DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

PABLO VILLANUEVA-PÉREZ

E-mail: pablo.villanueva.perez@ific.uv.es

Abstract. In this presentation a model independent and genuine test of T violation, disentangled from CP and CPT, is built. In the second section, a Monte Carlo simulation is done to show the possibility to perform this analysis at B factories.

1. THEORETICAL MOTIVATION

The violation of CP invariance has been observed in the $K^0 - \bar{K}^0$ and in the $B^0 - \bar{B}^0$ systems (Aubert et al., Abe et al. 2002). Up to now, the experimental results are in agreement with the CKM mechanism in the ElectroWeak Theory. Although all present tests of CPT invariance confirm this symmetry, imposed by any local quantum field theory with Lorentz invariance and Hermicity, it would be of great interest to observe Time-Reversal Violation (TRV) directly in a single experiment. A direct evidence for TRV would mean an experiment that, considered by itself, clearly shows T violation INDEPENDENT and unconnected to the results for CP violation. There is no existing result [1] that clearly demonstrates TRV in this sense. Sometimes the Kabir asymmetry $K^0 \rightarrow \bar{K}^0$ vs. $\bar{K}^0 \rightarrow K^0$ has been presented [2] as a proof for TRV. This process has, however, besides the drawbacks discussed in [1], the feature that $K^0 \rightarrow \bar{K}^0$ is a CPT-even transition, so that it is impossible to separate T violation from CP violation in the Kabir asymmetry: these two transformations are identical experimentally in this case.

There are effects in particle physics that are odd under time $t \rightarrow -t$, but they are not genuine T-violating, because do not correspond to an interchange of $in - states$ into $out - states$. These kinds of t-asymmetries, like the macroscopic and the Universe t-asymmetry, can occur in theories which have an exact T-symmetry in fundamental physics [3]. In fact, the t-asymmetry can only be connected [4] to T-asymmetry under the
assumptions of CPT invariance plus the absence of an absorptive part difference between the initial and final states of the transition. As a consequence, we have to disregard these t-asymmetries as direct evidence for T violation.

As shown in [4, 5], B-factories offer the unique opportunity to show SEPARATE evidence for T violation (and CP violation) and measure the corresponding effects. The proposal has been scrutinized by Lincoln Wolfenstein [1] and Helen Quinn [3] with the conclusion that it appears to be a true TRV-effect. The crucial role played by B-factories is the EPR entanglement [6] between the neutral B-mesons produced by the decay of the Υ(4S) resonance. Although this coherence imposed by Bose statistics has only been used for flavor tagging up to now, one has to emphasize, following what quantum mechanics dictates, that the individual state of the neutral meson is not defined before its collapse as a filter imposed by the observation of the decay process of its companion. Similarly to the writing of the physical state of the two particles in terms of Bose-correlated orthogonal $B^0$ and $\bar{B}^0$, which allows to infer the flavor of the still alive meson by observing the specific flavor decay of the other (and first decaying) meson, one can rewrite the two particle state in terms of any pair of orthogonal states of individual neutral $B$-mesons. In particular, let us consider the pair of orthogonal states $B^+_0$ and $B^-_0$ of neutral B-mesons, where $B_-$ is the state that decays to $J/\psi K_+$, $K_+$ being the neutral $K^+ \to \pi \pi$, and $B_+$ is the orthogonal state to $B_-$, i.e., not connected to $J/\psi K_+$. We may call the filter imposed by a first observation of one of these decays a “CP-tag” [6], because $B_+$ and $B_-$ are approximately, up to terms of $Re(\epsilon_K)$ giving the non-orthogonality of $K_L$ and $K_S$, the neutral $B$-mesons associated with final states of their decays which are CP-eigenstates, with the identification of $K_+ = K_S$. As we are going to discuss much larger expected effects, one is authorized to use the language of identifying $B_-$ by $J/\psi K_S$, and $B_+$ by $J/\psi K_L$. To clarify the point, $B_-$ and $B_+$ should not be associated with CP-eigenstates of the neutral $B$-mesons themselves.

The theoretical ingredient to be used for this proposal of showing genuine effects for the separate violation of the discrete symmetries T and CP is the EPR entanglement only. The experimental results, and their interpretation, will be thus free of any other theoretical prejudice. Let us consider the two particle state of the neutral B-mesons produced by the decay of $\Upsilon(4S)$,

$$|i> = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] = \frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)],$$

(1)

where the states 1 and 2 are defined by the time of their decay with $t_1 < t_2$. We may proceed to a partition of the complete set of events into four categories, defined by the tag in the first decay as $B_+, B_-, B^0$ or $\bar{B}^0$.

