Abstract. Although CP violation in the B meson system has been well established by the B factories, there has been no direct observation of time-reversal violation. The decays of entangled neutral B mesons into definite flavour states (B^0 or \bar{B}^0) or J/ψK^0_L or c\bar{c}K^0_S final states (referred to as B^+ or B^−), allow comparisons between the probabilities of four pairs of T-conjugated transitions, for example, B^0 → B^− and B^− → B^0, as a function of the time difference between the two B decays. Using 468 million B\bar{B} pairs produced in Υ(4S) decays collected by the BABAR detector at SLAC, T-violating parameters in the time evolution of neutral B mesons have been measured, yielding ∆S_T^+ = −1.37 ± 0.14 (stat.) ± 0.06 (syst.) and ∆S_T^− = 1.17 ± 0.18 (stat.) ± 0.11 (syst.) [1]. These non-zero results represent the first direct observation of T violation through the exchange of initial and final states in transitions that can only be connected by a T-symmetry transformation.

1. Time-reversal violation searches
The observations of CP-symmetry breaking, first in neutral K decays [2] and more recently in B mesons [3, 4], are consistent with the standard model (SM) mechanism of the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix being the dominant source of CP violation [5]. Local Lorentz invariant quantum field theories imply CPT invariance [6], in accordance with all experimental evidence [7, 8]. In spite of experimental evidence of CPT invariance, the theoretical connection between CP and T does not imply an identity, except for processes which are identical under CPT transformation.

We aim experiments that could provide direct evidence of T non-invariance, without using an observation which also violates CP, i.e., without any theoretical neither experimental connection with CP. Experiments in stable systems involve either non-vanishing expectation values of T-odd observables, or the exchange of initial and final states, which are not CP conjugates to each other, in the time evolution for transition processes. Among the former, there exist upper limits for electric dipole moments of the neutron and the electron [10]. The latter, requiring neutrinos or unstable particles, are particularly difficult to implement. In the case of unstable systems, since the SM is CPT invariant, it predicts T-violating effects in parallel to each CP-violation effect. These may appear in three different ways: T violation in decay; T violation in the mixing of neutral states; and T violation that arises from the interference between decay with and without mixing.
$T$ violation matched to $CP$ violation in decay has not been observed, because the difficulties of the preparation of the time-reversed decay process. Let us see the example [11] of the rare weak decay of neutral-$B$ mesons to $K^+\pi^-$, for which direct $CP$ violation is well established [4] (different decay rates $R_1$ and $R_2$ for $B^0 \to K^+\pi^-$ and $\bar{B}^0 \to K^-\pi^+$, respectively). $T$ violation as implied by this result, combined with CPT invariance, tells us that the rates for the inverse processes $K^+\pi^- \to B^0$ and $K^-\pi^+ \to \bar{B}^0$ should be $R_2$ and $R_1$, respectively. However, there is little chance to measure these inverse rates and check directly this prediction since the weak interaction production mechanism is highly suppressed ($B^0 \to K^+\pi^-$ branching ratio of order $10^{-5}$) and the strong interaction would completely swamp the feeble weak process.

$T$ violation associated to $CP$ violation in the mixing has been experimentally analysed in $K$ [12] and $B$ mesons [13]. Here one looks whether the rate for a neutral-$K$ ($B$) meson tagged at its production as $K^0$ ($B^0$) and identified afterwards as $\bar{K}^0$ ($\bar{B}^0$) is equal to the rate for the neutral particle tagged at its production as $K^0$ ($\bar{B}^0$) and identified later as $K^0$ ($B^0$). Any difference in this case is both $CP$ and $T$ violating, because $CP$ and $T$ are experimentally identical for this process. The experimental results for kaons yielded a $T$-violating difference in these rates. Such a difference is proportional not only to the $T$-violating term of the $K^0\bar{K}^0$ matrix that defines the mass eigenstates in terms of the flavour eigenstates, but also to the width difference $\Delta \Gamma$ between the two mass eigenstates. Therefore, this asymmetry shows $T$ violation proportional to $\Delta \Gamma$, time independent, experimentally identical to $CP$ violation, thus it is not an independent $T$ non-invariance test as one might like [14].

