete symmetries is violated the other one has to be violated in such a way to conserve $CPT$. Although $CPV$ in the $B^0 \bar{B}^0$ system has been established by the B-factories, implying indirectly TRV, there is still no direct evidence of $TRV$. We report on the observation of $TRV$ in the B-meson system performed with a dataset of $468 \times 10^6 B \bar{B}$ pairs produced in $\Upsilon(4S)$ decays collected by the $\text{BaBar}$ detector at the PEP-II asymmetric-energy $e^+e^-$ collider at the SLAC National Accelerator Laboratory. We also report on other $CPV$ measurements recently performed on the B-meson system.

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1. First direct observation of T-reversal violation in B-mesons

The Cabibbo-Kobayashi-Maskawa (CKM) matrix mechanism [1] for the quark mixing describes all transitions between quarks in terms of only four parameters: three rotation angles and one irreducible phase. This irreducible phase being the only source of CPV in the standard model (SM). CPV has been well established both in the K-meson [2] and B-meson [3] systems, being consistent with the CKM mechanism. Local Lorentz invariant quantum field theories imply CPT invariance [4], in agreement with all experimental evidence up to date [5]. It is therefore expected that the CP-violating weak interaction also violates T-reversal.

In stable systems, a signature of TRV would be a non-zero expectation value for a T-odd observable, e.g. neutron or electron electric dipole moments, but no such observation has been made up to date. The only evidence of TRV has been found in the neutral K-meson system, with the measurement of the difference between the probabilities of $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ transitions for a given elapsed time [6]. However, since this flavour mixing asymmetry violates both CP and T, it is impossible to disentangle TRV from CPV. In unstable systems, TRV can be explored by studying a process under the $t \rightarrow -t$ transition combined with the exchange of $|in\rangle$ and $|out\rangle$ states, which can be experimentally challenging to achieve. As an example, comparing the rates of $B^0 \rightarrow K^+\pi^-$ and $K^+\pi^- \rightarrow B^0$ is not feasible due to the need to prepare the initial state and to disentangle weak from strong effects. However, the coherent production of B-mesons pairs at the B-factories, offers a unique opportunity to compare couple of processes where the initial and final states are exchanged by Time-reversal.

The experimental method described in Ref. [7] proposes to use the entangled quantum state $|i\rangle$ of the two neutral B-mesons produced through the $\Upsilon(4S)$ decay. This two-body state usually written in terms of the flavour eigenstates, $B^0$ and $\bar{B}^0$, can be as well expressed in terms of mutually orthogonal $B_+$ and $B_-$ CP-eigenstates, which decay to CP = +1 and CP = −1, respectively: $|i\rangle = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] = \frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$. Experimentally, the $B_+$ and $B_-$ states are defined as the neutral B states filtered by the decay to CP eigenstates $J/\psi K_L^0$ (CP = +1) and $J/\psi K_S^0 \rightarrow \pi\pi$ (CP = −1). We define reference transitions and their T-transformed counterparts (see table [8]) and compare their transition rates as a test for T-reversal. The notation $(X,Y)$ denotes the final states of the time ordered B-meson decays from the entangled state, with $B \rightarrow X$ (B → Y) the earlier (later) decay. The time difference between the decays, $\Delta t = t_Y - t_X$, is then positive by definition. As an illustration, the pair of final states $(\ell^+, J/\psi K_L^0)$ denotes a $B^0 \rightarrow \ell^+X$ decay, meaning that at that time the other B in the event is a $\bar{B}^0$, followed in time by a $B \rightarrow J/\psi K_S^0$ decay, projecting to a $B_-$. The full process is the transition $\bar{B}^0 \rightarrow B_-$. A difference between this rate $\bar{B}^0 \rightarrow B_-$ and its T-transformed one is an indication of TRV. As shown in table [8], a total of four T-reversed transitions can be studied. The experimental analysis exploits identical reconstruction algorithms and selection criteria of the BaBar time-dependent CP asymmetry measurement in $B \rightarrow c\bar{c}K^{(*)0}$ decays [9]. The flavor tagging is combined for the first time with the CP tagging, as required for the construction of T-transformed processes.

