Observation of Time-Reversal Violation in the B^{0} Meson System

J. P. Lees *et al.* (The BABAR Collaboration)

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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 flavor states (B^0 or $\overline{B}^0$), and $J/\psi K_L^0$ or $c\overline{c}K_S^0$ final states (referred to as B_+ or B_-), allow comparisons between the probabilities of four pairs of T-conjugated transitions, for example, $\overline{B}^0 \to B_-$ and $B_- \to \overline{B}^0$, as a function of the time difference between the two B decays. Using 468 million $B\overline{B}$ pairs produced in $\Upsilon(4S)$ decays collected by the *BABAR* detector at SLAC, we measure T-violating parameters in the time evolution of neutral B mesons, yielding $\Delta S_T^+ = -1.37 \pm 0.14$ (stat.)$\pm$ 0.06 (syst.) and $\Delta S_T^- = 1.17 \pm 0.18$ (stat.) ± 0.11 (syst.). These nonzero 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.

The observations of CP-symmetry breaking, first in neutral K decays [1] and more recently in B mesons [2, 3], 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 [4]. Local Lorentz invariant quantum field theories imply CPT invariance [5], in accordance with all experimental evidence [6, 7]. Hence, it is expected that the CP-violating weak interaction also violates time reversal invariance.

To date, the only evidence related to T violation has been found in the neutral K system, where a difference between the probabilities of $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$ transitions for a given elapsed time has been measured [8]. This flavor mixing asymmetry is both CP- and T-violating (the two transformations lead to the same observation), independent of time, and requires a nonzero decay width difference $\Delta\Gamma_K$ between the neu-

tral K mass eigenstates to be observed [9–11]. The dependence with $\Delta\Gamma_K$ has aroused controversy in the interpretation of this observable [7, 10–12]. In the neutral B and B_s systems, where $\Delta\Gamma_d$ and $\Delta\Gamma_s$ are negligible and significantly smaller, respectively, the flavor mixing asymmetry is much more difficult to detect [13]. Experiments that could provide direct evidence supporting T non-invariance, without using an observation which also violates CP, involve either nonvanishing 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 [14]. The latter, requiring neutrinos or unstable particles, are particularly difficult to implement.

In this letter, 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 con-

nected by a T-symmetry transformation. The method is described in Ref. [15], based on the concepts proposed in Ref. [16] and further discussed in Refs. [11, 17, 18]. We use a data sample of 426 fb^{-1} of integrated luminosity at the $\Upsilon(4S)$ resonance, corresponding to 468×10^6 $B\overline{B}$ pairs, and 45 fb^{-1} at a center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$, recorded by the BABAR detector [19] at the PEP-II asymmetric-energy e^+e^- collider at SLAC. The experimental analysis exploits identical reconstruction algorithms, selection criteria, calibration techniques, and B meson samples to our most recent time-dependent CP asymmetry measurement in $B \to c\overline{c}K^{(*)0}$ decays [20], with the exception of $\eta_c K_S^0$ and $J/\psi K^{*0}(\to K_S^0 \pi^0)$ final states. The "flavor tagging" is combined here, for the first time, with the "CP tagging" [16], as required for the construction of T-transformed processes. Whereas the descriptions of the sample composition and time-dependent backgrounds are the same as described in Ref. [20], the signal giving access to the T-violating parameters needs a different data treatment. This echoes the fundamental differences between observables for T and CP symmetry breaking. The procedure to determine the T-violating parameters and their significance is thus novel [15].

In the decay of the $\Upsilon(4S)$, the two B mesons are in an entangled, antisymmetric state, as required by angular momentum conservation for a P-wave particle system. This two-body state is 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 $\overline{B}^0$, such as the B_+ and B_- states introduced in Ref. [15]. They are defined as the neutral B states filtered by the decay to CP-eigenstates $J/\psi K_L^0$ (CP-even) and $J/\psi K_S^0$, with $K_S^0 \to \pi\pi$ (CP-odd), respectively. The B_+ and B_- states 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 [21], and CP violation in neutral kaons is neglected.