Finally, we could also consider searches for $T$ violation arising from the interference between mixing and decay in neutral $B$ mesons. This is the place where the largest $CP$-violating asymmetry in Nature has been found between the rate for $B^0 \to J/\psi K^0$ and the $CP$-conjugate rate for $\bar{B}^0$ to decay to the same $CP$-eigenstate [3, 15]. Therefore, we expect the largest $T$ violation effect. However, these $CP$ violation results cannot be directly interpreted as $T$ violation since those results are obtained invoking $CPT$ invariance and $\Delta \Gamma = 0$, and not the reversal of time and the exchange of initial and final states, as required for a direct probe of $T$ non-invariance.

2. Method description and results

Up to now as we have delineated there is not a positive direct observation of $T$ unconnected to $CP$ violation. We report the direct observation of $T$ violation in the $B$ meson system, through the exchange of initial and final states in transitions that can only be connected by a $T$-symmetry transformation [1]. The method is described in Ref. [16], based on the concepts proposed in Ref. [17] and further discussed in Refs. [11, 18, 19].

The $B$ factories give us a unique opportunity to perform a test of $T$ as described above due to the EPR entanglement produced by the decay of the $Y(4S)$, yielding to an entangled, antisymmetric system of orthogonal states. This two-body state is usually written in terms of flavour eigenstates, such as $B^0$ and $\bar{B}^0$, $|i\rangle = 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$, but can be expressed in terms of any linear combinations of $B^0$ and $\bar{B}^0$, such as the $B_+$ and $B_-$ states introduced in Ref. [16], $|i\rangle = 1/\sqrt{2}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$. The $B_+$ and $B_-$ states are defined as the neutral $B$ states filtered by the decay to $CP$-eigenstates $J/\psi K^0$ ($CP$-even) and $J/\psi K^0$, with $K^0 \to \pi \pi$ ($CP$-odd), respectively. They are orthogonal to each other when there is only one weak phase involved in the $B$ decay amplitude, as it occurs in $B$ decays to $J/\psi K^0$ final states [20], and $CP$ violation in neutral kaons is neglected.

For this analysis we use events in which one $B$ candidate is reconstructed in a $B_+$ or $B_-$ state, and the flavour of the other $B$ is identified, referred to as flavour identification (ID). We generically denote reconstructed final states that identify the flavour of the $B$ as $\ell^- X$ for $\bar{B}^0$ and $\ell^+ \pi^0 X$ for $B^0$. The notation $(f_1, f_2)$ is used to indicate the flavour or $CP$ final states that are reconstructed at corresponding times $t_1$ and $t_2$, where $t_2 > t_1$, i.e., $B_1 \to f_1$ is the
If the first decay in the event and \( B_2 \rightarrow f_2 \) is the second decay. For later use in Eq. (1), we define \( \Delta \tau = t_2 - t_1 > 0 \). Once the \( B_1 \) state is filtered at time \( t_1 \), the living partner \( B_2 \) is prepared (“tagged”) by entanglement as its orthogonal state. The notation \( B_2(t_2) \rightarrow B_0(t_2) \) describes the transition of the \( B \) which decays at \( t_2 \), having tagged its state at \( t_1 \). For example, an event reconstructed in the time-ordered final states \((\ell^+X,J/\psi K^0)\) identifies the transition \( \overline{B}^0 \rightarrow B^- \) for the second \( B \) to decay. We compare the rate for this transition to its \( T \)-reversed \( B_- \rightarrow \overline{B}^0 \) (exchange of initial and final states) by reconstructing the final states \((J/\psi K^0,K^-X)\). Any difference in these two rates is evidence for \( T \)-symmetry violation. There are three other independent comparisons that can be made between \( B_+ \rightarrow B^0 (J/\psi K^0_1,\ell^+X), \overline{B}^0 \rightarrow B_+ (\ell^+X,J/\psi K^0_1), \) and \( B_+ \rightarrow B^0 (J/\psi K^0_1,\ell^+X) \) transitions and their \( T \)-conjugates, \( B^0 \rightarrow B_+ (\ell^-X,J/\psi K^0_1), B_+ \rightarrow \overline{B}^0 (J/\psi K^0_1,\ell^-X), \) and \( B_+ \rightarrow (\ell^-X,J/\psi K^0_1) \), respectively. Similarly, four different \( CP \) (\( CPT \)) comparisons can be made, e.g., between the \( \overline{B}^0 \rightarrow B^- \) transition and its \( CP \)-transformed \( B_+ \rightarrow (B_- \rightarrow \overline{B}^0) [16] \).