The decay rate is proportional to $g_{ij}^\pm(\Delta t) \propto e^{-T_\Delta(t)} \{ 1 + S_{ij}^\pm \sin(\Delta m_d \Delta t) + C_{ij}^\pm \cos(\Delta m_d \Delta t) \}$, where $i$ denotes $B^0$ or $\bar{B}^0$, $j$ denotes $J/\psi K_L^0$ or $J/\psi K_S^0$, and ± indicates whether the flavour final state occurs before (+) or after (−) the CP decay. $T_\Delta$ is the average decay width, $\Delta m_d$ is the $B^0\bar{B}^0$ mass difference. There are eight distinct sets of $C_{i,j}^\pm$ and $S_{i,j}^\pm$ parameters. An unbinned maximum
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Parameter Measurement

| Reference transition $(X, Y)$ | T-transformed transition $(X, Y)$ |
|-------------------------------|---------------------------------|
| $B^0 \rightarrow B_+(\ell^+, J/\psi K^0_S)$ | $B_+ \rightarrow B^0(J/\psi K^0_S, \ell^+)$ |
| $B^0 \rightarrow B_-(\ell^-, J/\psi K^0_S)$ | $B_- \rightarrow B^0(J/\psi K^0_S, \ell^+)$ |
| $\bar{B}^0 \rightarrow B_+(\ell^+, J/\psi K^0_S)$ | $B_+ \rightarrow \bar{B}^0(J/\psi K^0_S, \ell^-)$ |
| $B^0 \rightarrow B_-(\ell^-, J/\psi K^0_S)$ | $B_- \rightarrow \bar{B}^0(J/\psi K^0_S, \ell^-)$ |

Table 1: Reference transitions and their $T$-transformed.

A likelihood fit is performed to the $B^0, \bar{B}^0, c\bar{c}K^0_S$ and $J/\psi K^0_L$ samples, to extract the $C_{i,j}^\pm$ and $S_{i,j}^\pm$ parameters. Out of this set of fitted parameters, a different set of $T, CP$ and CPT violation parameters can be built, $\Delta C_{i,j}^\pm, \Delta S_{i,j}^\pm$ (with $i = T, CP, CPT$) which are constructed as differences of the $C_{i,j}^\pm$ and $S_{i,j}^\pm$ for symmetry-transformed transitions (see table 2). Any deviation of the $(\Delta C_{i,j}^\pm, \Delta S_{i,j}^\pm)$ from (0,0) signals the violation of the corresponding symmetry.

![Confidence level contours](image)

Figure 1: Confidence level contours at intervals of 1σ for $T$- (left), $CP$- (middle) and CPT- (right) differences results. $\Delta S_{i,j}^\pm$ and $C_{i,j}^\pm$ ($\Delta S_{i,j}^\pm$ and $C_{i,j}^-$) are shown as a blue dashed (solid red) curves. The no-violation point of the corresponding symmetry is indicated with a cross (+).

