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T and CPT in B-Factories

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Abstract: For the B_d meson system, CP, T and CPT indirect violation can be described using two physical parameters, ε and δ. The traditional observables based on flavour tag and used in the kaon system, are not helpful in the B_d case, and new asymmetries have to be introduced. Here such alternative observables, based on CP tag, are presented, together with the first estimation on the sensitivity that current asymmetric B-factories can achieve on their measurement.

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1. Introduction

Violation of CP, T and CPT symmetries in the time evolution of K^0-$\bar{K}^0$ was studied by the CP-LEAR experiment [1] from the preparation of definite flavour states. The study of this *flavour-to-flavour* evolution allows the construction of observables which violate CP and T, or CP and CPT. In order to be non-vanishing, nevertheless, these observables need the presence of an absorptive part in the effective Hamiltonian that governs neutral meson system. The different lifetimes of physical states K_L and K_S provides this ingredient. In the case of B_d mesons, on the contrary, the width difference $\Delta\Gamma$ between the physical states is expected to be negligible[2], so that the T- and CPT-odd observables proposed for kaons, and based on flavour tag, will practically vanish for a B_d system.

Here alternative observables are discussed, which allow the study of CP, T and CPT indirect violation in the B_d system[3]. Based on CP-tag[4], these observables do not need the presence of $\Delta\Gamma \neq 0$, and can be constructed from the entangled states of B_d mesons.

In the following section, the invariant parameters ε and δ are introduced to describe indirect violation of symmetries in the neutral meson system. In section 3 we describe the CP tag of B_d from the entangled states in a B-factory. Next, section 4 reviews three different kinds of asymmetries that can be constructed from these states, namely, *flavour-to-flavour* and both genuine and non-genuine *CP-to-flavour* asymmetries. Finally, in section 5 the first estimates on the reach and sensitivity of the experimental analysis are given.

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2. Invariant description of CP, T and CPT violation in the B system

The physical states in the neutral B-meson system are a linear combination of the definite flavour B^0 and $\bar{B}^0$. Physical states can also be written in terms of CP eigenstates, $|B_\pm\rangle \equiv \frac{1}{\sqrt{2}}(I \pm CP)|B^0\rangle$, which are physical iff the CP operator is well defined. To do so, one has to introduce two complex parameters, $\varepsilon_{1,2}$, to describe the CP mixing, so that $|B_{1(2)}\rangle = \frac{1}{\sqrt{1+|\varepsilon_{1(2)}|^2}}\left[|B_{+(-)}\rangle + \varepsilon_{1(2)}|B_{-(+)}\rangle\right]$. The complex parameters $\varepsilon_{1,2}$, invariant under rephasing of the meson states, are better interpreted in terms of $\varepsilon \equiv (\varepsilon_1 + \varepsilon_2)/2$ and $\delta \equiv \varepsilon_1 - \varepsilon_2$, whose observable character is explicit when they are written in terms of the effective hamiltonian matrix elements [5].

Discrete symmetries impose different restrictions on the effective mass matrix, $H = M - \frac{i}{2}\Gamma$, and thus on the invariant parameters ε and δ:

- CPT invariance requires[1] $H_{11} = H_{22}$, so that $\delta = 0$, with no restriction on ε;
- T invariance imposes $\mathrm{Im}(M_{12}\mathrm{CP}^*_{12}) = \mathrm{Im}(\Gamma_{12}\mathrm{CP}^*_{12}) = 0$, and so $\varepsilon = 0$;
- and CP conservation requires both $\varepsilon = \delta = 0$.

In the exact limit $\Delta\Gamma = 0$, an approximation that is expected to be excellent for the B_d system, both $\mathrm{Re}(\varepsilon)$ and $\mathrm{Im}(\delta)$ vanish. Then $\mathrm{Im}(\varepsilon) \neq 0$ is a proof of both CP and T violation, and $\mathrm{Re}(\delta) \neq 0$ is a proof of CP and CPT violation, but neither $\mathrm{Re}(\varepsilon) = 0$ nor $\mathrm{Im}(\delta) = 0$ are proof of a fundamental invariance. Information on the symmetry parameters can be extracted from the study of time evolution of B meson entangled states.

3. CP-Tag from entangled states

In a B factory operating at the $\Upsilon(4S)$ peak, correlated pairs of neutral B-mesons are produced through $e^+e^- \to \Upsilon(4S) \to B\bar{B}$. Charge conjugation together with Bose statistics require the initial state to be $|i>= \frac{1}{\sqrt{2}}\left(|B^0(\vec{k}), \overline{B}^0(-\vec{k})> - |\overline{B}^0(\vec{k}), B^0(-\vec{k})>\right)$. This permits the performance of a flavour tag: if at t_0 one of the mesons decays through a channel X, which is only allowed for one flavour, the other meson in the pair must have the opposite flavour at t_0, and will later evolve during $\Delta t = t - t_0$ until its final decay to some state Y.