Let us first take $B^0 \to B_+$ as process I, by observation of $l^-$ (produced by the semileptonic decay of the opposite $B^0$ meson) and $J/\psi K_L$ later, denoted as $(l^-, J/\psi K_L)$, and consider:
• i) Its CP transformed \( B^0 \rightarrow B^+ (l^+, J/\psi K_L) \), so that the asymmetry between \( B^0 \rightarrow B^+ \) and \( \bar{B}^0 \rightarrow B^+ \), as a function of \( \Delta t = t_2 - t_1 \), is a genuine CP-violating effect.

• ii) Its T transformed \( B^+ \rightarrow B^0 (J/\psi K_S, l^+) \), so that the asymmetry between \( B^0 \rightarrow B^+ \) and \( B^+ \rightarrow B^0 \), as a function of \( \Delta t = t_2 - t_1 \), is a genuine T-violating effect.

• iii) Its CPT transformed \( B^+ \rightarrow \bar{B}^0 (J/\psi K_S, l^-) \), so that the asymmetry between \( B^0 \rightarrow B^+ \) and \( B^+ \rightarrow \bar{B}^0 \), as a function of \( \Delta t = t_2 - t_1 \), is a genuine test of CPT invariance.

| Transition | \( B^0 \rightarrow B^+ \) | \( \bar{B}^0 \rightarrow B^+ \) | \( B^+ \rightarrow B^0 \) | \( B^+ \rightarrow \bar{B}^0 \) |
|------------|-----------------|-----------------|-----------------|-----------------|
| (X,Y)      | \( l^+, J/\psi K_L \) | \( l^-, J/\psi K_L \) | \( J/\psi K_S, l^- \) | \( J/\psi K_S, l^+ \) |

Table 1: Transitions and symmetry transformations related to process I tag as reference.

One may check, that the events used for the asymmetries i), ii), and iii), summarized in Table 1, are completely independent. Furthermore, the expectation is that the asymmetry described by ii) will prove and measure, for the first time, T violation with many standard deviations away from zero.

Similarly, one may take as reference process II \( B^0 \rightarrow B^- \), by observation of \( l^- \) first and \( J/\psi K_S \) later \( (l^-, J/\psi K_S) \). The corresponding transformations are summarized in Table 2.

| Transition | \( B^0 \rightarrow B^- \) | \( \bar{B}^0 \rightarrow B^- \) | \( B^- \rightarrow B^0 \) | \( B^- \rightarrow \bar{B}^0 \) |
|------------|-----------------|-----------------|-----------------|-----------------|
| (X,Y)      | \( l^-, J/\psi K_S \) | \( l^+, J/\psi K_S \) | \( J/\psi K_L, l^- \) | \( J/\psi K_L, l^+ \) |

Table 2: Transitions and symmetry transformations related to process II tag as reference.

Analogously, one may consider the process III \( \bar{B}^0 \rightarrow B^+ \) as the reference, by observation of \( (l^+, J/\psi K_L) \). In particular, between \( \bar{B}^0 \rightarrow B^+ \) and \( B^+ \rightarrow \bar{B}^0 \) \( (J/\psi K_S, l^-) \) we have again a T reversal transformation as shown in Table 3.

| Transition | \( \bar{B}^0 \rightarrow B^+ \) | \( B^+ \rightarrow \bar{B}^0 \) |
|------------|-----------------|-----------------|
| (X,Y)      | \( l^+, J/\psi K_L \) | \( J/\psi K_S, l^- \) |

Table 3: Transitions and symmetry transformations related to process III tag as reference.

Finally, one may consider the process IV \( B^0 \rightarrow B^- \) as the reference, by observation of \( (l^+, J/\psi K_S) \) and the new transformations are summarized in Table 4.

| Transition | \( B^0 \rightarrow B^- \) | \( \bar{B}^0 \rightarrow B^- \) |
|------------|-----------------|-----------------|
| (X,Y)      | \( l^+, J/\psi K_S \) | \( l^-, J/\psi K_S \) |

Table 4: Transitions and symmetry transformations related to process IV tag as reference.