We select events in which one B candidate is reconstructed in a B_+ or B_- state, and the flavor of the other B is identified, referred to as flavor identification (ID). We generically denote reconstructed final states that identify the flavor of the B as $\ell^- X$ for $\overline{B}^0$ and $\ell^+ X$ for B^0. The notation (f_1, f_2) is used to indicate the flavor 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 first decay in the event and $B_2 \to f_2$ 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 $B_2(t_1) \to B_2(t_2)$ 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 $(\ell^+ X, J/\psi K_S^0)$ identifies the transition $\overline{B}^0 \to B_-$ for the second B to decay. We compare the rate for this transition to its T-reversed

$B_- \to \overline{B}^0$ (exchange of initial and final states) by reconstructing the final states $(J/\psi K_L^0, \ell^- X)$. Any difference in these two rates is evidence for T-symmetry violation. There are three other independent comparisons that can be made between $B_+ \to B^0$ ($J/\psi K_S^0, \ell^+ X$), $\overline{B}^0 \to B_+$ ($\ell^+ X, J/\psi K_L^0$), and $B_- \to B^0$ ($J/\psi K_L^0, \ell^+ X$) transitions and their T-conjugates, $B^0 \to B_+$ ($\ell^- X, J/\psi K_L^0$), $B_+ \to \overline{B}^0$ ($J/\psi K_S^0, \ell^- X$), and $B^0 \to B_-$ ($\ell^- X, J/\psi K_S^0$), respectively. Similarly, four different CP (CPT) comparisons can be made, e.g., between the $\overline{B}^0 \to B_-$ transition and its CP (CPT)-transformed $B^0 \to B_-$ ($B_- \to B^0$) [15].

Assuming $\Delta\Gamma_d = 0$, each of the eight transitions has a general, time-dependent decay rate $g_{\alpha,\beta}^\pm(\Delta\tau)$ given by

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

where indices $\alpha = \ell^+, \ell^-$ and $\beta = K_S^0, K_L^0$ stand for $\ell^+ X, \ell^- X$ and $c\overline{c}K_S^0, J/\psi K_L^0$ final states, respectively, and the symbol $+$ or $-$ indicates whether the decay to the flavor final state α occurs before or after the decay to the CP final state β. Here, Γ_d is the average decay width, Δm_d is the mass difference between the neutral B mass eigenstates, and $C_{\alpha,\beta}^\pm$ and $S_{\alpha,\beta}^\pm$ 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 [21]. 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 $S_{\ell^+,K_S^0}^+$ and $S_{\ell^-,K_L^0}^-$.

In addition to $J/\psi K_S^0$, B_- states are reconstructed through the $\psi(2S)K_S^0$ and $\chi_{c1}K_S^0$ final states (denoted generically as $c\overline{c}K_S^0$), with $J/\psi, \psi(2S) \to e^+e^-, \mu^+\mu^-$, $\psi(2S) \to J/\psi \pi^+\pi^-$, $\chi_{c1} \to J/\psi\gamma$, and $K_S^0 \to \pi^+\pi^-, \pi^0\pi^0$ (the latter only for $J/\psi K_S^0$). B_+ states are identified through $J/\psi K_L^0$. The $J/\psi K_L^0$ candidates are characterized by the difference ΔE between the reconstructed energy of the B and the beam energy in the e^+e^- c.m. frame, E_{beam}^*, while for the $c\overline{c}K_S^0$ modes we use the beam-energy substituted invariant mass $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$, where p_B^* is the B momentum in the c.m. frame.

The flavor ID of the other neutral B meson in the event, not associated with the reconstructed B_+ or B_-, is made on the basis of the charges of prompt leptons, kaons, pions from D^* mesons, and high-momentum charged particles. These flavor ID inputs are combined using a neural network (NN), trained with Monte Carlo (MC) simulated data. The output of the NN is then divided into six hierarchical, mutually exclusive flavor categories of increasing misidentification (misID) probability w. Events for which the NN output indicates very low discriminating power are excluded from further analysis. We determine the signed difference of proper time

$\Delta t = t_\beta - t_\alpha$ between the two B decays from the measured separation of the decay vertices along the collision axis. Events are accepted if the reconstructed $|\Delta t|$ and its estimated uncertainty, $\sigma_{\Delta t}$, are lower than 20 ps and 2.5 ps, respectively. The performances of the flavor ID and Δt reconstruction algorithms are evaluated by using a large sample of flavor-specific neutral B decays to $D^{(*)-}[\pi^+, \rho(770)^+, a_1(1260)^+]$ and $J/\psi K^{*0}(\to K^+\pi^-)$ final states (referred to as B_{flav} sample). The Δt resolution function is the same as in Ref. [20] except that all Gaussian offsets and widths are modeled to be proportional to $\sigma_{\Delta t}$.

