DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

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1. Simmetries in Physics

The study of symmetries is fundamental in Physics. The invariance of physical systems under different transformations is connected to the conservation of definite magnitudes, whose knowledge can determine the behaviour of the system. Thus it is important to understand which quantities are conserved or violated and why. In Particle Physics, ones has to pay spacial attention to continous symmetries, if they can be obtained by applying a sucesion of infinitesimal transformations, or discrete symmetries, if not as C, P and T. It has been shown that they are preserved by strong and electromagnetic interactions, but broken in weak processes. Moreover it is also known that , while C and P are maximally violated in Nature by electroweak interactions, CP breaking happend at a much lower order. Regarding T symmetry , although CPT theorem realtes it with CP, a direct proof is needed. Discrete have an especial interest in our work, so we will develop them in a whole section.

2. Discrete Simmeries

2.1. **Parity or Space Inversion (P).** Parity symmetry, usually called P, consist in the invariance of physiscs undes a discrete transformation which changes the sign of the space coordinates x,y, and z ($\vec{r} \rightarrow -\vec{r}$). This correponds to the inversion of the handedness of the system of axes, so a right-handed system becomes a left-handed upon the parity transformation. In three dimensions, the P transformation turns a system into its mirror image. In case of P invariance, then, a process cannot be distinguished from its specular image and one cannot define absolutely the concepts of left and right. The momenta are reversed too, $\vec{p} \rightarrow -\vec{p}$, as a consequence, the velocity of the particle,

$$\vec{v} = \frac{d\vec{r}}{dt} \tag{2.1}$$

because:

$$\vec{p} = m\vec{v} \tag{2.2}$$

The angular momentum,

$$\vec{J} = \vec{r} \times \vec{p} \tag{2.3}$$

is invariant under P, because both $\vec{r}$ and $\vec{p}$ change sign, so spins are not affected.

2.2. **Time Reveral (T).** Time-reversal transformation, usually called T, consist of changing the sign of the time coordinate t. From equation 2.1 we see that, when $t \to -t$, then the velocity $\vec{v} \to -\vec{v}$. While $\vec{x} \to \vec{x}$. So bothe momentum and spin are reversed under T ($\vec{p} \to -\vec{p}$ and $\vec{J} \to -\vec{J}$). The result of such an operation on adynamical system is the time-reversed sequence of its evolution (exchange of in-states to out-states and vice versa). Thus, in case on T invariance, one process and its time-reversed would be equally physical and occour with the same probability, and would not be able to define a direction for the time arrow in an absolute way.

2.3. **Charge Conjugation (C).** Contrary to P and T, charge-conjugation symmetry C does not have an analque in classical physics, C is an internal operation, which changes the sign of all internal charges, such as electric charge or baryon number, and leaves the space-time properties unaltered. This is a prediction fo relativistic quantum theory which has been brilliantly confirmed by experiment, in particular through the discovery of the positron (Anderson 1933) and of the antiproton (Chamberlain et al. 1955). If C was a good symmetry, all experiment performed in a world of antimatter would give the same results they would give in ours. However, C is not a good symmetry in Nature, and it does not transform a physical particle in its antiparticle, because its definition is made on free fields, which do not necessarily correspond to the physical ones. To define the antiparticle one has to make use of the combined transformation CPT.

2.4. **Violation of C, P and CP.** Before 1956 it was assumed that P and C were separately conserved in elementary processes. The possibility of left-right asymmetry in physical laws was suggested that year by Lee and Yang and discovered experimentally a few months later in weak processes. It turns out that the whole body of weak interactions works differently for matter and antimatter. Moreover, weak interactions also are left-right asymmetric. On the other hand CP, made out of simultaneous C and P transformations, (most) weak interactions reamain identical to themselves-cross sections and decay rates remain unchanged. Namely, the conceptual problem of distinguishing matter from antimatter con only acquire a solution if we are able to eliminate the convention of what is 'left' and what is 'right' from the game. It is not enough that C be violated, CP must be violated too in order that matter may be distinguished from antimatter.

The fact that CP symmetry is preserved even while C and P symmetries are violated was first pointed out by Landau (1957). Only much later was CP discovered to be violated too (Christenson et al. 1964). The first evidence for CP violation is the charge asymmetry in K_{l3} decays. The kaon K_L is a neutral particle with well-defined mass and decay width. Moreover, there is no other particle with equal mass. Therefore, K_L must be its own antiparticle. It decays both to $\pi^+ e^- \bar{\nu}_e$ and to the C-conjugate mode $\pi^- e^+ \nu_e$. However, it decays slightly less often to the first than to the second mode. This fact unequivocally establishes both C violation and CP violation. CP violation is explained in the Standar Model (SM) with the existence of three generations in the unitary matrix of Cabibbo-Kobayashi-Maskawa (CKM), this fact allows the presence of one physical phase.

