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, $\varepsilon$ and $\delta$. 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 \textit{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 $\varepsilon$ and $\delta$ 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, \textit{flavour-to-flavour} and both genuine and non-genuine \textit{CP-to-flavour} asymmetries. Finally, in section 5 the first estimates on the reach and sensitivity of the experimental analysis are given.

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 $|B_{1(2)}\rangle = \sqrt{\frac{1}{1+|\varepsilon_{1(2)}|^2}} [ |B_+\rangle + \varepsilon_{1(2)} |B_-\rangle ]$.

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 $\varepsilon$ and $\delta$:

- CPT invariance requires\footnote{Here $H_{ij}$, $M_{ij}$, and so on, represent the matrix elements in the flavour basis $B^0-\bar{B}^0$.} $H_{11} = H_{22}$, so that $\delta = 0$, with no restriction on $\varepsilon$;

- T invariance imposes $\text{Im}(M_{12} \text{CP}^*_{12}) = \text{Im}(\Gamma_{12} \text{CP}^*_{12}) = 0$, 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 \( \text{Re}(\varepsilon) \) and \( \text{Im}(\delta) \) vanish. Then \( \text{Im}(\varepsilon) \neq 0 \) is a proof of both CP and T violation, and \( \text{Re}(\delta) \neq 0 \) is a proof of CP and CPT violation, but neither \( \text{Re}(\varepsilon) = 0 \) nor \( \text{Im}(\delta) = 0 \) 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 \( e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB \). Charge conjugation together with Bose statistics require the initial state to be

\[
|i> = \frac{1}{\sqrt{2}} \left( |B_0^{0}(\vec{k}), B_0^{0}(\vec{-k})> - |B_0^{0}(\vec{-k}), B_0^{0}(\vec{k})> \right)
\]  

(1)

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

\[
|i> = \frac{1}{\sqrt{2}} \left( |B_+^{0}(\vec{k}), \bar{B}_+^{0}(\vec{-k})> - |\bar{B}_+^{0}(\vec{-k}), B_+^{0}(\vec{k})> \right)
\]

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 \( \Delta t \). In Ref. [4] we described how this determination is possible and unambiguous to \( O(\lambda^3) \), 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.

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 \( (\ell, \ell) \), with flavour definite (for example, semileptonic) decays detected on both sides of the detector, corresponds to \textit{flavour-to-flavour} transition at the meson level. The equivalence is shown in Table 1. The first two processes in the Table are conjugated under CP and also
Table 1: Flavour-to-flavour transitions.

<table>
<thead>
<tr>
<th>(X, Y)</th>
<th>Meson Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ℓ⁺, ℓ⁺)</td>
<td>B₀ → B₀</td>
</tr>
<tr>
<td>(ℓ⁻, ℓ⁻)</td>
<td>B₀ → B₀</td>
</tr>
<tr>
<td>(ℓ⁺, ℓ⁻)</td>
<td>B₀ → B₀</td>
</tr>
<tr>
<td>(ℓ⁻, ℓ⁺)</td>
<td>B₀ → B₀</td>
</tr>
</tbody>
</table>

under T. The corresponding Kabir asymmetry[6] is, to linear order in the CPT violating δ,

\[ A(\ell^+, \ell^+) \approx \frac{\text{Re}(\epsilon)}{1+4\text{Re}(\epsilon)^2}, \]

which does not depend on time. However, in the exact limit ΔΓ = 0, Re(ε) vanishes, and this quantity will be zero. For the B₅ system, experimental limits on Re(ε) 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,

\[ A(\ell^+, \ell^-) \approx -2\frac{\text{Re} \left( \frac{i}{1-i} \right) \sinh \frac{\Delta m \Delta t}{2} - \text{Im} \left( \frac{i}{1-i} \right) \sin(\Delta m \Delta t)}{\cosh \frac{\Delta m \Delta t}{2} + \cos(\Delta m \Delta t)}, \]

which is an odd function of time. This asymmetry also vanishes unless ΔΓ ≠ 0. Present limits [7] on Im(δ) 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.

In Table 2 we show the mesonic transitions, with their related final configurations, connected by genuine symmetry transformations to B⁺ → B₀.

Table 2: Transitions connected to (J/ΨKₛ, ℓ⁺).