The composition of the final sample is determined through fits to the m_{ES} and ΔE distributions, using parametric forms and distributions extracted from MC simulation and dilepton mass sidebands in data to describe the signal and background components. Figure 1 shows the m_{ES} and ΔE data distributions for events that satisfy the flavor ID and vertexing requirements, overlaid with the fit projections. The final sample contains 7796 $c\bar{c}K_S^0$ events, with purities in the signal region $(5.27 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2)$ ranging between 87% and 96%, and 5813 $J/\psi K_L^0$ events, with a purity of 56% in the $|\Delta E| < 10$ MeV region.
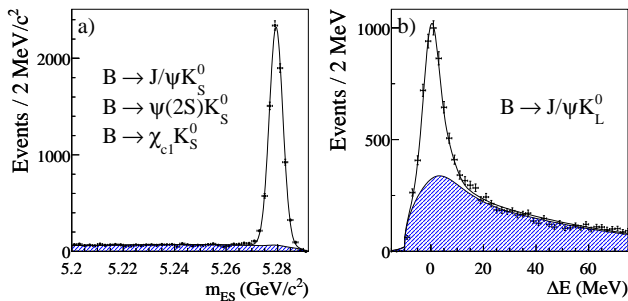

FIG. 1: (color online). Distributions of (a) m_{ES} and (b) ΔE for the neutral B decays reconstructed in the $c\bar{c}K_S^0$ and $J/\psi K_L^0$ final states, respectively, after flavor ID and vertexing requirements. In each plot, the shaded region is the estimated background contribution. The two samples of events are identical to those used in our most recent CP-violation study [20], but excluding $\eta_c K_S^0$ and $J/\psi K^{*0}(\to K_S^0\pi^0)$ final states.

We perform a simultaneous, unbinned maximum likelihood fit to the Δt distributions for flavor identified $c\bar{c}K_S^0$ and $J/\psi K_L^0$ events, split by flavor category. The signal probability density function (PDF) is [15]

$$\mathcal{H}_{\alpha,\beta}(\Delta t) \propto g^+_{\alpha,\beta}(\Delta t_{\text{true}})H(\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}) + \quad (2)$$
$$g^-_{\alpha,\beta}(-\Delta t_{\text{true}})H(-\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}),$$

where Δt_{true} is the signed difference of proper time between the two B decays in the limit of perfect Δt reconstruction, H is the Heaviside step function, $\mathcal{R}(\delta t; \sigma_{\Delta t})$ with $\delta t = \Delta t - \Delta t_{\text{true}}$ is the resolution function, and $g^\pm_{\alpha,\beta}$ are given by Eq. (1). Note that Δt_{true} is equivalent to

$\Delta\tau$ $(-\Delta\tau)$ when a true flavor (CP) tag occurs. Because of the convolution with the resolution function, the distribution for $\Delta t > 0$ contains predominantly true flavor-tagged events, with a small contribution from true CP-tagged events at low Δt, and conversely for $\Delta t < 0$. Mistakes in the flavor ID algorithm mix correct and incorrect flavor assignments, and dilute the T-violating asymmetries by a factor of approximately $(1-2w)$. Backgrounds are accounted for by adding terms to Eq. (2) [20]. Events are assigned signal and background probabilities based on the m_{ES} or ΔE distributions, for $c\bar{c}K_S^0$ or $J/\psi K_L^0$ events, respectively.

A total of 27 parameters are varied in the likelihood fit: eight pairs of $(S^\pm_{\alpha,\beta}, C^\pm_{\alpha,\beta})$ coefficients for the signal, and 11 parameters describing possible CP and T violation in the background. All remaining signal and background parameters are fixed to values taken from the B_{flav} sample, J/ψ-candidate sidebands in $J/\psi K_L^0$, world averages for Γ_d and Δm_d [22], or MC simulation [20]. From the 16 signal coefficients [23], we construct six pairs of independent asymmetry parameters $(\Delta S^\pm_T, \Delta C^\pm_T)$, $(\Delta S^\pm_{CP}, \Delta C^\pm_{CP})$, and $(\Delta S^\pm_{CPT}, \Delta C^\pm_{CPT})$, as shown in Table I. The T-asymmetry parameters have the advantage that T-symmetry breaking would directly manifest itself through any nonzero value of $\Delta S^\pm_T$ or $\Delta C^\pm_T$, or any difference between $\Delta S^\pm_{CP}$ and $\Delta S^\pm_{CPT}$, or between $\Delta C^\pm_{CP}$ and $\Delta C^\pm_{CPT}$ (analogously for CP- or CPT-symmetry breaking). The measured values for the asymmetry parameters are reported in Table I. 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 I or Ref. [23].