| Parameter | Measurement | Parameter | Measurement |
|-----------|-------------|-----------|-------------|
| $\Delta S_T^+ = S_t^+ - S_{t^0}^+$ | $-1.37 \pm 0.14 \pm 0.06$ | $\Delta C_T^+ = C_t^+ - C_{t^0}^+$ | $0.10 \pm 0.14 \pm 0.08$ |
| $\Delta S_T^- = S_t^- - S_{t^0}^-$ | $1.17 \pm 0.18 \pm 0.11$ | $\Delta C_T^- = C_t^- - C_{t^0}^-$ | $0.04 \pm 0.14 \pm 0.08$ |
| $\Delta S_{CP}^+ = S_{CP}^+ - S_{CP}^0$ | $-1.30 \pm 0.11 \pm 0.07$ | $\Delta C_{CP}^+ = C_{CP}^+ - C_{CP}^0$ | $0.07 \pm 0.09 \pm 0.03$ |
| $\Delta S_{CP}^- = S_{CP}^- - S_{CP}^0$ | $1.33 \pm 0.12 \pm 0.06$ | $\Delta C_{CP}^- = C_{CP}^- - C_{CP}^0$ | $0.08 \pm 0.10 \pm 0.04$ |
| $\Delta S_{CPT}^+ = S_{CPT}^+ - S_{CPT}^0$ | $-1.30 \pm 0.11 \pm 0.07$ | $\Delta C_{CPT}^+ = C_{CPT}^+ - C_{CPT}^0$ | $0.07 \pm 0.09 \pm 0.03$ |
| $\Delta S_{CPT}^- = S_{CPT}^- - S_{CPT}^0$ | $1.33 \pm 0.12 \pm 0.06$ | $\Delta C_{CPT}^- = C_{CPT}^- - C_{CPT}^0$ | $0.08 \pm 0.10 \pm 0.04$ |

Table 2: Measured values of the $T, CP$ and CPT difference parameters. The first uncertainty is statistical and the second systematic. The indexes $t^\pm$ and $K^0_S/K^0_L$ are described in the text.

The results on the $T, CP$ and CPT asymmetries are shown in table 2. The significance of the corresponding differences is shown graphically in figure 1, with the two-dimensional contours in the $(\Delta S_{i,j}^\pm, \Delta C_{i,j}^\pm)$ planes ($i = T, CP, CPT$). time-reversal violation is clearly established, with the exclusion of the (0,0) point with a significance of 14σ. CP-violation is also observed at the level of 16σ. No evidence of CPT-violation is observed, the measurement being consistent with the conservation hypothesis within the 1σ level [8].
2. CP-violation in $B^0\bar{B}^0$ mixing

Two of the three types of CP-violation that can be observed in neutral B-mesons systems have been well established, i.e. CP-violation in direct $B^0$ decays and in the interference between mixing and decay \cite{3}. The third one, CP-violation in mixing has so far eluded observation. The weak-Hamiltonian eigenstates are related to the flavour eigenstates as $|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$. The asymmetry between the oscillation probabilities $P = P(B^0 \rightarrow \bar{B}^0)$ and $\bar{P} = P(\bar{B}^0 \rightarrow B^0)$ is defined as: $A_{\text{CP}} = \frac{\bar{P} - P}{\bar{P} + P} = \frac{1 - |q/p|^2}{1 + |q/p|^2} \approx 2(1 - |q/p|^2)$. Hence, there is CP-violation in mixing if the parameter $|q/p| \neq 1$. The SM prediction is $A_{\text{CP}} = -(4.0 \pm 0.6) \times 10^{-4}$ \cite{10}.

![Figure 2: $\Delta t$ distribution for the continuum subtracted data (points with error bars) and fitted contribution from $K_R$ (dark) and $K_T$ (light) for $\ell^+K^+$ (top-left), $\ell^-K^-$ (top-right), $\ell^-K^+$ (middle-left) and $\ell^+K^-$ (middle-right) events. The bottom plot is the $\Delta t$-dependent raw asymmetry between $\ell^+K^+$ and $\ell^-K^-$ events.](image)

