$\mathcal{T}$ symmetry invariance tests in neutral meson decays

Adrian Bevan, Gianluca Inguglia, Michele Zoccali

Abstract:

The laws of quantum physics can be studied under the mathematical $\mathcal{T}$ operation that inverts the direction of time. Strong and electromagnetic forces are known to be invariant under temporal inversion, however the weak force is not. The *BaBar* experiment recently exploited the quantum-correlated production of neutral *B* mesons to show that $\mathcal{T}$ is a broken symmetry for weak decays. Here we show that it is possible to perform a wide range of tests of quark flavour changing processes, described by the weak interaction, under the $\mathcal{T}$ symmetry in order to validate the Kobayashi-Maskawa mechanism and the Standard Model of particle physics, and note the existence of an exactly orthonormal $\mathcal{CP}$ filter basis.

Introduction: Last year *BaBar* published an experimental result showing $\mathcal{T}$ non-invariance in the decay of entangled B mesons into flavour filter and chamonium+$K_{L/S}$ $\mathcal{CP}$ filter eigenstate decays [1]. The method used [2] and experimental results are briefly summarised, to set the context of a wider range of tests of the Koybayashi-Maskawa mechanism that can be performed under the $\mathcal{T}$ symmetry, by including studies of charm mesons, and moving from an approximately orthonormal $\mathcal{CP}$ conjugate basis pair of decays, to exactly orthonormal pairs. The asymmetry tested is:

$$A_T = \frac{P(|i\rangle \to |f\rangle) - P(|f\rangle \to |i\rangle)}{P(|i\rangle \to |f\rangle) + P(|f\rangle \to |i\rangle)}$$

i.e. one compares a process with the $\mathcal{T}$ inverted one.

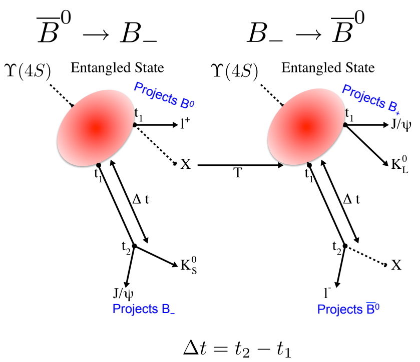
The method [2] in brief: In order to test the $\mathcal{T}$ symmetry independently of $\mathcal{CP}$ one has to use two different orthonormal filter bases with a entangled neutral meson-pair system.

$$\Phi = \frac{1}{\sqrt{2}}\left(P_1^0 \overline{P}_2^0 - \overline{P}_1^0 P_2^0\right)$$

For convenience one can use flavour and $\mathcal{CP}$ filters:

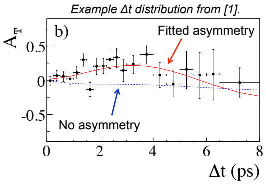
- Flavour filters: flavour specific decays, e.g. $B^0 \to Xl^{\pm}\nu$, where the lepton charge in this case tags the flavour of the neutral B meson, and the orthonormal basis consists of the B^0 and B^0 decay into the flavour specific states.

- $\mathcal{CP}$ filters: Orthonormal basis consisting of a $\mathcal{CP}$ even and a $\mathcal{CP}$ odd decay mode. For example a neutral B meson decaying into J/ψ K_L and J/ψ K_S provides such a basis (approximately).



- The clock starts ticking when the entangled state collapses.
- Four time asymmetries are constructed from t=0, according to the time-and filter-type ordering possibilities of the decaying entangled states.

Example Δt distribution from [1].



The BaBar result [1] in brief: A stark 14 sigma effect was observed. The measured observables $\Delta S_T^{\pm}$ are related to CKM angles, in this case the angle β = ϕ_1.

For charmonium + K^0 CP filters:

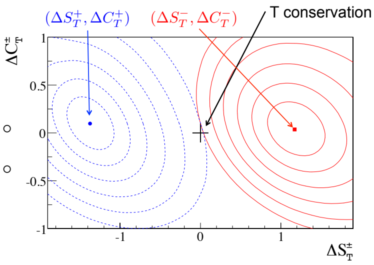
$$\Delta S^{\pm} = \mp 2\sin 2\beta \simeq \mp 1.4$$

and the *BaBar* result gives:

$$\Delta S^- \quad : \quad \beta_{SM} = (17.9^{+3.9}_{-3.6})^\circ$$

$$\Delta S^+ \quad : \quad \beta_{SM} = (21.6^{+3.2}_{-2.9})^\circ$$

which is compatible with SM expectations.



Are there exactly orthonormal CP filter bases?: The $\mathcal{CP}$ filter basis pair of decays that differ by a neutral K meson, a K_S ($\mathcal{CP}$ = −1) or K_L ($\mathcal{CP}$ = +1) are approximate, as can be seen when writing the kaon admixtures in terms of their quark content. This raises two questions:

- Are there other (exact) $\mathcal{CP}$ filter bases that could of of interest for $\mathcal{T}$ symmetry invariance tests?