Assuming \( \Delta \Gamma_d = 0 \), each of the eight transitions has a general time-dependent decay rate given by

\[
g_{\alpha,\beta}^\pm(\Delta \tau) = e^{-\Gamma_d \Delta \tau} \left\{ 1 + S_{\alpha,\beta}^\pm \sin(\Delta m_d \Delta \tau) + C_{\alpha,\beta}^\pm \cos(\Delta m_d \Delta \tau) \right\},
\]

where indices \( \alpha = \ell^+, \ell^- \) and \( \beta = K^0_1, K^0_1 \) stand for \( \ell^+X, \ell^-X \) and \( \ell^+X, \ell^-X \) final states, respectively, and the symbol + or − indicates whether the decay to the flavour final state \( \alpha \) occurs before or after the decay to the \( CP \) final state \( \beta \). Here, \( \Gamma_d \) is the average decay width, \( \Delta m_d \) is the mass difference between the neutral \( B \) mass eigenstates, and \( S_{\alpha,\beta}^\pm \) and \( C_{\alpha,\beta}^\pm \) are model-independent coefficients. The sine term, expected to be large in the SM, results from the interference between direct decay of the neutral \( B \) to the \( J/\psi K^0 \) final state and decay after \( B^0, \overline{B}^0 \) oscillation, while the cosine term arises from the interference between decay amplitudes with different weak and strong phases, and is expected to be negligible [20]. \( T \) violation would manifest itself through differences between the \( S_{\alpha,\beta}^\pm \) or \( C_{\alpha,\beta}^\pm \) values for \( T \)-conjugated processes, for example between \( S_{\ell^+,K^0_1}^{\ell^-,K^0_1} \) and \( S_{\ell^-,K^0_1}^{\ell^+,K^0_1} \).

\( B_- \) states are reconstructed into the \( J/\psi K^0_1 \) or \( \psi(2S)K^0_1 \), \( \chi_{c1}K^0_1 \) final states (denoted generically as \( c\bar{c}K^0_1 \)), while \( B_+ \) are into \( J/\psi K^0_1 \). We also reconstruct a large sample of self-flavour tagging neutral \( B \) decays into open charm and charmonium final states, \( B^0 \rightarrow D^{(*)-}[\pi^+, (p(770)^+, a_1(1260)^+) \] \) and \( B^0 \rightarrow J/\psi K^{*0} \rightarrow (K^+ \pi^-) \), which are used for calibration of the time resolution function and the performance of the inclusive \( B \) flavour \( (B_0 \) or \( \overline{B}^0 \)) identification. Finally we reconstruct a large sample of charged \( B \) decays into charmonium, \( B^+ \rightarrow J/\psi K^+, \psi(2S)K^+, J/\psi K^{*+} \), which are used as control sample. We use the standard kinematic constraints available at \( B \) factories from the beam energies to reconstruct the mass and the energy difference of the \( B \) mesons, \( m_{ES} = \sqrt{(E_{beam}^*)^2 - p_T^2} \) and \( \Delta E = E_B^* - E_{beam}^* \), where \( E_B, p_T^2 \) are the energy and momentum of the \( B \) in c.m., respectively. We also exploit the different topology of signal and \( qq \) events to reject continuum background. The final sample contains 7796 \( B_- \) signal events with purities ranging from 87 to 96%, and 5813 \( B_+ \) signal events with purity about 56%.

