Observation of Time-reversal Violation at BABAR

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Proceedings of CKM 2012, the 7th International Workshop on the CKM Unitarity Triangle, University of Cincinnati, USA, 28 September – 2 October 2012

1 Time-reversal violation

In stable systems, violation of Umkehr der Bewegungsrichtung \[1, 2\], or time-reversal \((T)\), symmetry is indicated by a non-zero value of \(T\)-odd observables such as the neutron or electron electric dipole moments \((d_n < 2.9 \times 10^{-26} \text{ e-cm}, d_e < 10.5 \times 10^{-28} \text{ e-cm}, \text{at 90\% CL})\).\[3\] \(T\) violation would also be indicated by different probabilities for \(a \rightarrow b\) at a given time than for \(b \rightarrow a\), such as \(\nu_e \rightarrow \nu_\mu\) vs. \(\nu_\mu \rightarrow \nu_e\) at a muon storage ring.

In unstable systems, \(T\) violation can be explored by study of a process under the transformation \(t \rightarrow -t\) combined with exchange of \(|\text{in}\rangle\) and \(|\text{out}\rangle\) states, which can be experimentally challenging to achieve. 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. Comparing mixing rates \(B^0 \rightarrow \bar{B}^0\) and \(\bar{B}^0 \rightarrow B^0\) does not distinguish \(CP\) from \(T\) violation and assumes \(CPT\) non-invariance \[4, 5\]. Searches in interference between mixing and decay \((B^0 \rightarrow \bar{B}^0, \bar{B}^0 \rightarrow f_{CP}\) vs. \(B^0 \rightarrow f_{CP}\) does not exchange \(|\text{in}\rangle\) and \(|\text{out}\rangle\) states or \(t \rightarrow -t\) and assumes \(CPT\) non-invariance and \(\Delta \Gamma = 0\).

2 Experimental procedure

We use the entangled quantum state \(|i\rangle\) of two \(B\) mesons from an \(\Upsilon(4S)\) decay:

\[
|i\rangle = 1/\sqrt{2} \left[ B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2) \right] \\
\]

\[
= 1/\sqrt{2} \left[ B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2) \right]
\]

where \(B_+\) and \(B_-\) are mutually orthogonal states decaying to the \(CP\) eigenstates \(J/\psi K^0_L\) and \(J/\psi K^0_S\) \((K^0_S \rightarrow \pi \pi)\) with \(CP = +\) and \(CP = -\), respectively. We define

\(^1\)Speaker on behalf of the BABAR Collaboration.
Table 1: Reference transitions and their $T$-transformed counterparts. $B_+$ and $B_-$ are orthogonal states decaying to $CP$ eigenstates with $CP = +$ and $CP = -$ , respectively; the notation $(X,Y)$ indicates the final states of both $B$ mesons where $X$ is the earlier decay; and the notation $l^+$ ($l^-$) identifies the $B$ meson as a $B^0$ ($B^0$).

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

reference transitions and their $T$-transformed counterparts as shown in Table [1]. We use the notation $(X,Y)$ to denote the final states of both $B$ mesons which decay from an entangled state where $B \rightarrow X$ is the first decay and $B \rightarrow Y$ is the second decay such that the decay time difference is positive by construction: $\Delta t = t_Y - t_X > 0$. As an example, the final state $(l^+, J/\psi K^0_S)$ represents a $B^0 \rightarrow l^+ X$ decay followed in time by a $\bar{B}^0 \rightarrow B_-$ decay. We know the second $B$ starts in a $\bar{B}^0$ flavor state from the orthogonality of the initial state and its $CP$ eigenvalue at decay is indicated by its decay mode. A difference between this rate and that of the time-reversed transition $B_- \rightarrow \bar{B}^0$, with final state $(J/\psi K^0_L, l^-)$, is an indication of $T$ violation. A total of four $T$-reversed transitions can be studied (see Table [1]). Four other final-state combinations can be compared to study $CP$ violation and another four for $CPT$ violation, all independent.

The dataset and event selection are essentially the same as that of the BABAR $CP$ violation study [6]. The decay rate $g_{a,\beta}^\pm(\Delta t)$ is proportional to

$$g_{a,\beta}^\pm(\Delta t) \propto e^{-\Gamma_d \Delta t} \{ 1 + S_{a,\beta}^\pm \sin(\Delta m_d \Delta t) + C_{a,\beta}^\pm \cos(\Delta m_d \Delta t) \}. \quad (1)$$