At present there is evidence that in our Universe each of the three discrete symmetries C, P and T is violated. The same happens to any bilinear product, such as CP, TC, etc. However the triple product CPT represents an exact symmetry in any local quantum field theory with Lorentz invariance.

3. Time Reversal Violation In Neutral B-Meson System

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 $Re(\epsilon_K)$ 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 Bmesons 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 $\Upsilon(4S)$:

$$|i\rangle = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] = \frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)], \tag{3.1}$$

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 take as a first process I $B^0 \to B_+$, by observation of l^- (produced by the semileptonic decay of the opposite $\bar{B}^0$ meson) and $J/\psi K_L$ later, denoted as (l^-,$J/\psi K_L$), and consider:

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

Transition	$B^0 \to B_+$	$\bar{B}^0 \to B_+$	$B_+ \to \bar{B}^0$	$B_+ \to B^0$
(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 1. Transitions and symmetry transformations related to process I tag as reference.

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

Transition	$B^0 \to B_-$	$\bar{B}^0 \to B_-$	$B_- \to \bar{B}^0$	$B_- \to B^0$
(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

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

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

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.

On purpose of the master thesis, 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]. Despite 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.

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

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

3.1. **Coherent B-meson formalism.** The neutral B-meson system can be described by the effective Hamiltonian $H = M - i\Gamma/2$, where M and Γ are 2×2 Hermitian matrices describing, respectively, the mass and decay-rate components CP or CPT symmetry imposes that $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$, the index 1 indicating B^0 and 2 indicating $\bar{B}^0$. In the limit of CP or T invariance, $\Gamma_{12}/M_{12} = \Gamma_{21}/M_{21} = \Gamma^*_{12}/M^*_{12}$, so Γ_{12}/M_{12} is real. These conditions do not depend on the phase conventions chosen for the B^0 and $\bar{B}^0$. The masses $m_{H,L}$ and decay rates $\Gamma_{H,L}$ of the two eigenstates of H form the complex eigenvalues $\omega_{H,L}$

(3.2)
$$\omega_{H,L} \equiv m_{H,L} - \frac{i}{2}\Gamma_{H,L} = m - \frac{i}{2}\Gamma \pm \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M^*_{12} - \frac{i}{2}\Gamma^*_{12}\right) + \frac{1}{4}\left(\delta m - \frac{i}{2}\delta\Gamma\right)^2}$$

where the real part of the square root is taken to be positive and where we define

$$m \equiv \frac{1}{2}(M_{11} + M_{22}) \quad , \quad \Gamma \equiv \frac{1}{2}(\Gamma_{11} + \Gamma_{22}) \tag{3.3}$$

$$\delta m \equiv M_{11} - M_{22} \quad , \quad \delta\Gamma \equiv \Gamma_{11} - \Gamma_{22} \tag{3.4}$$

Assuming CPT invariance($\delta m = 0$, $\delta\Gamma = 0$), and anticipating that $|\Delta\Gamma| \ll \Delta m$, we have

$$\Delta m \equiv m_H - m_L \approx 2|M_{12}| \tag{3.5}$$

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L \approx 2|M_{12}|\Re(\Gamma_{12}/M_{12}) \tag{3.6}$$

Here we have taken Δm to be the mass of the heavier eigenstate minus the mass of the lighter one. Thus, $\Delta\Gamma$ is the decay rate of the heavier state minus the decay rate of the lighter one and its sign is not known a priori. With CPT symmetry, the light and heavy mass eigenstates of the neutral-B-meson system can be written

$$\begin{aligned} |B_L> &= p|B^0> + q|\bar{B}^0>, \\ |B_H> &= p|B^0> - q|\bar{B}^0> \end{aligned} \tag{3.7}$$

where

$$\frac{q}{p} \equiv -\sqrt{\frac{M^*_{12} - \frac{i}{2}\Gamma^*_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}} \tag{3.8}$$

The magnitude of q/p is very nearly unity:

$$\left|\frac{q}{p}\right|^2 \approx 1 - \Im\frac{\Gamma_{12}}{M_{12}} \tag{3.9}$$

In the Standard Model (SM), the CP and T-violating quantity $|q/p|^2 - 1$ is small not just because $|\Gamma_{12}|$ is small, but additionally becays the CP-violating quantity $\Im(\Gamma_{12}/M_{12})$ is suppressed by an additional factor $(m_c^2 - m_u^2)/m_b^2 \approx 0.1$ relative to $|\Gamma_{12}/M_{12}|$. CPT violation in mixing can be described conveniently by the phase-convention-independent quantity

$$
\begin{aligned}
z &\equiv \frac{\delta m - \frac{i}{2}\delta\Gamma}{2\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right) + \frac{1}{4}\left(\delta m - \frac{i}{2}\delta\Gamma\right)^2}} \\
&= \frac{\delta m - \frac{i}{2}\delta\Gamma}{\Delta m - \frac{i}{2}\Delta\Gamma}
\end{aligned}
\tag{3.10}
$$