<table>
<thead>
<tr>
<th>(X, Y)</th>
<th>Transition</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J/ΨKₛ, ℓ⁻)</td>
<td>B⁺ → B₀</td>
<td>CP</td>
</tr>
<tr>
<td>(ℓ⁻, J/ΨKₗ)</td>
<td>B₀ → B⁺</td>
<td>T</td>
</tr>
<tr>
<td>(ℓ⁺, J/ΨKₗ)</td>
<td>B₀ → B⁺</td>
<td>CPT</td>
</tr>
</tbody>
</table>
Comparing the intensities of the four processes, we may construct three genuine asymmetries, namely $A(\text{CP})$, $A(\text{T})$ and $A(\text{CPT})$ [3].

$$A(\text{CP}) = -2 \frac{\text{Im}(\varepsilon)}{1 + |\varepsilon|^2} \sin(\Delta m \Delta t) + \frac{1 - |\varepsilon|^2}{1 + |\varepsilon|^2} \frac{2 \text{Re}(\varepsilon)}{1 + |\varepsilon|^2} \sin^2(\Delta m \Delta t),$$ \hspace{1cm} (4)

the CP odd asymmetry, contains both T-violating and CPT-violating contributions, which are, respectively, odd and even functions of $\Delta t$. 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.

$$A(\text{T}) = -2 \frac{\text{Im}(\varepsilon)}{1 + |\varepsilon|^2} \sin(\Delta m \Delta t) \left[ 1 - \frac{1 - |\varepsilon|^2}{1 + |\varepsilon|^2} \frac{2 \text{Re}(\varepsilon)}{1 + |\varepsilon|^2} \sin^2(\Delta m \Delta t) \right],$$ \hspace{1cm} (5)

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

$$A(\text{CPT}) = \frac{1 - |\varepsilon|^2}{1 + |\varepsilon|^2} \frac{2 \text{Re}(\varepsilon)}{1 + |\varepsilon|^2} \frac{\sin^2(\Delta m \Delta t)}{1 - 2 \frac{\text{Im}(\varepsilon)}{1 + |\varepsilon|^2} \sin(\Delta m \Delta t)},$$ \hspace{1cm} (6)

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 $\Delta t$, consisting of the exchange in the order of appearance of decay products $X$ and $Y$, which cannot be associated with any fundamental symmetry.

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 $\Delta \Gamma = 0$, $\Delta t$ and T operations are found to become

<table>
<thead>
<tr>
<th>$(X, Y)$</th>
<th>Transition</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(J/\Psi K_S, \ell^-)$</td>
<td>$B_+ \to B^0$</td>
<td>CP</td>
</tr>
<tr>
<td>$(\ell^+, J/\Psi K_S)$</td>
<td>$B^0 \to B_-$</td>
<td>$\Delta t$</td>
</tr>
<tr>
<td>$(\ell^-, J/\Psi K_S)$</td>
<td>$B^0 \to B_-$</td>
<td>$\Delta t + \text{CP}$</td>
</tr>
</tbody>
</table>
equivalent, so that the temporal asymmetry satisfies \( A(\Delta t) \equiv A(\ell^+, J/\Psi K_S) = A(T) \) and moreover \( A(CP\Delta t) \equiv A(\ell^-, J/\Psi K_S) = A(CPT) \). 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 \( A(CP\Delta t) \) 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 \( \Delta t \) resolution function. The coefficients of terms with different temporal dependencies contain the information on the symmetry parameters.

\[
\begin{array}{|l|l|l|}
\hline
\text{Parameter} & \text{(Generated)} & \text{Statistical error} \\
\hline
Re(\delta) & (0) & 0.09 \\
\frac{1}{1+|\varepsilon|^2} & (0) & 0.007 \\
\frac{\Delta \Gamma}{\varepsilon} & (0) & 0.07 \\
\frac{1}{1+|\varepsilon|^2} & (0.35) & 0.04 \\
\Delta m & (0.472 \text{ ps}^{-1}) & 0.009 \\
\hline
\end{array}
\]

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

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

6 Conclusions

We have shown how the two complex rephasing invariant parameters \( \varepsilon \) and \( \delta \) 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 \( \text{Im}(\varepsilon) \) and \( \text{Re}(\delta) \). Observables based on flavour-to-flavour transitions are sensitive to \( \text{Re}(\varepsilon) \), 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 \( \varepsilon \), and on the other CP and CPT
violation, given by \( \delta \).

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References


