Separate T, CP, CPT Asymmetries in Neutral Meson Transitions

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Separate T, CP, CPT Asymmetries in Neutral Meson Transitions

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Abstract. Symmetries, and symmetry breakings, in the laws of physics play a crucial role in fundamental science. Parity and charge conjugation violations prompted the consideration of chiral fields in the construction of the Standard Model, whereas CP-violation needed at least three families of quarks leading to flavour physics. In this lecture I will discuss the conceptual basis and the present experimental results for a direct evidence of separate reversal-in-time T, CP and CPT genuine asymmetries in decaying particles like neutral meson transitions, using quantum entanglement and the decay as a filtering measurement. The eight transitions associated to the flavour-CP eigenstate decay products of entangled neutral mesons have demonstrated with impressive significance a separate evidence of TRV and CPV in B_d-physics, whereas a CPTV asymmetry shows a 2-σ effect interpreted as an upper limit. Novel CPTV observables are discussed for K and B_d transitions. Their observation would lead to a change of paradigm beyond quantum field theory, however there is nothing in quantum mechanics forbidding CPTV. A clean methodology to disentangle CPTV effects in the Hamiltonian dynamics and the $g^2/2$-effect weakening entanglement in a given experiment is discussed.

1. The Fundamental Role of Symmetry Breaking
In everyday life, we observe symmetries of objects, as characteristic features of geometric forms, material objects or biological bodies. In all cases the symmetry is related to their invariance under definite transformations. We say that an object is symmetric if, after a transformation is applied, it remains "invariant". In physics we are interested in the symmetries of the physical laws, and their breakings, which have played a crucial role in the advance of knowledge. Conservation laws lead to regularity and order in the description of physical phenomena even when there is no input from dynamics. In the second half of the XXth century, a conceptual revolution appeared when the requirement of local gauge symmetries was understood as originating the interactions themselves with their charges. The emergence of the Standard Model (SM) $SU(3)_c \times SU(2)_L \times U(1)_Y$ prompted a spectacular development of particle physics with precise experimental results in agreement with theoretical predictions. The symmetry is exact for massless particles only, which is evidently wrong in Nature. This apparent contradistinction was solved by the Brout-Englert-Higgs mechanism [1] of spontaneous breaking of the electroweak gauge symmetry $SU(2)_W \times U(1)_Y$ into $U(1)_{e.m.}$. This
methodology for explaining the origin of mass leaves as a remnant the Higgs boson, discovered [2] at CERN by the ATLAS and CMS Collaborations.

With respect to the discrete symmetries, P, C, CP and T have been observed to be separately broken by weak interactions. Their breakings have had a fundamental imprint in the construction of the SM:

- Parity violation first observed in nuclear beta decay [3] and later, together with the violation of charge conjugation, in charged pion decays [4], led to the V-A theory for charged current weak interactions [5] and the role of chirality as the essential ingredient of requiring different transformation properties under the gauge group for left- and right-handed fermionic fields. The chiral fields are the starting components of the theory in the SM. The electroweak unification [6, 7, 8] culminated with the discovery [9] of neutral current weak interactions by the Gargamelle experiment at CERN.

- CP Violation was unexpectedly discovered in 1964 [10] first in the decay of the long lived neutral kaon K^0 into two pions, a decay forbidden by the conservation law. The proposal to incorporate this breaking into the SM by means of enlarging the particle content of the theory to at least three quark families and using the Cabibbo-Kobayashi-Maskawa Quark Mixing [11, 12] was clearly supported by the discovery and results of CPV in the B_d-system in the B-Factories [13, 14] in 2001. The physical phenomena associated to the existence of several fermion families of quarks and leptons are nowadays included in the so-called flavour physics.

- Time reversal violation is more difficult to be directly observed. Contrary to P, C and CP, reversal-in-time is a transformation which, in the space of physical quantum states, is implemented by an antiunitary operator. This has two important implications: i) there is no conservation law associated to this symmetry; ii) the test of its invariance in a given transition i → f requires its comparison with the f → i transition. We may expect that, according with the CPT theorem [15], T should be violated as well as CP in the systems in which the CP symmetry violation has been observed. However, kaons and B mesons are unstable particles and, as emphasized by Wolfenstein [16] and others, the decay is irreversible and "the T-transform of a decaying state is not a physical state". This NO-GO argument suggests that a direct evidence for TRV is impossible for unstable particles. The bypass to this argument came [17, 18] in 1999 from the strategy of not including explicitly the decay products in the TRV asymmetry and using: i) the decay as a filtering measurement of the projected meson state only; ii) quantum entanglement of the neutral meson system in order to transfer the information from the decaying meson to its (still alive) orthogonal partner; iii) the asymmetry is searched in the time evolution of this last partner Under a deep scrutiny of this conceptual basis by many authors, the first observation [19] of TRV in the time evolution of B_d's was announced in 2012 by the BABAR Collaboration, using the methodology that was previously defined in [20]. Its observation triggered [21, 22] a revisit to the conditions under which the asymmetry becomes a genuine observable of TRV. For the neutral kaon system there is a proposal in the DAPhNE-Factory using entanglement.