We perform a simultaneous, unbinned maximum likelihood fit to the reconstructed, signed difference of proper times between the two \( B \) decays, \( \Delta t \equiv t_\beta - t_\alpha \), to flavor identified, \( c\bar{c}K^0_1 \) and \( J/\psi K^0_1 \) events. The signal probability density function (PDF) is [16]

\[
H_{\alpha,\beta}(\Delta t) \propto g_{\alpha,\beta}^+(\Delta t_{\text{true}}) H(\Delta t_{\text{true}}) \otimes R(\delta t; \sigma_{\Delta t}) + g_{\alpha,\beta}^-(\Delta t_{\text{true}}) H(-\Delta t_{\text{true}}) \otimes R(\delta t; \sigma_{\Delta t}),
\]

where \( \Delta t_{\text{true}} \) is the signed difference of proper times in the limit of perfect \( \Delta t \) resolution, \( H \) is the Heaviside step function, \( R(\delta t; \sigma_{\Delta t}) \) with \( \delta t = \Delta t - \Delta t_{\text{true}} \) is the resolution function, and
$g_{\alpha,\beta}$ are given by Eq. (1). Note that $\Delta t_{\text{true}}$ is equivalent to $\Delta \tau$ when the flavour of the $B$ is identified at $t_1$, determining the flavour of the still living partner (flavour tag), or equivalent to $-\Delta \tau$ when at $t_1$ we reconstruct a $CP$ final state, filtering the still living $B$ meson to the orthogonal state projected by the reconstructed decay ($CP$ tag) [17]. Because of the convolution with the resolution function, the distribution for $\Delta t > 0$ contains predominantly true flavour-tagged events, with a contribution from true $CP$-tagged events at low $\Delta t$, and conversely for $\Delta t < 0$. Backgrounds are accounted for by adding terms to Eq. (2) [21]. Events are assigned signal and background probabilities based on the $m_{ES}$ or $\Delta E$ distributions, for $\bar{c}K^0_L$ or $J/\psi K^0_L$ events, respectively.

We obtain in total 16 signal coefficients [16] which allow us to construct six pairs of independent asymmetry parameters ($\Delta S^T_+, \Delta C^T_+$), ($\Delta S^C_{CP}, \Delta C^C_{CP}$), and ($\Delta S^{CP}_{CPT}, \Delta C^{CP}_{CPT}$), as shown in Table 1. The $T$-asymmetry parameters have the advantage that $T$-symmetry breaking would directly manifest itself through any nonzero value of $\Delta S^T_+$ or $\Delta C^T_+$, or any difference between $\Delta S^C_{CP}$ and $\Delta S^{CP}_{CPT}$, or between $\Delta C^C_{CP}$ and $\Delta C^{CP}_{CPT}$ (analogously for $CP$- or $CPT$-symmetry breaking). The measured values for the asymmetry parameters [1] are reported in Table 1. There is another two times three pairs of $T$-, $CP$-, and $CPT$-asymmetry parameters, but they are not independent and can be derived from Table 1 or Ref. [16].

**Table 1.** Measured values of the $T$-, $CP$-, and $CPT$-asymmetry parameters, defined as the differences in $S^\pm_{\alpha,\beta}$ and $C^\pm_{\alpha,\beta}$ between symmetry-transformed transitions. The values of reference coefficients are also given at the bottom. The first uncertainty is statistical and the second systematic. The indices $\ell^-, \ell^+ K^0_L$, and $K^0_L$ stand for reconstructed final states that identify the $B$ meson as $\bar{B}^0$, $B^0$, $B_-$, and $B_+$, respectively.