The entangled $B - \bar{B}$ state can also be expressed in terms of the CP eigenstates as $|i>= \frac{1}{\sqrt{2}}(|B_-, B_+> - |B_+, B_->)$. Thus it is also possible to carry out a CP tag, if we have a CP-conserving decay into a definite CP final state X, so that its detection allows us to identify the decaying meson as a B_+ or a B_-, which decays into Y after a time Δt. In Ref. [4] we described how this determination is possible and unambiguous to $\mathcal{O}(\lambda^3)$, the flavour-mixing parameter of the CKM matrix.

If we consider only decay channels X, Y which are either flavour or CP conserving, then the final configuration (X, Y) corresponds to a single particle mesonic transition. The intensity for the final configuration, $I(X, Y, \Delta t) \equiv \frac{1}{2}\int_{\Delta t}^{\infty} dt' |(X, Y)|^2$ is proportional to the time dependent probability for the meson transition.

[1] Here H_{ij}, M_{ij}, and so on, represent the matrix elements in the flavour basis $B^0 - \bar{B}^0$.

4. Asymmetries

By comparing the probabilities corresponding to different processes we build time-dependent asymmetries that can be classified into three types.

4.1 Flavour-to-flavour genuine asymmetries

The final configuration denoted by (ℓ, ℓ), with flavour definite (for example, semileptonic) decays detected on both sides of the detector, corresponds to *flavour-to-flavour* transition at the meson level. The equivalence is shown in Table 1.

(X, Y)	Meson Transition
(ℓ^+, ℓ^+)	$\bar{B}^0 \to B^0$
(ℓ^-, ℓ^-)	$B^0 \to \bar{B}^0$
(ℓ^+, ℓ^-)	$\bar{B}^0 \to \bar{B}^0$
(ℓ^-, ℓ^+)	$B^0 \to B^0$

Table 1: *Flavour-to-flavour* transitions.

The first two processes in the Table are conjugated under CP and also under T. The corresponding Kabir asymmetry[6] is, to linear order in the CPT violating δ,

$$A(\ell^+, \ell^+) \approx \frac{4\frac{\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}}{1+4\frac{\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}}, \tag{4.1}$$

which does not depend on time. However, in the exact limit $\Delta\Gamma = 0$, $\mathrm{Re}(\varepsilon)$ vanishes, and this quantity will be zero. For the B_d system, experimental limits on $\mathrm{Re}(\varepsilon)$ are of few parts in a thousand[7] [8].

A second asymmetry arises from the last two processes in Table 1, related by a CP or a CPT transformation,

$$A(\ell^+, \ell^-) \approx -2\frac{\mathrm{Re}\left(\frac{\delta}{1-\varepsilon^2}\right)\sinh\frac{\Delta\Gamma\Delta t}{2} - \mathrm{Im}\left(\frac{\delta}{1-\varepsilon^2}\right)\sin(\Delta m\Delta t)}{\cosh\frac{\Delta\Gamma\Delta t}{2} + \cos(\Delta m\Delta t)}, \tag{4.2}$$

which is an odd function of time. This asymmetry also vanishes unless $\Delta\Gamma \neq 0$. Present limits [7] on $\mathrm{Im}(\delta)$ are at the level of few percent.

4.2 CP-to-flavour genuine asymmetries

Alternative asymmetries can be constructed making use of the CP eigenstates, which can be identified in this system by means of a CP tag. If the first decay product, X, is a CP eigenstate produced along the CP-conserving direction, i.e. the decay is free of CP violation, and Y is a flavour definite channel, then the mesonic transition corresponding to the configuration (X, Y) is of the type *CP-to-flavour*.

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

Table 2: Transitions connected to $(J/\Psi K_S, \ell^+)$.

In Table 2 we show the mesonic transitions, with their related final configurations, connected by genuine symmetry transformations to $B_+ \to B^0$.

Comparing the intensities of the four processes, we may construct three genuine asymmetries, namely $A(\mathrm{CP})$, $A(\mathrm{T})$ and $A(\mathrm{CPT})$ [3].

$$A(\mathrm{CP}) = -2\frac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m\Delta t) + \frac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\frac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\sin^2\left(\frac{\Delta m\Delta t}{2}\right), \tag{4.3}$$

the CP odd asymmetry, contains both T-violating and CPT-violating contributions, which are, respectively, odd and even functions of Δt. This asymmetry corresponds to the "gold plate" decay [9] and has been measured recently [10]. T and CPT violating terms can be separated by constructing other asymmetries.

$$A(\mathrm{T}) = -2\tfrac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m \Delta t)\left[1 - \tfrac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\tfrac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\sin^2\left(\tfrac{\Delta m \Delta t}{2}\right)\right], \tag{4.4}$$

the T asymmetry, needs $\varepsilon \neq 0$, and turns out to be purely odd in Δt in the limit we are considering.

$$A(\mathrm{CPT}) = \tfrac{1-|\varepsilon|^2}{1+|\varepsilon|^2}\tfrac{2\mathrm{Re}(\delta)}{1+|\varepsilon|^2}\frac{\sin^2\left(\frac{\Delta m \Delta t}{2}\right)}{1-2\frac{\mathrm{Im}(\varepsilon)}{1+|\varepsilon|^2}\sin(\Delta m \Delta t)}, \tag{4.5}$$

is the CPT asymmetry. It needs $\delta \neq 0$, and includes both even and odd time dependences.