- Although P, C, CP and T symmetries have been observed to be separately broken, there is no experimental evidence of CPT Violation. Its observation would imply a change of paradigm to beyond QFT. There is, however, nothing at the level of quantum mechanics which forbids CPTV.

In Section 2 we discuss the implication of antiunitarity for the T and CPT symmetries and the wording, related to physics, for constructing true asymmetries valid for a symmetry test. The state of the art for genuine T, CP, CPT separate asymmetries in B_d transitions is presented in Section 3. Direct measurements of TRV in neutral kaon transitions at KLOE-2 are discussed in Section 4 and the direct tests of CPT in neutral kaons at KLOE-2 in Section 5. For entangled neutral mesons, the possibility of a ω-effect weakening entanglement, due to an ill-defined CPT operator, is analysed in Section 6. Conclusions and outlook are given in Section 7.

2. T and CPT Tests for unstable particles
In quantum mechanics, there is an operator U_{CP} implementing the CP-symmetry acting on the states of the physical system, such that
The operator $U_{\text{CP}}$ is both unitary and self adjoint and so observable with conservation laws: $K_{\text{L}} \rightarrow \pi \pi$ would be a forbidden process and its observation [10] was an undisputable proof of CP violation.

The operator $U_T$ implementing reversal-in-time T symmetry is such that

$$U_T \bar{r} U_T^+ = \bar{r}, \quad U_T \bar{p} U_T^+ = -\bar{p}, \quad U_T \bar{s} U_T^+ = -\bar{s}$$

(2)

By considering the commutator $[r_f, p_f] = i\hbar \delta_{ij} I$ the operator $U_T$ must be antiunitary: unitary for conserving probabilities, antilinear for complex conjugation. Antiunitarity introduces many interesting subtleties between the reference and T-transformed transition amplitudes for $\ i \rightarrow f$

$$S_{i \rightarrow f} \rightarrow \gamma S_{U_i \rightarrow f} U_i$$

(3)

so that T-violation (TRV) means an asymmetry under the interchange of in and out states.

In a similar way, the antiunitary $U_{\text{CPT}}$ operator needs for its test as a symmetry not only the exchange of initial and final states, but also the transformation of particles into the corresponding antiparticles.

It is highly interesting to clarify the language used for asymmetries as a true proof of symmetry breaking:

i) DIRECT evidence of symmetry breaking
   . For CP, violation of the conservation law
   . For All T, CP, CPT $\rightarrow$ comparison between the probabilities for a reference process and its symmetry-transformed in a single experiment
   . NOT by a fit of parameters describing symmetry breaking in a given theoretical framework.

ii) GENUINE asymmetries
   . A set of observables, for each symmetry, in yes-no biunivocal correspondence with symmetry violation.
   . NO fake terms or controlled in the same experiment.

iii) SEPARATE T, CP, CPT asymmetries
   . TRV independent of CPV or CPT invariance.
   . Different information content from different transformed processes.

iv) TRANSITION processes
   . Interest in going beyond "expectation values" of symmetry breaking.
   . In 1st order of perturbation theory in SB, diagonal matrix elements vanish if perturbation is odd under non-perturbed quantum numbers: $< + | - > = < - | + > = 0$.

   Well known examples of this result are the Stark effect in atomic physics or the TRV e. d. m. in particle physics.

   We center the interest in neutral meson transitions of the $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ systems, for which a clear evidence of CPV exists.

   But these particles are unstable and the decay is irreversible. As we have explained before, T and CPT are antiunitary needing however the exchange of initial and final states. As illustrated in a devastating statement by Wolfenstein [16]: "The T-reverse of a decaying state is not a physical state".

   The conceptual basis for bypassing this no-go argument came [17, 18] from not including the decay products in the asymmetry and write it in terms of initial and final meson states.