We will develop the results expected for all these genuine asymmetries in the Weisskopf-Wigner effective Hamiltonian approach for the time evolution of the \( B^0 - \bar{B}^0 \) system [4, 5].
Table 3: Transitions and symmetry transformations related to process III tag as reference.

| Transition | $\bar{B}^0 \to B_+$ | $B^0 \to B_+$ | $B_+ \to B^0$ | $B_+ \to \bar{B}^0$ |
|------------|-------------------|----------------|----------------|-------------------|
| $(X,Y)$    | $(l^+, J/\psi K_L,)$ | $(l^-, J/\psi K_L,)$ | $(J/\psi K_S, l^+)$ | $(J/\psi K_S, l^-)$ |
| Transformation | Reference | CP | CPT | T |

Table 4: Transitions and symmetry transformations related to process IV tag as reference.

| Transition | $\bar{B}^0 \to B_-$ | $B^0 \to B_-$ | $B_- \to B^0$ | $B_- \to \bar{B}^0$ |
|------------|-------------------|----------------|----------------|-------------------|
| $(X,Y)$    | $(l^+, J/\psi K_S,)$ | $(l^-, J/\psi K_S,)$ | $(J/\psi K_L, l^+)$ | $(J/\psi K_L, l^-)$ |
| Transformation | Reference | CP | CPT | T |

However our goal is to demonstrate and measure the violation of time reversal invariance without using the procedure of fitting parameters in a given theory. The outcome will be highly rewarding as a model-independent observation of $T$ violation.

## 2. MONTE CARLO STUDY

In this section we describe the procedure we have followed to generate the simulated samples of the required decays, as discussed in the theoretical motivation. On the second part, we estimate the $T$ violation asymmetry and its significance.

We first explain briefly the technique used at B factories to determine the difference of proper-time $\Delta t$ of the two decaying $B$ mesons, as well as the flavor tagging and the reconstruction. These techniques are described in detail in Ref. [7]. At the asymmetric-energy B factories the $\Upsilon(4S)$ decay products are Lorentz boosted along the longitudinal axis and fly enough for their decay paths to be comparable or larger than the experimental resolution. Since no charged stable particles emerge from the $\Upsilon(4S)$ decay point, the decay length of the individual $B$ mesons from the $\Upsilon(4S)$ decay is unknown and we are left to determine the difference $\Delta z$ between them, from which $\Delta t$ can be calculated since the boost of the center-of-mass is well known. One of the two $B$ mesons is fully reconstructed in a CP eigenstate ($B_+, B_-$), while the other $B$ is partially reconstructed through their decay products (e.g. semileptonic decays, dominant hadronic decays producing charged kaons, etc.) and used for tagging as $B^0$ or $\bar{B}^0$ and for vertexing. In Figure 1 we sketch the event topology and how the reconstruction of the $\Upsilon(4S)$ decay is performed.

Concerning the Monte Carlo simulation, it has been done using an standard Probability
Density Function (PDF) which contains effects of T, CP and CPT violation and is based on the Wigner-Weiskopff formalism [8]. Neglecting effects from mistags, CPT violation (complex parameter $z$ set to zero), and taking $\Delta \Gamma = 0$, $|q/p| = 1$, the decay rate $g_\pm$ from a neutral $B$ meson to a CP eigenstate ($B_+, B_-$) is given by equation 2 taken from [8, 9]. To generate our samples we have set the parameter $Im(\lambda_f)$ (i.e. the well known CP-violating parameters sin 2$\beta$) to 0.672, and $|\lambda_f| = 1$ (i.e. no direct CP violation in the $B_+, B_-$ decays), taken from [9]:

$$\begin{align*}
\{ S_f = 0.672 \} &= \{ Im(\lambda_f) = 0.672 \} \\
\{ C_f = 0 \} &= \{ |\lambda_f| = 1 \}.
\end{align*}$$

$$g_\pm(\Delta t) = \frac{e^{-|\Delta t|}}{4\tau_B^0} \cdot \{1 \pm [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\} (2)$$

With this PDF the eight samples can be generated, from which we evaluate our asymmetries, as described in section 1.

The T asymmetry is built counting the number of entries in the physics sample ($N_a$) and its T transformed ($N_b$). So we subtract bin per bin $\Delta t$ in both samples, correcting by efficiency effects.

$$A_T = \frac{N_a - cN_b}{N_a + cN_b} = \frac{1 - \Gamma_b}{\Gamma_b} \frac{N_a}{N_a} = \frac{1 - \Gamma_b}{\Gamma_a} \frac{N_b}{N_a} = \frac{1 - \Gamma_b}{\Gamma_a} \frac{N_b}{N_a}$$

$$\frac{1 - \Gamma_b}{\Gamma_a} \frac{N_b}{N_a} (3)$$
Figure 2: T asymmetries for the four reference processes. The red curve on the plots is the one obtained using the curves without T, CP, and CPT violating effects.

where

\[ c = \frac{\varepsilon_{KL}}{\varepsilon_{KS}} = \frac{\frac{N_{KL}}{\varepsilon_{KL}}}{\frac{N_{KL}}{\varepsilon_{KL}}} = \frac{N_{KL}^{\text{exp}}}{N_{KL}^{\text{tot}}} \]