We build time-dependent asymmetries $A_T(\Delta t)$ to visually demonstrate the T-violating effect. For transition $\overline{B}^0 \to B_-$,

$$A_T(\Delta t) \equiv \frac{\mathcal{H}^-_{\ell^-, K_L^0}(\Delta t) - \mathcal{H}^+_{\ell^+, K_S^0}(\Delta t)}{\mathcal{H}^-_{\ell^-, K_L^0}(\Delta t) + \mathcal{H}^+_{\ell^+, K_S^0}(\Delta t)}, \quad (3)$$

where $\mathcal{H}^\pm_{\alpha,\beta}(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t)H(\Delta t)$. With this construction, $A_T(\Delta t)$ is defined only for positive Δt values. Neglecting reconstruction effects, $A_T(\Delta t) \approx \frac{\Delta S^+_T}{2}\sin(\Delta m_d\Delta t) + \frac{\Delta C^+_T}{2}\cos(\Delta m_d\Delta t)$. We introduce the other three T-violating asymmetries similarly. Figure 2 shows the four observed asymmetries, overlaid with the projection of the best fit results to the Δt distributions with and without the eight T-invariance restrictions: $\Delta S^\pm_T = \Delta C^\pm_T = 0$, $\Delta S^\pm_{CP} = \Delta S^\pm_{CPT}$, and $\Delta C^\pm_{CP} = \Delta C^\pm_{CPT}$ [23].

Using large samples of MC simulated data, we determine that the asymmetry parameters are unbiased and have Gaussian errors. Splitting the data by flavor category or data-taking period give consistent results. Fitting a single pair of (S, C) coefficients, reversing the sign of S under $\Delta t \leftrightarrow -\Delta t$, or $B_+ \leftrightarrow B_-$ or $B^0 \leftrightarrow \overline{B}^0$ exchanges, and the sign of C under $B^0 \leftrightarrow \overline{B}^0$ exchange, we obtain

TABLE I: Measured values of the T-, CP-, and CPT-asymmetry parameters, defined as the differences in $S_{\alpha,\beta}^{\pm}$ and $C_{\alpha,\beta}^{\pm}$ 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 ℓ^-, ℓ^+, K_S^0, and K_L^0 stand for reconstructed final states that identify the B meson as $\overline{B}^0$, B^0, B_-, and B_+, respectively.

Parameter	Result
$\Delta S_T^+ = S_{\ell^-,K_L^0}^- - S_{\ell^+,K_S^0}^+$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S_{\ell^-,K_L^0}^+ - S_{\ell^+,K_S^0}^-$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C_{\ell^-,K_L^0}^- - C_{\ell^+,K_S^0}^+$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C_{\ell^-,K_L^0}^+ - C_{\ell^+,K_S^0}^-$	$0.04 \pm 0.14 \pm 0.08$
$\Delta S_{CP}^+ = S_{\ell^-,K_S^0}^+ - S_{\ell^+,K_S^0}^+$	$-1.30 \pm 0.11 \pm 0.07$
$\Delta S_{CP}^- = S_{\ell^-,K_S^0}^- - S_{\ell^+,K_S^0}^-$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C_{CP}^+ = C_{\ell^-,K_S^0}^+ - C_{\ell^+,K_S^0}^+$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C_{CP}^- = C_{\ell^-,K_S^0}^- - C_{\ell^+,K_S^0}^-$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S_{CPT}^+ = S_{\ell^+,K_L^0}^- - S_{\ell^+,K_S^0}^+$	$0.16 \pm 0.21 \pm 0.09$
$\Delta S_{CPT}^- = S_{\ell^+,K_L^0}^+ - S_{\ell^+,K_S^0}^-$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C_{CPT}^+ = C_{\ell^+,K_L^0}^- - C_{\ell^+,K_S^0}^+$	$0.14 \pm 0.15 \pm 0.07$
$\Delta C_{CPT}^- = C_{\ell^+,K_L^0}^+ - C_{\ell^+,K_S^0}^-$	$0.03 \pm 0.12 \pm 0.08$
$S_{\ell^+,K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$
$S_{\ell^+,K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$
$C_{\ell^+,K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$
$C_{\ell^+,K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$