   In addition, the decay should not be an essential ingredient for getting a non-vanishing value of the asymmetry. In precise terms,
a) Use the observed decay as a quantum filtering measurement of the meson state only. It is given by the orthogonal state to that which is not leading to the decay products.

b) Use quantum entanglement for information transfer from the first decay to the (still alive) orthogonal partner. This tags the preparation of the initial meson state as the non-decay state.

c) The test of the symmetries is made in the time evolution of the living partner FROM THE FIRST TO THE SECOND DECAY.

After a detailed scrutiny of the concept, Wolfenstein stated [23]: "it appears to be a true TRV effect".

3. Separate T, CP, CPT asymmetries in $B_d$ transitions

For unstable particles, the decay products should not be included in the states building the asymmetries for T or CPT. However, these decay products are what we observe. Therefore, the problem is in the preparation and filtering of the appropriate initial and final meson states from the observed two decay channels. For (flavour, CP) eigenstate decay products, the Editors of Rev. Mod. Phys. decided to put "what is T-transformation experimentally" in the cover page of the volume in which the colloquium article [24] was published. This Figure 1 provides the explanation of what has to be measured in order to build a true genuine TRV asymmetry.

![Figure 1.- Experimental T-transformation](image)

The Figure has illustrated the Reference $\bar{B}^0 \rightarrow B_-$ transition, transformed by T into the transition $B_+ \rightarrow \bar{B}^0$. The named neutral meson states $B_+$, $B_-$ correspond to the filtered states by the CP = +, - eigenstate decay products $J/\psi K_s$, $J/\psi K_s$. In a B-Factory operating at the $\Upsilon(4S)$ peak, our initial two-meson state is Einstein-Podolsky-Rosen entangled as

$$|\Psi_0\rangle = \frac{1}{\sqrt{2}} \left( |B_d^0\rangle |\bar{B}_d^0\rangle - |\bar{B}_d^0\rangle |B_d^0\rangle \right) = \frac{1}{\sqrt{2}(p_{LQH} + p_{HQL})} \left( |B_L\rangle |B_H\rangle - |B_H\rangle |B_L\rangle \right),$$

which maintains its antisymmetric entangled character in the Hamiltonian eigenstate basis. This implies the antisymmetric character of the two meson state at all times and for any two independent
linear combinations of entangled $B_d^0$ and $\bar{B}_d^0$. The corresponding evolution before the first decay is therefore trivial for perfect entanglement.

Given a decay "f", the partner meson is tagged by means of the decay amplitudes $A_f$ from $B^0$ and $\bar{A}_f$ from $\bar{B}^0$ as

$$|B_{\sigma f}\rangle = \frac{1}{\sqrt{|A_f|^2 + |\bar{A}_f|^2}} (A_f|B_d^0\rangle - \bar{A}_f|\bar{B}_d^0\rangle)$$  \hspace{1cm} (5)

and the "filtered" state is its orthogonal. The filtering identity establishes the connection between the meson transition probability and the experimental "reduced" Intensity for the pair of decay channels $(f,g)$

$$I(f,g; t) = \frac{|\langle g|^{\bar{T}}|B_{\sigma f}(t)\rangle|^2}{|A_g|^2 + |\bar{A}_g|^2} = \left|\langle B_{\sigma f}|B_{\sigma f}(t)\rangle\right|^2$$  \hspace{1cm} (6)

As seen in (6), there are no fake terms for a proof of symmetry breaking if the ratio of the two decay amplitudes $\bar{A}/A$ is a pure phase. This requirement may be controlled in the same experiment.

How many (Flavour, CP) decay channels we have at our disposal experimentally? 2 Flavours x 2 CP x 2 time-ordering = 8.

These 8 transitions may be grouped in two blocks with extremely important properties. Within each block, the 4 transitions correspond to one reference and the three different transitions transformed from the reference by the T, CP and CPT transformations separately. These amazing properties for (Flavour, CP) eigenstate decay channels of the entangled system of neutral mesons are represented in figure 2, where the time-dependent Intensities of the 8 transitions are organised appropriately in order to make the direct connection of the transitions by the three discrete symmetries apparent. The red (left) and blue (right) blocks connected by time exchange are not connected by the symmetries.