The usual observable to measure the mixing $A_{\text{CP}}$ is the di-lepton asymmetry, $A_{\text{CP}} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)}$, where $\ell = e$ or $\mu$, and $\ell^+ (\ell^-)$ tags a $B^0 (\bar{B}^0)$. This measurement benefits from the high statistics but has the drawback on relying on control samples to subtract charge-asymmetric backgrounds. The systematic uncertainty related to this correction constitutes a severe limitation on the precision of the measurement. The present analysis measures $A_{\text{CP}}$ with a new technique in which one of the $B^0$-mesons in the event is reconstructed in $B^0 \rightarrow D^{*+}X \ell^+\nu$ (referred to as the $B_R$), with a partial reconstruction of the $D^{*-} \rightarrow \pi^- \bar{B}^0$ decay. The flavour of the other $B^0$ (referred to as the $B_T$) is tagged by looking at the charge of the charged kaons in the event ($K_T$). Because a $B^0 (\bar{B}^0)$ decays most often to a $K^+ (K^-)$, then when mixing takes place $\ell$ and $K_T$ have the same charge. A kaon with the same sign as $\ell$ may also come from the partially reconstructed $D^0$ in the event ($K_R$). To extract $A_{\text{CP}}$, three raw asymmetries are measured,

\begin{align}
A_\ell &= A_{rl} + A_{\text{CP}} \chi_d, \\
A_T &= \frac{N(\ell^+K_T^+) - N(\ell^-K_T^-)}{N(\ell^+K_T^+) + N(\ell^-K_T^-)} = A_{rl} + A_K + A_{\text{CP}}, \\
A_R &= \frac{N(\ell^+K_R^+) - N(\ell^-K_R^-)}{N(\ell^+K_R^+) + N(\ell^-K_R^-)} = A_{rl} + A_K + A_{\text{CP}},
\end{align}

where $\chi_d$ is a diagonal matrix to correct for biases in the tag generator. 

\cite{10}
where $A_\ell$ is the inclusive single lepton asymmetry, i.e. the asymmetry between events with $\ell^+$ compared to those with $\ell^-$, $\chi_d = 0.1862 \pm 0.0023 \ [11]$ and $A_{\ell\ell}$ ($A_K$) the detector induced charge asymmetry in the $B_R$ ($K^{\pm}$) reconstruction.

The $B_R$ is selected by combining a high momentum lepton and an opposite charge soft pion from the decay $D^{*-} \rightarrow \bar{D}^0 \pi_\ell^-$, both consistent with originating from a common vertex. The $B_R$ events are discriminated against backgrounds by using the unobserved neutrino mass squared $\Delta \nu = (E_{\text{beam}} - E_D - E_\ell)^2 - (p_{D^0} + p_\ell)^2$, where the $B^0$ momentum is neglected. $E_\ell$ and $p_\ell$ are the energy and momentum of the lepton, and $p_{D^0}$ is an estimation of the of the $D^*$ momentum by approximating its direction the same as the $\pi_\ell^-$ and parameterizing its momentum as a linear function of $p_{\pi^-}$ using MC. $\mathcal{M}_\nu^2$ peaks near zero for signal. The production point of the reconstructed $K$ ($K$-vertex) is estimated by the intersection of its track and the beam-region. $\Delta z$ is defined as the distance from the $\ell \pi_\ell$ vertex and $K$-vertex along the beam-axis. Finally, the proper time difference $\Delta t$ between $B_R$ and $B_T$ is defined as $\Delta t = \Delta z / \beta \gamma$ (with $\beta \gamma = 0.56$ the average Lorentz boost of the $e^+e^-$ collision). The estimated error on the estimated $\Delta t$, $\sigma(\Delta t)$, is as well used as a discriminant variable. Events in which $\ell$ and $K$ have the same sign are defined as mixed and unmixed otherwise. $K_R$ candidates tend to have a smaller $\Delta t$ than $K_T$ candidates, therefore $\Delta t$ is used as one of the main discriminant variables. Furthermore, $K_R$ are usually emitted mainly back-to-back with respect to $\ell$, while $K_T$ are produced at random, so we use in addition the angle $\theta_{\ell K}$ between $K$ and $\ell$.