| Parameter | Result         |
|-----------|----------------|
| $\Delta S^T_+$ = $S^+_{\ell^+,K^0_L} - S^+_{\ell^+,K^0_S}$ | $-1.37 \pm 0.14 \pm 0.06$ |
| $\Delta S^T_- = S^-_{\ell^+,K^0_L} - S^-_{\ell^+,K^0_S}$ | $1.17 \pm 0.18 \pm 0.11$ |
| $\Delta C^T_+ = C^+_{\ell^+,K^0_L} - C^+_{\ell^+,K^0_S}$ | $0.10 \pm 0.14 \pm 0.08$ |
| $\Delta C^T_- = C^-_{\ell^+,K^0_L} - C^-_{\ell^+,K^0_S}$ | $0.04 \pm 0.14 \pm 0.08$ |
| $\Delta S^C_{CP} = S^+_{\ell^+,K^0_L} - S^+_{\ell^+,K^0_S}$ | $-1.30 \pm 0.11 \pm 0.07$ |
| $\Delta S^C_{CPT} = S^+_{\ell^+,K^0_L} - S^+_{\ell^+,K^0_S}$ | $0.16 \pm 0.21 \pm 0.09$ |
| $\Delta C^C_{CP} = C^+_{\ell^+,K^0_L} - C^+_{\ell^+,K^0_S}$ | $-0.03 \pm 0.13 \pm 0.06$ |
| $\Delta C^C_{CPT} = C^+_{\ell^+,K^0_L} - C^+_{\ell^+,K^0_S}$ | $0.14 \pm 0.15 \pm 0.07$ |
| $\Delta S^C_{CPT}$ | $0.03 \pm 0.12 \pm 0.08$ |

\begin{align*}
S^+_{\ell^+,K^0_S} & = 0.55 \pm 0.09 \pm 0.06 \\
S^-_{\ell^+,K^0_S} & = -0.66 \pm 0.06 \pm 0.04 \\
C^+_{\ell^+,K^0_S} & = 0.01 \pm 0.07 \pm 0.05 \\
C^-_{\ell^+,K^0_S} & = -0.05 \pm 0.06 \pm 0.03
\end{align*}
We build time-dependent asymmetries \( A_T(\Delta t) \) to visually demonstrate the \( T \)-violating effect. For transition \( \bar{B}^0 \to B_\ell \),

\[
A_T(\Delta t) \equiv \frac{H^\ell_{-,-K_0^S}(\Delta t) - H^\ell_{+,-K_0^S}(\Delta t)}{H^\ell_{-,-K_0^S}(\Delta t) + H^\ell_{+,-K_0^S}(\Delta t)},
\]

where \( H^\ell_{\alpha,\beta}(\Delta t) = H_{\alpha,\beta}(\pm\Delta t) H(\Delta t) \). With this construction, \( A_T(\Delta t) \) is defined only for positive \( \Delta t \) values \[1\]. Neglecting reconstruction effects, \( A_T(\Delta t) \approx \Delta S^\pm + T^2 \sin(\Delta m_d\Delta t) + \Delta C^\pm + T^2 \cos(\Delta m_d\Delta t) \).

We introduce the other three \( T \)-violating asymmetries similarly. Figure 1 shows the four observed asymmetries, overlaid with the projection of the best fit results to the \( \Delta t \) distributions with and without the eight \( T \)-invariance restrictions: \( \Delta S^\pm_{CP} = \Delta S^\pm = 0 \), \( \Delta S^\pm_{CP T} \), and \( \Delta C^\pm_{CP} = \Delta C^\pm_{CP T} \) \[16\].

**Figure 1.** The four independent \( T \)-violating asymmetries for transition a) \( \bar{B}^0 \to B_\ell^- (\ell^+ X, c\bar{c}K^0_S) \), b) \( B_+ \to B^0 (c\bar{c}K^0_S, \ell^+ X) \), c) \( \bar{B}^0 \to B_+ (\ell^+ X, J/\psi K^0_L) \), d) \( B^- \to B^0 (J/\psi K^0_L, \ell^+ X) \), for combined flavour categories with low misID (leptons and kaons), in the signal region \( 5.27 < m_{ES} < 5.29 \) GeV/\( c^2 \) for \( c\bar{c}K^0_S \) modes and \( |\Delta E| < 10 \) MeV for \( J/\psi K^0_L \). 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.