![Figure 2 – Reference transition and Separate T, CP, CPT transformed transitions.](image)

Using quantum mechanics for the time evolution of the two-state $B^0 - \bar{B}^0$ system and no particular Hamiltonian dynamics, each time dependent Intensity has the following general form

$$I(\Delta t) \sim e^{-\Gamma \Delta t}\left\{C_c \cos(\Delta m \Delta t) + S_c \sin(\Delta m \Delta t) + C_h \cosh(\Delta \Gamma \Delta t) + S_h \sinh(\Delta \Gamma \Delta t)\right\}$$  \hspace{1cm} (7)

where the coefficients $C_c$, $S_c$, $C_h$ and $S_h$ depend on the selected transition. Without more dynamical theoretical framework, these coefficients are unknown. From the experiment we can construct asymmetry parameters $\Delta C_c$, $\Delta S_c$ and $\Delta C_h$ (in the $B_s$-system $\Delta I = 0$) for each discrete symmetry T, CP,
CPT. In total, we have 9 asymmetry parameters with different information content within each block. Any non-vanishing value of the 3 asymmetry parameters for each symmetry is a bona-fide genuine proof of the violation of that symmetry.

In Ref. [25] the authors have worked out the explicit effective Hamiltonian dynamics associated to a Weisskopf-Wigner (WW) quantum description [26] of the meson-antimeson system. In this way the 9 asymmetry parameters can be written in terms of the parameters of the Hamiltonian matrix and the decay amplitudes. Two results are worth mentioning:

i) the asymmetries are genuine signals of symmetry breaking, as they should for any dynamics;
ii) the 9 asymmetry parameters appear with different information content.

Using data from the BABAR analysis [19], in which the intensities (7) were normalised by dividing by $C_h$ with $\Phi \Gamma = 0$, the authors of [25] have re-derived the 9 asymmetry parameters with some mild additional information. The resulting TRV and CPV asymmetries give the result

$$\Delta S^T_c = -0.687 \pm 0.020; \quad \Delta S^{CP}_c = -0.680 \pm 0.021$$

(8)

These results constitute an impressive separate evidence of TRV and CPV. We emphasize that they are independent results and TRV is established without any assumption on either CPV or CPT invariance.

The analysis performed assuming perfect entanglement of the neutral meson system in which the two-body state is antisymmetric under the permutation exchange of the two mesons, has also been used to extract the CPTV asymmetry parameters. The unique antisymmetric state remains unaltered under the time evolution of the entangled system before the first decay, even with mixing under these conditions, given the time ordered (f, g) decays, the reversed time ordering (g, f) decays satisfy the exchange symmetry conditions

$$C_h(f,g) = C_h(g,f); \quad C_c(f,g) = C_c(g,f); \quad S_c(f,g) = -S_c(g,f)$$

(9)

Notice that the exchange symmetry has nothing to do with the discrete symmetries T, CP, CPT associated to the dynamics of the system. As a consequence, one has to consider the measurements associated with (f, g) and (g, f) decays as two independent experimental processes measuring the same properties, once equations (9) are imposed. The CPTV asymmetry is generated in the WW approach by the $\theta$ parameter in the diagonal Hamiltonian matrix elements distinguishing particle and antiparticle properties. The correlated fit to $\text{Re}(\theta)$ and $\text{Im}(\theta)$ is presented [25] in figure 3

![Figure 3 – Correlated fit to the CPTV $\text{Re}(\theta)$ and $\text{Im}(\theta)$](image)

and gives an intriguing 2$\sigma$ effect for CPTV in $\text{Re}(\theta)$.

Under an ill-defined CPT operator expected in models of quantum gravity, the perfect entanglement can be weakened [27] by the presence of an $\omega$-effect associated to the "wrong" exchange
symmetry of the neutral meson and antimeson. Equations (9) are no longer valid and their violation would then be a signal of this new form of CPT breaking.

4. Time reversal violation in neutral Kaon transitions

Similarly to the $B^0 - \bar{B}^0$ system, EPR correlations at a $\Phi$ Factory can be exploited to study $T$-conjugated transitions between $K^0, \bar{K}^0$ states and the orthogonal $K_+, K_-$ states filtered by CP eigenstate decay products

$$\begin{align*}
|i\rangle &= \frac{1}{\sqrt{2}} \left[ K^0(\bar{p})|K^0(-\bar{p})\rangle - |\bar{K}^0(p)|K^0(-\bar{p})\rangle \right] \\
&= \frac{1}{\sqrt{2}} \left[ K_+(\bar{p})|K_+(-\bar{p})\rangle - |K_-(\bar{p})|K_-(-\bar{p})\rangle \right]
\end{align*}$$

(10)

Using the decays as filtering measurements of the meson states and entanglement for the preparation of the living partner initial state, we identify the reference process, for example $K^0 \rightarrow K_-$