The number of $B_R$ events is extracted by fitting the $\mathcal{M}_\nu^2$ distributions. The events are split in four lepton categories ($e^\pm, \mu^\pm$) and in eight tagged samples ($e^\pm K^\pm, \mu^\pm K^\pm$) for the extraction of $A_{\ell}$ and ($A_T, A_R$), respectively. A total of $(5.945 \pm 0.007) \times 10^6$ peaking events are found. We measure $A_{CP}$ with a binned four dimensional fit to $\Delta t$, $\sigma(\Delta t)$, cos($\theta_{\ell K}$) and $p_K$. Figure 2 show the fit projections for $\Delta t$. We find $A_{CP} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$, and $1 - |q/p|^2 = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3} \ [12]$. This is the single most precise measurement of this mixing asymmetry well in agreement with the SM expectations.

3. Time-dependent amplitude analysis of $B^0 \rightarrow (\rho \pi)^0$

The $B^0 \rightarrow \pi^+\pi^-\pi^0$ decay is well suited for $CP$-violation studies. The phase space of this final state is dominated by intermediate vector resonances ($\rho$). A complete time-dependent Dalitz plot (DP) analysis is sensitive to the interference between the resonant $\rho^+$, $\rho^-$ and $\rho^0$ intermediate states, allowing to extract the strong and weak relative phases, and of the $CP$-violation parameter $\alpha = \arg \left[ \frac{-(V_{td}V_{tb}^*)}{(V_{ud}V_{ub})^*} \right]$, with $V_{iq'}$ the elements of the CKM matrix \[14\].

The time-dependent amplitude for $B^0$ decays to the $\pi^+\pi^-\pi^0$ is given by $A_{3\pi} = f_+ A_+ + f_- A_- + f_0 A_0^0$, and similarly for $\bar{B}^0$ decays, with the $A_i$ replaced by $\bar{A}_i$ ($i = +, -, 0$). The DP-dependent $f_i$, and are defined in terms of modified Breit-Wigner resonances. The time-dependent probability for a meson which is a $B^0$ ($g_{3\pi}^+$) or $\bar{B}^0$ ($g_{3\pi}^-$) at the time the other one decays, to decay to $\pi^+\pi^-\pi^0$ is given by,

$$g_{3\pi}^{\pm}(\Delta t, DP) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}(|A_{3\pi}|^2 + |\bar{A}_{3\pi}|^2) \left( 1 + C_{3\pi} \cos(\Delta m_d \Delta t) \pm S_{3\pi} \sin(\Delta m_d \Delta t) \right) \tag{3.1}$$

where $C_{3\pi} = |A_{3\pi}|^2 - |\bar{A}_{3\pi}|^2$, $S_{3\pi} = 2 \text{Im} \left\{ \frac{q/p}{A_{3\pi} A_{3\pi}^*} \right\}$ and $\tau_{B^0}$ is the $B^0$ lifetime. The decay amplitudes $A_{3\pi}$ and $\bar{A}_{3\pi}$ \[15\] are written in terms of 27-real valued parameters $U$ and $I$ coefficients which have a
number of advantages: there is a unique solution of the \( U-I \) from the fit to data; their uncertainties are more Gaussian than those from fits where the decay amplitudes are directly parameterized in terms of the \( A_i \) moduli and phases; and it is simpler to combine measurements from different experiments. The physical quantities (branching fraction, \( CP \)-asymmetry) for each \( \rho \pi \) charge states are functions of the \( U \) and \( I \) parameters.

The present analysis \([15]\) is an update of the previous \( \text{BaBar} \) measurement \([13]\) with the full dataset. Background events are discriminated by using two kinematic variables: \( m_{ES}^2 = |(s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i|^2 - |\vec{p}_B|^2 \) and \( \Delta E = E_B^0 - \sqrt{s}/2 \), where \( \sqrt{s} \) is the \( e^+e^- \) beam energy in the CM frame, \((E_i, \vec{p}_i)\) and \( \vec{p}_B \) the four-momentum of the \( e^+e^- \) system and the momentum of the \( B \)-candidate in the laboratory frame, and \( E_B^0 \) the \( B \)-candidate energy in the CM frame. \( m_{ES} \) and \( \Delta E \) peak at the \( B \)-mass and at zero for signal events, respectively. Further background discrimination is achieved by using a neural-network (NN) which exploits the topological differences between signal and background. A maximum likelihood fit using the \( \Delta \) and DP variables, as well as \( m_{ES}, \Delta E \) and NN, is performed to extract the values of the \( U-I \) coefficients. Two direct \( CP \)-violation parameters,