FIG. 2: (color online). The four independent T-violating asymmetries for transition a) $\overline{B}^0 \to B_-$ ($\ell^+ X, c\bar{c}K_S^0$), b) $B_+ \to B^0$ ($c\bar{c}K_S^0, \ell^+ X$), c) $\overline{B}^0 \to B_+$ ($\ell^+ X, J/\psi K_L^0$), d) $B_- \to B^0$ ($J/\psi K_L^0, \ell^+ X$), for combined flavor categories with low misID (leptons and kaons), in the signal region ($5.27 < m_{ES} < 5.29$ GeV/c^2 for $c\bar{c}K_S^0$ modes and $|\Delta E| < 10$ MeV for $J/\psi K_L^0$). 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.

identical results to those obtained in Ref. [20]. Performing the analysis with B decays to $c\bar{c}K^\pm$ and $J/\psi K^{*\pm}$ final states instead of the signal $c\bar{c}K_S^0$ and $J/\psi K_L^0$, 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. [20], with small changes [23]. We considered the statistical uncertainties on the flavor misID probabilities, Δt resolution function, and m_{ES} parameters. Differences in the misID probabilities and Δt resolution function between B_{flav} and CP final states, uncertainties due to assumptions in the resolution for signal and background components, compositions of the signal and backgrounds, the m_{ES} and ΔE PDFs, and the branching fractions for the backgrounds and their CP properties, have also been accounted for. We also assign a systematic uncertainty corresponding to any deviation of the fit for MC simulated asymmetry parameters from their generated MC values, taking the largest between the deviation and its statistical uncertainty. Other sources of uncertainty such
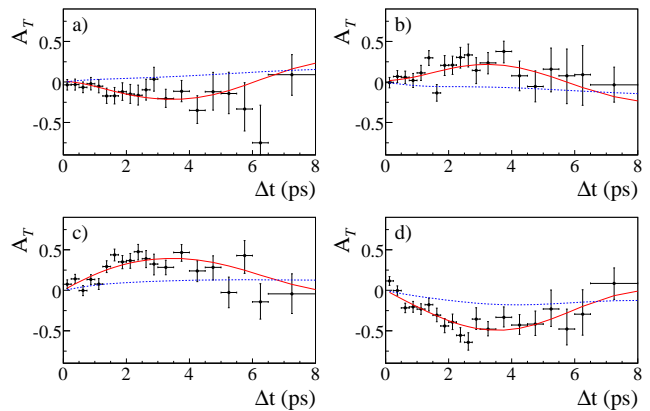
as our limited knowledge of Γ_d, Δm_d, and other fixed parameters, the interaction region, the detector alignment, and effects due to a nonzero $\Delta\Gamma_d$ value in the time dependence and the normalization of the PDF, are also considered. Treating $c\bar{c}K_S^0$ and $J/\psi K_L^0$ as orthogonal states and neglecting CP violation for flavor categories without leptons, has an impact well below the statistical uncertainty. The total systematic uncertainties are shown in Table I [23].

The significance of the T-violation signal is evaluated based on the change in 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 3 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 (σ), 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 17σ and 0.3σ, consistent with CP violation and CPT invariance.
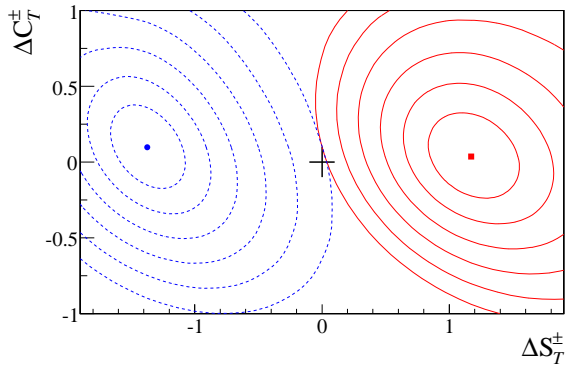
FIG. 3: (color online). The central values (blue point and red square) and two-dimensional CL contours for $1 - \text{CL} = 0.317$, 4.55×10^{-2}, 2.70×10^{-3}, 6.33×10^{-5}, 5.73×10^{-7}, and 1.97×10^{-9}, calculated from the change in the value of $-2\Delta \ln \mathcal{L}$ compared with its value at 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.

In summary, we have measured T-violating parameters in the time evolution of neutral B mesons, by comparing the probabilities of $\overline{B}^0 \to B_-$, $B_+ \to B^0$, $\overline{B}^0 \to B_+$, 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.) ± 0.06 (syst.) and $\Delta S_T^- = 1.17 \pm 0.18$ (stat.) ± 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 14σ. Our results are consistent with current CP-violating measurements obtained invoking CPT invariance. They constitute the first 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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