![Figure 4 - Neutral Kaon transition $K^0 \rightarrow K_-$ filtered by the $l^- \rightarrow \pi^0$ decay first, $3\pi^0$ decay later](image)

For this reference, the $T$-conjugated process is $K_+ \rightarrow K^0$, separated from the CP conjugated $R^0 \rightarrow K_-$ and the CPT-conjugated $K_- \rightarrow R^0$. The $T$-conjugated process is associated to the time-ordered $2\pi$ decay first, $l^- \rightarrow \pi^0$ decay later

![Figure 5 - The Reversal-in-Time Neutral Kaon transition $K_+ \rightarrow K^0$](image)

For a $T$-symmetry test one has a priori 4 possible comparisons of transitions as given in Table 1

| T symmetry test |
|-----------------|
| **Reference**   | **Decay products** |
| $K^0 \rightarrow K_-$ | $(\ell^-, \pi^0 \pi^0 \pi^0)$ |
| $K_+ \rightarrow K^0$ | $(\pi^0 \pi^0 \pi^0, \ell^+)$ |
| $\bar{K}^0 \rightarrow K_+$ | $(\ell^+, \pi \pi)$ |
| $K_- \rightarrow K^0$ | $(\pi \pi, \ell^+)$ |

| $T$-conjugate | **Transition** | **Decay products** |
|----------------|-----------------|
| $K_+ \rightarrow K^0$ | $(\ell^-, \pi \pi)$ |
| $K^0 \rightarrow K_+$ | $(\pi^0 \pi^0 \pi^0, \ell^-)$ |
| $\bar{K}^0 \rightarrow K_-$ | $(\ell^+, \pi \pi)$ |
| $K_- \rightarrow K^0$ | $(\pi \pi, \ell^-)$ |

One can then define [28] the following ratios of time dependent probabilities
Any deviation from $R = 1$ constitutes a direct evidence of a violation of T-symmetry.

These theoretical ratios for meson state transitions can be connected to experimental ratios of intensities for pairs of decay channels as

$$
R_1(\Delta t) = P[K^o(0) \to K^-(\Delta t)] / P[K^+(0) \to K^o(\Delta t)],
$$

$$
R_2(\Delta t) = P[K^o(0) \to K^+(\Delta t)] / P[K^+(0) \to K^0(\Delta t)],
$$

$$
R_3(\Delta t) = P[K^o(0) \to K^-(\Delta t)] / P[K^-(0) \to K^0(\Delta t)],
$$

$$
R_4(\Delta t) = P[K^0(0) \to K^-(\Delta t)] / P[K^-(0) \to K^0(\Delta t)].
$$

(11)

where the co-factors of equation (12) are related to the corresponding branching ratios. In practice, one has two measurable ratios with the two time-orderings either $\Phi_t > 0$ or $\Phi_t < 0$, due to the inverse connections

$$
R_2^{\exp}(\Delta t) = \frac{1}{R_1^{\exp}(\Delta t)} = \frac{1}{R_3(\Delta t)} \times \frac{C(\ell^-, \pi^0)}{C(\ell^+, 3\pi^0)}
$$

$$
R_4^{\exp}(\Delta t) = \frac{1}{R_1^{\exp}(\Delta t)} = \frac{1}{R_3(\Delta t)} \times \frac{C(\ell^+, \pi^0)}{C(\ell^-, 3\pi^0)}.
$$

(13)

In figures 6 we give [28] the Standard Model expectations for the two experimental ratios $R_2^{\exp}$ and $R_4^{\exp}$, in arbitrary units, as function of $\Phi_t$ for the two time orderings

![Figure 6](image)

Figure 6 – The experimental ratios $R_2^{\exp}$ (left) and $R_4^{\exp}$ (right) for TRV expected in the Standard Model

One reaches the conclusion that this T-test could be feasible in KLOE-2 at DAPHNE with a luminosity of about 10 fb$^{-1}$.

5. Direct test of CPT in neutral kaon transitions

In theories beyond the quantum field theory paradigm, the CPT-Theorem may be not applicable and, in fact, CPT breaking appears in quantum gravity models. It would be of highest interest to construct explicit predictive theories incorporating CPT violation and phenomenological models, as a guide, to be tested by experiments.