The generalizations of the eigenstates in Eq.3.7 when we account for CPT violation can be written

$$
\begin{aligned}
|B_L> &= p\sqrt{1-z}|B^0> + q\sqrt{1+z}|\bar{B}^0>, \\
|B_H> &= p\sqrt{1+z}|B^0> - q\sqrt{1-z}|\bar{B}^0>
\end{aligned}
\tag{3.11}
$$

where we maintain the definition of q/p given in Eq.3.8. The result, when time evolution is included, is that states that begin as purely B^0 or $\bar{B}^0$ after a time t will be mistures

$$
\begin{aligned}
|B^0_{phys}(t)> &= [g_+(t) + zg_-(t)]|B^0> - \sqrt{1-z^2}\frac{q}{p}g_-(t)|\bar{B}^0>, \\
|\bar{B}^0_{phys}(t)> &= [g_+(t) - zg_-(t)]|\bar{B}^0> - \sqrt{1-z^2}\frac{p}{q}g_-(t)|B^0>
\end{aligned}
\tag{3.12}
$$

where we have introduced

$$
g_\pm(t) = \frac{1}{2}(e^{-i\omega_H t} \pm e^{-i\omega_L t})
\tag{3.13}
$$

At the $\Upsilon(4S)$ resonance, neutral-B mesons are produced in coherent p-wave pairs(Eq.3.1). If we subsequently observe one B-meson decay to the state f_1 at time $t_0 = 0$ and the other decay to the state f_2 at some later time t, we cannot in general know whetehr f_1 came from the decay of a B^0 or a $\bar{B}^0$, and similarly for the state f_2. If $A_{1,2}$ and $\bar{A}_{1,2}$, are the amplitudes for the decay of B^0 and $\bar{B}^0$, respectively, to the states f_1 and f_2, then the overall amplitude is given by

$$
\mathcal{A} = a_+ g_+(t) + a_- g_-(t),
\tag{3.14}
$$

where

$$
\begin{aligned}
a_+ &= -A_1\bar{A}_2 + \bar{A}_1 A_2, \\
a_- &= \sqrt{1-z^2}\left[\frac{p}{q}A_1A_2 - \frac{q}{p}\bar{A}_1\bar{A}_2\right] + z[A_1\bar{A}_2 + \bar{A}_1A_2]
\end{aligned}
\tag{3.15}
$$

Using the realtions

$$|g_\pm(t)|^2 = \frac{1}{2}e^{\Gamma t}[\cosh(\Delta\Gamma t/2) \pm \cos(\Delta m t)] \tag{3.16}$$

and

$$g_+^*(t)g_-(t) = -\frac{1}{2}e^{-\Gamma t}[\sinh(\Delta\Gamma t/2) + i\sin(\Delta m t)] \tag{3.17}$$

we find the decay rate

$$\frac{dN}{dt} \propto e^{-\Gamma t}\left\{\frac{1}{2}c_+\cosh(\Delta\Gamma t/2) + \frac{1}{2}c_-\cos(\Delta m t) - \Re(s)\sinh(\Delta\Gamma t/2) + \Im(s)\sin(\Delta m t)\right\} \tag{3.18}$$

where

$$c_\pm = |a_+|^2 \pm |a_-|^2, s = a_+^* a_-. \tag{3.19}$$

The absolute value in teh leading exponential in Eq3.18 is in troduced for later convenience. Now let us take $f_1 \equiv f_{tag}$ to be the state that is incompletely reconstructed and that provides the tagging decay, and $f_2 \equiv f_{rec}$ to be the fully reconstructed state (flavor or CP eigenstate). Then we have $t = t_{rec} - t_{tag}$ and Eq.3.15 becomes

$$\begin{aligned} a_+ &= -A_{tag}\bar{A}_{rec} + \bar{A}_{tag}A_{rec}, \\ a_- &= \sqrt{1-z^2}\left[\frac{p}{q}A_{tag}A_{rec} - \frac{q}{p}\bar{A}_{tag}\bar{A}_{rec}\right] + z[A_{tag}\bar{A}_{rec} + \bar{A}_{tag}A_{rec}] \end{aligned} \tag{3.20}$$

If instead the tagged decay occurs second and the reconstruction first the Eq.3.18 is actually unaffected.

4. Experimental Set-Up

En esta seccin se desarrolara: -PepII y como genera el upsion(4s). -La forma del detector babar y componentes. -Como se reconstruyen los events relacionado con nuestro analisis.

5. Analysis

-Recuperar el texto de la nota de la estancia experimental. -Analisis de los datos reales. -Cosas a hacer: 1. Delta gamma. 2. Splots 3. chicuadrado

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