(4)

or

\[ c = \frac{\varepsilon_{KS}}{\varepsilon_{KL}} = \frac{\frac{N_{KL}}{\varepsilon_{KL}}}{\frac{N_{KL}}{\varepsilon_{KL}}} = \frac{N_{KL}^{\text{exp}}}{N_{KL}^{\text{tot}}} \]

(5)

Eq. (4) has to be used when the \( a \) sample is reconstructed as \( J/\psi K_L \) and the \( b \) sample as \( J/\psi K_S \). Analogously, equation 5 will be used when the \( a \) sample is reconstructed as \( J/\psi K_S \) and the \( b \) sample as \( J/\psi K_L \).

At BaBar, there are 3255\( K_L \) signal events and 7750\( K_S \) signal events, as extracted from
the experimental analysis. So we obtain the black line in the T asymmetry plots (figure 2). The red dotted curves are those obtained after setting \( Im(\lambda_{CP}) = 0 \), which in practice correspond to the integration over the bin size of the curve without T violation. These curves have been done using 1 million events (i.e. a virtually infinite statistics). We perform this comparison since our final goal is to compare the asymmetries with T violation and the corresponding ones without T violation with all the experimental effects included. This comparison will be done through a \( \chi^2 \) test.

We also have included approximate \( \Delta t \) resolution, mistags and reconstruction efficiencies as it is done at the B factories.

We perform a \( \chi^2 \) test for each of the four statistically independent T asymmetries, using the \( \chi^2 \) ansatz given by

\[
\chi^2_0 = \sum_{\Delta t_i} \frac{(A_{T\exp}^{\Delta t_i} - A_{T\,No\,T\,-\,Violation}^{\Delta t_i})^2}{\sigma_{A_{T\exp}^{\Delta t_i}}^2 + \sigma_{A_{T\,No\,T\,-\,Violation}^{\Delta t_i}}^2},
\]

from which a confidence level (or equivalently a significance of the T violation effect) can be computed. For this study we assume a \( \chi^2 \)-distributed variable, although in the experimental analysis a careful study of the true distribution will have to be pursued.

Assuming a \( \chi^2 \) distribution, the results of the \( \chi^2 \) test for T asymmetry with proper-time resolution, mistags, and efficiency effects for our simulated samples are summarized in table 5. We can compute that \( \chi^2/dof \approx 14 \) for the TRV test, so we can anticipate to establish directly for the first time T violation with a significance above 10 standard deviations.

| T asymmetries Test | \( B^0 \to B_+ \) | \( B^0 \to B_- \) | \( \tilde{B}^0 \to B_+ \) | \( \tilde{B}^0 \to B_- \) |
|-------------------|-----------------|-----------------|-----------------|-----------------|
| \( \chi^2_0 \)    | 99.04, 23 bins  | 159.47, 22 bins | 150.05, 22 bins | 106.36, 21 bins |
| Prob(\( \chi^2 > \chi^2_0 \)) | 2.06 \cdot 10^{-11} | 7.69 \cdot 10^{-23} | 4.69 \cdot 10^{-21} | 2.13 \cdot 10^{-13} |
| Standard Deviations | 6.70            | 9.84            | 9.42            | 7.34            |

Table 5: \( \chi^2 \) test of the T asymmetries.

3. ACKNOWLEDGEMENTS

This research has been supported by the Grants FPA 2008-02878 from MICINN and PROMETEO 2008/004 from Generalitat Valenciana.
4. REFERENCES

[1] L. Wolfenstein, Int. J. Mod. Phys. E 8, 501 (1999).
[2] T. Nakada, Discrete’08 Conference, Valencia 2008, J. Phys. Conf. Ser. 171, 011001 (2009).
[3] H. R. Quinn, Discrete’08 Conference, Valencia 2008, J. Phys. Conf. Ser. 171, 011001 (2009).
[4] M. C. Bañuls and J. Bernabeu, Phys. Lett. B 464, 117 (1999), [arXiv:hep-ph/9908353].
[5] M. C. Bañuls, J. Bernabeu, Nucl. Phys. B 590, 19 (2000), [arXiv:hep-ph/0005329].
[6] M. C. Bañuls, J. Bernabeu, JHEP 032, 9906 (1999), [arXiv:hep-ph/9807430].
[7] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 66, 032003 (2002).
[8] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 92, 181801 (2004); Phys. Rev. D 70, 012007 (2004).
[9] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 79, 072009 (2009).