The most immediate consequences of CPT invariance are the equality of masses, lifetimes and absolute values of charges and magnetic moments for a particle and its antiparticle. The neutral meson
systems offer unique possibilities to test CPT invariance. Taking as figure of merit the fractional difference between the masses of a particle and its antiparticle, the best CPT Violation limits are

\[
\begin{align*}
\left| \frac{m_{K^0} - m_{\bar{K}^0}}{m_K} \right| &< 10^{-18} \quad [29] \\
\left| \frac{m_{B^0} - m_{\bar{B}^0}}{m_B} \right| &< 10^{-14} \quad [25] \\
\left| \frac{m_p - m_{\bar{p}}}{m_p} \right| &< 8 \cdot 10^{-10} \quad [30]
\end{align*}
\] (14)

In the following we discuss the CPT test at CPLEAR [29] from the time evolution of neutral kaons using the semileptonic decay charge asymmetry. The initial neutral kaon state is tagged at CPLEAR as the flavour state as indicated in figure 7.

![Figure 7](image.png)

Figure 7.- Semileptonic decay from $K^0_s$ assuming the $\mathcal{F}S = \mathcal{F}Q$ rule

From the four time-dependent semileptonic decay rates, including violations of the $\mathcal{F}S = \mathcal{F}Q$ rule, one may construct the asymmetry defined in equation (15)

\[
\begin{align*}
A_\beta (\tau) &= \frac{\bar{R}_+ (\tau) - \alpha \bar{R}_- (\tau)}{\bar{R}_+ (\tau) + \alpha \bar{R}_- (\tau)} + \frac{\bar{R}_- (\tau) - \alpha \bar{R}_+ (\tau)}{\bar{R}_- (\tau) + \alpha \bar{R}_+ (\tau)} \\
R_+ (\tau) &= R \left( K^0_{t=0} \rightarrow (e^{+}(\pi^{-}(-))_{\tau}) \right) \\
R_- (\tau) &= R \left( \bar{K}^0_{t=0} \rightarrow (e^{-}(\pi^{+}(-))_{\tau}) \right) \\
\alpha &= 1 + 4 \Re \varepsilon_L
\end{align*}
\] (15)

The experimental results for this time-dependent asymmetry are shown in figure 8.

![Figure 8](image.png)

Figure 8.- CPLEAR time-dependent semileptonic decay charge asymmetry
In the time region above the interference effects $\tau >> \tau_S$, the asymmetry becomes a constant which disentangles the "$\delta$" CPTV contribution to the diagonal matrix elements of the effective Hamiltonian in the Weisskopf-Wigner approach \[26\] and it is given by

$$A_\delta (\tau >> \tau_S) = 8R\delta$$

(16)

The fit \[29\] to the experimental data gives the value

$$R\delta = (0.30 \pm 0.33 \pm 0.06) \cdot 10^{-3}$$

(17)

At the $\Phi$-Factory DAPHNE, the entanglement between the two neutral kaon states induced by their antisymmetric exchange allows a separate selection of observable asymmetries from either $K_L$ or $K_S$ states. The charge asymmetry from these states is given by

$$A_{S,L} = \frac{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) - \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) + \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})} = 2 \left[ \text{Re} \left( \epsilon_K \right) \pm \text{Re} \left( \delta_K \right) - \text{Re} \left( \gamma \right) \right]$$

(18)

where, in addition to the CPV and CPTV parameters in the Hamiltonian matrix, a possible CPTV in the flavour decay amplitude of Figure 7, parameterised by "$\gamma$", is included. As seen, the difference between these two charge asymmetries $A_S - A_L$ is able to disentangle CPTV effects in the diagonal matrix elements of the mass matrix.

The value of $A_L$ is well known from hadronic machines, with the best precise result from the KTeV Collaboration \[31\]

$$A_L = (3.332 \pm 0.058_{\text{stat}} \pm 0.047_{\text{syst}}) \cdot 10^{-3}$$

(19)

The measurement of $A_S$ was undertaken in the first period of the KLOE experiment with the result \[32\]

$$A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \cdot 10^{-3}$$

(20)

An important improvement of this result is expected at KLOE-2.

EPR correlations at a $\Phi$-Factory can also be exploited to study CPT-conjugated transitions involving flavour $K^0, \bar{K}^0$ states and the orthogonal $K_+, K_-$ states filtered by CP eigenstate decay products.

Using the decays as filtering measurements of the meson states and entanglement for the preparation of the living partner initial state, we identify the reference process, for example $K^0 \rightarrow K_-$ as in figure 4.