There are eight distinct sets of $S_{a,\beta}^\pm$, $C_{a,\beta}^\pm$ parameters, where $a$ indicates $l^\pm$, $\beta$ indicates $K^0_S$ or $K^0_L$, and $\pm$ indicates whether the flavor final state decay occurs before or after the $CP$ decay $\beta$. $\Gamma_d$ is the average decay width, $\Delta m_d$ is the mass difference of $B^0$ and $\bar{B}^0$. By comparison, the standard $CP$ study [6] has one set of $S$, $C$ parameters and assumes $\Delta \Gamma$ is zero. An independent flavor sample is used to determine time-resolution parameters and wrong-sign fit fractions. An unbinned, maximum-likelihood fit is performed to the $B^0$, $\bar{B}^0$, $c\bar{c}K^0_S$, and $J/\psi K^0_L$ samples, yielding the $S_{a,\beta}^\pm$, $C_{a,\beta}^\pm$ parameters. The $T$, $CP$, and $CPT$ violating parameters $\Delta S^\pm_i$, $\Delta C^\pm_i$, where $i = T$, $CP$, or $CPT$, are constructed as the differences in $S_{a,\beta}^\pm$ and $C_{a,\beta}^\pm$ for symmetry-transformed transitions (e.g., $\Delta S_T^\pm = S_{-;K_S}^\pm - S_{+;K_S}^\pm$, $\Delta C_{CPT}^\pm = C_{+;K_L}^\pm - C_{-;K_L}^\pm$).
### Table 2: Central values of parameters from the $T$, $CP$, and $CPT$ fits. The first uncertainty is statistical, the second is systematic.

| Param. Final result | Param. Final result | Param. Final result |
|---------------------|---------------------|---------------------|
| $\Delta S^+_T$     | $-1.37 \pm 0.14 \pm 0.06$ | $\Delta S^+_T$     | $-1.30 \pm 0.10 \pm 0.07$ | $\Delta S^+_CPT$ | $0.16 \pm 0.20 \pm 0.09$ |
| $\Delta S^-_T$     | $1.17 \pm 0.18 \pm 0.11$ | $\Delta S^-_T$     | $1.33 \pm 0.12 \pm 0.06$ | $\Delta S^-_CPT$ | $-0.03 \pm 0.13 \pm 0.06$ |
| $\Delta C^+_T$     | $0.10 \pm 0.16 \pm 0.08$ | $\Delta C^+_T$     | $0.07 \pm 0.09 \pm 0.03$ | $\Delta C^+_CPT$ | $0.15 \pm 0.17 \pm 0.07$ |
| $\Delta C^-_T$     | $0.04 \pm 0.16 \pm 0.08$ | $\Delta C^-_T$     | $0.08 \pm 0.10 \pm 0.04$ | $\Delta C^-_CPT$ | $0.03 \pm 0.14 \pm 0.08$ |

Figure 1: Central values (blue points and red squares) and contours of $1 - \text{C.L.}$ at $1\sigma$ intervals for the $T$ (left), $CP$ (middle), and $CPT$ (right) results. Systematic uncertainties are incorporated (the largest being the fit bias from simulation). Contours for $\Delta S^+_i$, $\Delta C^+_i$ ($i = T, CP$, or $CPT$) are shown as blue dashed curves. Contours for $\Delta S^-_i$, $\Delta C^-_i$ ($i = T, CP$, or $CPT$) are shown as red solid curves. The no-violation point is shown in each plot as a plus sign (+).

### 3 Results and conclusion

Results are shown in Table 2. Their confidence level significances can be shown graphically as two-dimensional contour plots for $\Delta S^+_i$, $\Delta C^+_i$, $i = T, CP$, or $CPT$ (see Figure 1). No assumptions about $CP$ or $CPT$ violation or invariance are made. $T$ violation is observed at the $14\sigma$ level, consistent with measurements of $CP$ violation that assume $CPT$ invariance. This is the first direct observation of $T$ violation in the $B$ system. $CP$ violation is also observed at the $16\sigma$ level. No evidence for $CPT$ non-invariance is seen [7].

We are grateful for the excellent luminosity and machine conditions made possible by our PEP-II colleagues which have made this work possible and for the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank the SLAC National Accelerator Laboratory for its support and kind hospitality. This work is supported by the U.S. Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto
Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Education and Science of the Russian Federation, Ministerio de Educación y Ciencia (Spain), and the Science and Technology Facilities Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation (USA), and the Binational Science Foundation (USA-Israel).

References

[1] Eugene P. Wigner. Relativistic Invariance and Quantum Phenomena. Rev. Mod. Phys., 29:255–268, 1957.

[2] G. Lüders. Zur Bewegungsumkehr in quantisierten Feldtheorien. Z. Phys., 133:325–329, 1952.

[3] J. Beringer et al. Review of Particle Physics (RPP). Phys. Rev., D86:010001, 2012.

[4] P.K. Kabir. What is not invariant under time reversal? Phys. Rev., D2:540–542, 1970.

[5] A. Angelopoulos et al. First direct observation of time reversal noninvariance in the neutral kaon system. Phys. Lett., B444:43–51, 1998.

[6] Bernard Aubert et al. Measurement of Time-Dependent CP Asymmetry in $B^0 \rightarrow c\pi K^{(*)0}$ Decays. Phys. Rev., D79:072009, 2009.

[7] J.P. Lees et al. Observation of Time Reversal Violation in the $B^0$ Meson System. Phys. Rev. Lett., 109:211801, 2012.