\[
A_{\rho\pi}^+ = \frac{\Gamma(B^0 \rightarrow \rho^- \pi^+) - \Gamma(B^0 \rightarrow \rho^+ \pi^-)}{\Gamma(B^0 \rightarrow \rho^- \pi^+) + \Gamma(B^0 \rightarrow \rho^+ \pi^-)}, \quad A_{\rho\pi}^- = \frac{\Gamma(B^0 \rightarrow \rho^+ \pi^-) - \Gamma(B^0 \rightarrow \rho^- \pi^+)}{\Gamma(B^0 \rightarrow \rho^+ \pi^-) + \Gamma(B^0 \rightarrow \rho^- \pi^+)}
\]

are extracted with the values \( A_{\rho\pi}^+ = 0.09^{+0.05}_{-0.06} \pm 0.04 \) and \( A_{\rho\pi}^- = -0.12 \pm 0.08^{+0.04}_{-0.05} \). A two-dimensional likelihood scan is provided in the left hand plot of figure \([3]\). The origin, corresponding to no direct \( CP \)-violation, is excluded at the level of \( \sim 2\sigma \).

Scans of the likelihood function in fits where a given value of the \( CKM \) \( \alpha \) angle is assumed are performed enforcing the \( SU(2) \) symmetry in a loose (unconstrained) analysis using only the \( B^0 \rightarrow \rho \pi \) amplitudes) or tight (constrained) analysis adding the charged \( B^+ \rightarrow \rho \pi \) amplitudes) fashion. The \( \Sigma \) scan vs \( \alpha \) is shown in the right hand plot of figure \([3]\). The \( \Sigma \) value is commonly referred as "1 - C.L.", however robustness studies have shown that with the current data sample the \( \Sigma \) cannot interpreted in terms of the usual Gaussian statistics \([13]\). Hence with the current statistics, the analysis cannot reliably determine the angle \( \alpha \). This analysis would benefit greatly from increased sample sizes available at higher-luminosity experiments.

![Figure 3](image)

**Figure 3:** Left: two-dimensional likelihood scan of \( A_{\rho\pi}^+ \) vs \( A_{\rho\pi}^- \) with 1,2 and 3 \( \sigma \) C.L contours. The yellow dot inside the contours indicate the central value. Right: Isospin-constrained (solid red) and unconstrained (dashed black) scans of \( \Sigma \) (see text) as a function of \( \alpha \).
4. Conclusion

We presented the first direct observation of $T$-reversal violation in the $B$-meson system, which is established at the level of $14\sigma$. Deviations of $CPT$ conservation are also tested giving null results, in agreement with the expectations of the $CPT$-theorem. We also reported on a new experimental technique for the measurement of the mixing induced $CP$-violation parameter $1 - |q/p|^2$. The measurement is the most precise single measurement up to date and is well in agreement with the SM expectations. Finally, we reported on the update using the full $BaBar$ dataset of the time-dependent amplitude analysis of the $B^0 \rightarrow \pi^+ \pi^- \pi^0$ decays. Measurements of direct $CP$-violation asymmetries are measured, excluding the $CP$-violation conservation hypothesis at the level of $2\sigma$. Constrains on the $\alpha$ CKM angle are calculated. Robustness studies show that with the current dataset the method for extracting $\alpha$ is not robust, meaning that the current constrains cannot be interpreted in terms of the usual Gaussian statistics, but the analysis should benefit from increased data-samples from future experiments.

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