For this reference, the CPT-conjugated process is $K_- \rightarrow \bar{K}^0$, separated out from the CP-conjugated $\bar{K}^0 \rightarrow K_-$ and the T-conjugated $K_- \rightarrow K^0$. The CPT-conjugated process is associated to the time-ordered decay channels.

![Figure 9](image-url)

Figure 9. The CPT-transformed $K_- \rightarrow \bar{K}^0$ is associated to the $2\pi$ decay first, the $\gamma$ decay later.
For a CPT-symmetry test one has a priori 4 possible comparisons of transitions as given in table 2.

| Reference | Decay products | CPT-conjugate | Transition | Decay products |
|-----------|----------------|---------------|------------|----------------|
| $K^0 \rightarrow K^+$ | ($\ell^-, \pi \pi$) | $K^+ \rightarrow \bar{K}^0$ | ($3\pi^0, \ell^-$) |
| $K^0 \rightarrow K^-$ | ($\ell^-, 3\pi^0$) | $K^- \rightarrow \bar{K}^0$ | ($\pi \pi, \ell^-$) |
| $\bar{K}^0 \rightarrow K^+$ | ($\ell^+, \pi \pi$) | $K^+ \rightarrow K^0$ | ($3\pi^0, \ell^+$) |
| $\bar{K}^0 \rightarrow K^-$ | ($\ell^+, 3\pi^0$) | $K^- \rightarrow K^0$ | ($\pi \pi, \ell^+$) |

One can then define [33] the following ratios of time dependent probabilities

$$R_{1,\text{CPT}}(\Delta t) = \frac{P[K_+(0) \rightarrow \bar{K}^0(\Delta t)]}{P[K^0(0) \rightarrow K_+(\Delta t)]}$$

$$R_{2,\text{CPT}}(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]}$$

$$R_{3,\text{CPT}}(\Delta t) = \frac{P[K_+(0) \rightarrow K^0(\Delta t)]}{P[\bar{K}^0(0) \rightarrow K_+(\Delta t)]}$$

$$R_{4,\text{CPT}}(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]}$$

Any deviation from $R_{\text{CPT}} = 1$ constitutes a direct evidence of a violation of CPT-symmetry.

These theoretical ratios for meson state transitions can be connected to experimental ratios of intensities for pairs of decay channels as indicated in Table 2.

For visualisation purposes, we plot [33] in figure 10 these four ratios for CPT-Violation using a “$\delta$” parameter in the Hamiltonian matrix with values $\text{Re}(\delta)=3.3 \cdot 10^{-4}$ and $\text{Im}(\delta) = 1.6 \cdot 10^{-5}$ (continous line -) and $\text{Im}(\delta) = 0$ (broken line --).

![Figure 10](image)

Figure 10.- The ratios of transition probabilities (20) between a Reference and its CPT- transformed for values of the $\delta$ parameter as explained in the text.

For the most interesting $\Phi t$ region larger than the short lifetime of $K_S$, $\tau_S$, one has

$$R_{2,\text{CPT}}(\Delta t > \tau_S) = 1 - 4\text{Re}(\delta)$$

$$R_{4,\text{CPT}}(\Delta t > \tau_S) = 1 + 4\text{Re}(\delta)$$

One cannot imagine a better clearcut test of CPT symmetry in transitions as the one shown in equations (22). This test is feasible at KLOE-2.
6. The \( \omega \)-effect

In presence of decoherence and CPT breaking induced by quantum gravity effects, the CPT operator is "ill-defined" and the definition of the particle-antiparticle states could be modified. This in turn could induce a weakening of the entanglement \[27\] imposed by Bose statistics as an EPR correlation

\[
|\psi\rangle = c_1 |(K^+)(K^-) - (K^-)(K^+)angle + c_2 |(K^+)(K^-) + (K^-)(K^+)angle
\]

(23)

In some microscopic models of space-time foam \[34\] with stochastic fluctuations of defect recoils in the propagation of particles, the magnitude of the \( \omega \)-parameter in equation (23) can reach values \( 10^{-4} \) - \( 10^{-5} \).

The maximum sensitivity to \( \omega \) is expected for a symmetric decay pair of the entangled state \( f_1 = f_2 = \pi^+ \pi^- \), which is CP-violating from the dominant antisymmetric state of equation (23). As a consequence, one gets a fantastic enhancement of the \( \omega \)-effect from the "wrong" component in equation (23) as \( \omega/\epsilon \), where \( \epsilon \) is the small CPV parameter in K-physics. In figure 11 we plot the expected double decay rate time-dependent Intensities for vanishing and non-vanishing values of \( \omega \) accessible at KLOE-2.