Using large samples of MC simulated data, we determine that the asymmetry parameters are unbiased and have Gaussian errors. Fitting a single pair of \((S,C)\) coefficients, reversing the sign of \( S \) under \( \Delta t \leftrightarrow -\Delta t \), or \( B_+ \leftrightarrow B_- \) or \( B^0 \leftrightarrow \bar{B}^0 \) exchanges, and the sign of \( C \) under \( B^0 \leftrightarrow \bar{B}^0 \) exchange, we obtain identical results to those obtained in Ref. \[21\]. Performing the analysis with \( B \) decays to \( c\bar{c}K^\pm \) and \( J/\psi K^\ast \pm \) final states instead of the signal \( c\bar{c}K^0_S \) and \( J/\psi K^0_L \), respectively, we find that all the asymmetry parameters are consistent with zero.

In evaluating systematic uncertainties in the asymmetry parameters, we follow the same procedure as in Ref. \[21\], with small changes \[16\]. The total systematic uncertainties are shown in the extra material of Ref. \[1\].
The significance of the $T$-violation signal is evaluated based on the change in negative log-likelihood with respect to the maximum ($-2\Delta \ln \mathcal{L}$). We reduce $-2\Delta \ln \mathcal{L}$ by a factor $1 + \max\{m_i^2\} = 1.61$ to account for systematic errors in the evaluation of the significance. Here, $m_i^2 = -2(\ln \mathcal{L}_i - \ln \mathcal{L})/s^2$, where $\ln \mathcal{L}$ is the maximum log-likelihood, $\ln \mathcal{L}_i$ is the log-likelihood with asymmetry parameter $i$ fixed to its total systematic variation and maximized over all other parameters, and $s^2 \approx 1$ is the change in $2\ln \mathcal{L}$ at 68% confidence level (CL) for one degree of freedom (d.o.f.). Figure 2 shows CL contours calculated from the change $-2\Delta \ln \mathcal{L}$ in two dimensions for the $T$-asymmetry parameters ($\Delta S^+_T, \Delta C^+_T$) and ($\Delta S^-_T, \Delta C^-_T$). The difference in the value of $2\ln \mathcal{L}$ at the best fit solution with and without $T$ violation is 226 with eight d.o.f., including systematic uncertainties. Assuming Gaussian errors, this corresponds to a significance equivalent to 14.0 standard deviations ($\sigma$), and thus constitutes direct observation of $T$ violation. The significance of $CP$ and $CPT$ violation is determined analogously, obtaining 307 and 5, respectively, equivalent to 17$\sigma$ and 0.3$\sigma$, consistent with $CP$ violation and $CPT$ invariance.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The central values (blue point and red square) and two-dimensional CL contours for $1 - \text{CL} = 0.317$, 4.55 $\times$ 10$^{-2}$, 2.70 $\times$ 10$^{-3}$, 6.33 $\times$ 10$^{-5}$, 5.73 $\times$ 10$^{-7}$, and 1.97 $\times$ 10$^{-9}$, calculated from the change in the value of $-2\Delta \ln \mathcal{L}$ compared with its value at maximum ($-2\Delta \ln \mathcal{L} = 2.3, 6.2, 11.8, 19.3, 28.7, 40.1$), 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.}
\end{figure}

3. Conclusions
We have measured $T$-violating parameters in the time evolution of neutral $B$ mesons, by comparing the probabilities of $\bar{B}^0 \to B^-$, $B_+ \to B^0$, $\bar{B}^0 \to B^+$, and $B_- \to B^0$ transitions, to their $T$ conjugate. We determine for the main $T$-violating parameters $\Delta S^+_T = -1.37 \pm 0.14$ (stat.) $\pm 0.06$ (syst.) and $\Delta S^-_T = 1.17 \pm 0.18$ (stat.) $\pm 0.11$ (syst.), and observe directly for the first time a departure from $T$ invariance in the $B$ meson system, with a significance equivalent to 14$\sigma$. Our results are consistent with current $CP$-violating measurements obtained invoking $CPT$ invariance. They constitute the first direct observation of $T$ violation in any system through the exchange of initial and final states in transitions that can only be connected by a $T$-symmetry transformation.
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