The above expressions correspond to the limit $\Delta\Gamma = 0$, but, being genuine observables, a possible absorptive part could not induce by itself a non-vanishing asymmetry.

4.3 CP-to-flavour non-genuine asymmetries

The construction of the quantities described in the previous paragraphs requires to tag both B_+ and B_- states, and thus the reconstruction of the experimentally challenging decay $B \to J/\Psi K_L$. Conversely, non-genuine asymmetries offer a possibility to measure the symmetry parameters from the reconstruction of $J/\Psi K_S$ only. But they involve the discrete transformation that we denote Δt, consisting of the exchange in the order of appearance of decay products X and Y, which cannot be associated with any fundamental symmetry.

(X, Y)	Transition	Transformation
$(J/\Psi K_S, \ell^-)$	$B_+ \to B^0$	CP
$(\ell^+, J/\Psi K_S)$	$\bar{B}^0 \to B_-$	Δt
$(\ell^-, J/\Psi K_S)$	$\bar{B}^0 \to B_-$	Δt+CP

Table 3: Final configurations with only $J/\Psi K_S$.

Table 3 shows the different transitions we may study from such final states. Besides the genuine CP asymmetry, there are two new quantities that can be constructed from the comparison between $(J/\Psi K_S, \ell^+)$ and the processes in the table. In the exact limit $\Delta\Gamma = 0$, Δt and T operations are found to become equivalent, so that the temporal asymmetry satisfies $A(\Delta t) \equiv A(\ell^+, J/\Psi K_S) = A(\mathrm{T})$ and moreover $A(\mathrm{CP}\Delta t) \equiv A(\ell^-, J/\Psi K_S) = A(\mathrm{CPT})$. Since this result holds for $\Delta\Gamma \approx 0$, it is expected to be valid for the B_d system, but not for B_s and even less for K. The asymmetries $A(\Delta t)$ and $A(\mathrm{CP}\Delta t)$ are non-genuine, and the presence of $\Delta\Gamma \neq 0$ may induce non-vanishing values for them, even if there is no true T or CPT violation. These fake effects, nevertheless, can be calculated and are thus controllable.

5. CP, T, CPT indirect violation reach at asymmetric B-Factories

The asymmetries described in the previous section can be already constructed from the current data taken at Asymmetric B-Factories [10]. The experimental analysis is based on a simultaneous unbinned likelihood fit of the flavour and CP intensities $I(X, Y; \Delta t)$, together with the $B^0/\bar{B}^0$ mistag rates and the Δt resolution function. The coefficients of terms with different temporal dependencies contain the information on the symmetry parameters.

From a simulation study, estimations on the reachable statistical precision for the relevant parameters have been calculated for $\approx$60 fb^{-1} (assuming yields from Ref. [10]) and are shown in Table 4.

Parameter	(Generated)	Statistical error
$\frac{\mathrm{Re}(\delta)}{1+\|\varepsilon\|^2}$	(0)	0.09
$\frac{\mathrm{Re}(\varepsilon)}{1+\|\varepsilon\|^2}$	(0)	0.007
$\frac{\Delta\Gamma}{\Gamma}$	(0)	0.07
$\frac{\mathrm{Im}(\varepsilon)}{1+\|\varepsilon\|^2}$	(0.35)	0.04
Δm	(0.472 ps^{-1})	0.009

Table 4: Projections for 60 fb^{-1}.

6. Conclusions

We have shown how the two complex rephasing invariant parameters ε and δ describe CP, T and CPT indirect violation in $B^0 - \bar{B}^0$. In the exact limit $\Delta\Gamma = 0$ the number of parameters is reduced to Im(ε) and Re(δ). Observables based on *flavour-to-flavour* transitions are sensitive to Re(ε), but need $\Delta\Gamma \neq 0$, and thus are not promising in B-factories. Conversely, these experimental facilities allow the construction of new asymmetries based on combination of flavour and CP tags.

First estimations on the sensitivity reachable on B-factories have been presented. This data will be crucial to achieve the separation of the two ingredients: on one hand CP and T violation, described by ε, and on the other CP and CPT violation, given by δ.

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