![Figure 11](image1)

**Figure 11.** Time-dependent intensity for the symmetric pair of decay channels \((\pi^+ \pi^-, \pi^- \pi^-)\) for vanishing and non-vanishing \( \omega \)-parameter.

Previous measurement of the \( \omega \)-effect by KLOE \[35\] for analysed data with 1.5 fb-1 led to the limits represented in figure 12.

![Figure 12](image2)

**Figure 12.** Correlated limits for Re (\( \omega \)) and Im (\( \omega \)) from KLOE

Explicitly the values for these limits are
where one notices the ample room for statistical improvement.

In the B-system the best limits for $\text{Re} \left( \frac{\omega}{g_{22}/g_{27}} \right)$ come from the equal-sign dilepton intensity, which again should vanish from the allowed component ($\omega = 0$) of the entangled state at equal decay times. The analysis of this intensity in terms of $\frac{\omega}{g_{22}}$ led [36] to the limit

$$-0.0084 \leq \text{Re} \left( \frac{\omega}{g_{22}/g_{27}} \right) \leq 0.0100 \quad (25)$$

at 95 % CL.

Recently a novel signal for separating both $\text{Re}$ and $\text{Im} \left( \frac{\omega}{g_{22}/g_{27}} \right)$ in B-physics was found [37] when (flavour, CP) eigenstate decay channels are used from the entangled state (23). The presence of $\omega \neq 0$ violates the $(f, g) \leftrightarrow (g, f)$ connection between the two time-orderings imposed by antisymmetry, as given in equation (9) of Section 3. As a consequence, the authors of [37] have proposed the measurements of

$$C(f, g) - C(g, f); S(f, g) + S(g, f) \quad (26)$$

to look for non-vanishing values of these quantities as a signal of $\omega \neq 0$. The three figures 13 demonstrate the non-correlation of the values of the CPTV $\theta$ term due to the dynamical Violation in the Hamiltonian $[\text{CPT}, H] \neq 0$ and the $\omega$-parameter weakening entanglement of the neutral meson pair, with the results obtained by means of a careful analysis of experimental data from BABAR [19].

![Figure 13.- Correlated values of Re (ω)-Imω and Re (θ)─Im (θ) and intriguing non-correlated Re (θ)-Im (ω) 2σ values](image)

The present result $\text{Im} \left( \frac{\omega}{g_{22}/g_{27}} \right) = 0.06 \pm 0.03$ is the first measurement of this parameter in B-physics and an important improvement is expected with the sensitivity reachable at BELLE II.

7. Conclusions and Outlook

The breaking of the discrete symmetries has played a fundamental role in the understanding of the laws of physics. It emphasizes the importance of looking for genuine asymmetries of separate T, CP, CPT in transitions of neutral meson states. In dealing with the antiunitary T and CPT, entanglement is needed for bypassing the decay irreversibility.
The main concept involves the connection between the theoretical transition probabilities for meson states and the experimental intensities for the double decay rate of entangled states. The flavour-CP transitions in entangled $B^0 - \bar{B}^0$ have demonstrated genuine separate asymmetries for T and CP with high statistical significance and, with a 2σ tension, compatibility with CPT invariance. This effect in the diagonal matrix elements of the mass matrix induces a CPTV asymmetry that can be further explored at BELLE II and, being CPV too, in the unconventional "cosine" term of the intensities at LHCb. KLOE-2 at the upgraded DAPHNE is in the best condition to accomplish a complete program of genuine separate asymmetries for T, CP and CPT in flavour-CP transitions for $K^0 - \bar{K}^0$. Possible fake effects can be controlled within the same experiment.

The measurement of the semileptonic charge asymmetry from $K_S^0$ by KLOE-2 allows, by comparison with the known semileptonic charge asymmetry from $K_L^0$, the separation of CPTV in the mass matrix of $K^0 - \bar{K}^0$.

The best way to study the $\omega$-effect weakening entanglement due to an ill-defined CPT operator is the CP-violating correlated decay ($\pi^+ \pi^-$, $\pi^+ \pi^-$) at KLOE-2. In the B-system, BELLE II can address the studies of the equal-sign lepton charge Intensity and the violation of the connection between the Intensity coefficients for the double decay rates of the time-ordered (flavour, CP) and (CP, flavour) channels as a bona-fide signal of the $\omega$-effect. All these measurement have a distinctive signature from the dynamical CPTV in the effective Hamiltonian for the neutral meson system.

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