DIRECT EVIDENCE AND MEASUREMENT OF TIME REVERSAL VIOLATION

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The violation of CP invariance has been observed in the $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ systems. Up to now, the experimental results are in agreement with the Standard 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, 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 $K^0 \to \bar{K}^0$ vs. $\bar{K}^0 \to K^0$ has been presented [2] as a proof for TRV. This process has, however, besides the drawbacks discussed in [1], the feature that $K^0 \to \bar{K}^0$ is a CPT-even transition, so that it is impossible to separate T violation from CP violation in the Kabir asymmetry.

There are effects in particle physics that are odd under time t to $-t$, 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 [3] in theories which have an exact T-symmetry in fundamental physics. 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 Refs. [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 $\Upsilon(4S)$. Although this coherence imposed by Bose statistics has only been used for flavour 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 flavour of the still alive meson by observing the specific flavour 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_+ and B_- 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 $\mathrm{Re}(\epsilon_K)$ 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's 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 $\Upsilon(4S)$:

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

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 cathegories, defined by the tag in the first decay as B_+, B_-, B^0 or $\bar{B}^0$. Let us take as a first process I $B_+ \to B^0$, by observation of $J/\psi K_S$ first and l^+ later, denoted as $(J/\psi K_S, l^+)$, and consider:

I.i) Its CP transformed $B_+ \to \bar{B}^0(J/\psi K_S, l^-)$, so that the asymmetry between $B_+ \to B^0 and B_+ \to \bar{B}^0$, as a function of $\Delta t = t_2 - t_1$, is a genuine CP-violating effect.

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

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

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

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

One may check, a fortiori, that the events used for the asymmetries 1i), 1ii) and 1iii) are completely independent. Furthermore, the expectation is that the asymmetry described by 1ii) 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 $B_- \to B^0$, by observation of $J/\psi K_L$ first and l^+ later $(J/\psi K_L, l^+)$. The corresponding asymmetries are summarized in Table 2 wich are genuine symmetry violating effects:

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

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

And still more:
Analogously, one may consider the process III $\bar{B}^0 \to B_+$ as the reference, by observation of $(l^+, J/\psi K_L)$. Particularly, between $\bar{B}^0 \to B_+$ and $B_+ \to \bar{B}^0$ $(J/\psi K_S, l^-)$ is again a genuine signal of T violation.

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

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

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

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

On purpose, in this note there is no reference to the results expected [4,5] for all these genuine asymmetries in the Weisskopf- Wigner effective hamiltonian approach for the time evolution of the B0-B0bar system and, even less, within the standard CKM mechanism for CP violation. The discussion of these expectations is left for a separate note. First, it is crucial 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 significant signal of T violation.

[1] L. Wolfenstein, Int. J. Mod. Phys. E 8, 501 (1999).
[2] See, for example, 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. Banuls, J. Bernabeu, Phys. Lett. B 464, 117 (1999), [arXiv:hep-ph/9908353].
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[6] M. C. Banuls, J. Bernabeu, JHEP 9906:032 (1999), [arXiv:hep-ph/9807430].