The answers to this question is *yes*. The key points are listed below:

- The transversity basis for the set of pseudoscalar decays to two vector mesons provides a natural way to experimentally distinguish between $\mathcal{CP}$ filter basis pair (+1 and −1 states) as there are three parts:

$$CP - even\ longitudinal: \quad A_L = A_0$$

$$CP - even\ transverse: \quad A_{||} = \frac{A_{+1} + A_{-1}}{\sqrt{2}}$$

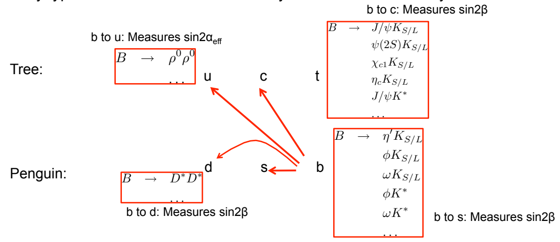
$$CP - odd\ transverse: \quad A_{\perp} = \frac{A_{+1} - A_{-1}}{\sqrt{2}}$$

- Experimentally it is possible to distinguish between these three amplitudes using an angular analysis of the final state, where each amplitude has a distinct signature as a function of the transversity angles.
- A long list of possible B and D decays to VV final states can be thought of as viable to study, including:

$$B \to \rho\rho, \phi\rho, \phi K^*, \omega K^*, D^*D^*, K^*K^*$$

$$D \to \rho\rho, \phi\rho$$

Other modes to study: The focus so far has been to use the charmonium + $K_{L/S}$ $\mathcal{CP}$ filter decays to test $\mathcal{T}$. However there are a number of other modes that can be studied in B and D decays using this methodology that include $\mathcal{CP}$ filter bases of the $K_{L/S}$ type and of a VV decay type. Here we note a few B decay variants and what they measure:



Together these provide a set of tests of the following quark transitions under the $\mathcal{T}$ symmetry: $b \to u, d, s, c$ (covering both tree and loop diagrams).

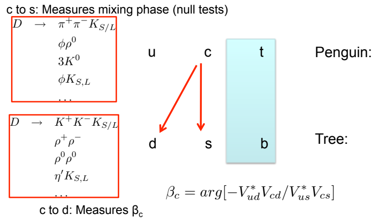
We estimate the following precisions attainable for these asymmetries – note there is insufficient experimental data to make sensible estimates for some decays.

$\mathcal{CP}$ *filters*	$\sigma(\Delta S^{\pm})$ [*B Factory*]	$\sigma(\Delta S^{\pm})$ [*Belle II*]
$\eta' K^0$	0.56	0.08
ϕK^*	1.14	0.13
ϕK^0	1.84	0.17
ωK^0	1.95	0.22
D^*D^*	2.0	0.29

- For these modes Belle II should be able to test $\mathcal{T}$ symmetry invariance and observe $\mathcal{T}$ violation at the 5 sigma level for SM effects.

- Similar measurements are possible at an asymmetric energy tau-charm factory.

- Ignoring penguin contributions one can test $\mathcal{T}$ symmetry invariance mediated by the phase of charm mixing and through interference between mixing and decay amplitudes.



Conclusion:

Last year *BaBar* observed $\mathcal{T}$ violation using entangled pairs of B mesons decaying into pairs of flavour and $\mathcal{CP}$ filters, where the $\mathcal{CP}$ filters were based on tree level B decays to charmonium + $K_{L/S}$ final states. Here we note that a programme of similar measurements can be performed to study loop transitions, and a parallel set of measurements could be performed in charm decays at an asymmetric energy charm factory operating at the centre of mass energy of the ψ(3770). In addition the $K_{L/S}$ $\mathcal{CP}$ filter basis is approximate, and one can utilise a transversity analysis of B and D decays to two vector particle final states to obtain an exactly orthonormal $\mathcal{CP}$ filter basis. Together the set of possible measurements at tree and loop level covers all kinematically accessible b and c quark flavour transitions in the SM, i.e. one can over-constrain the KM mechanism in terms of the antiunitary $\mathcal{T}$ operator by performing the measurements proposed here [3].

References:

[1] J. P. Lees et al. [BABAR Collaboration], Phys. Rev. Lett. **109**, 211801 (2012).
[2] M. C. Banuls and J. Bernabeu, Phys. Lett. B **464**, 117 (1999); M. C. Banuls and J. Bernabeu, Nucl. Phys. B **590**, 19 (2000).
[3] A. Bevan, G. Inguglia, M. Zoccali, arXiv:1302.4191.

Queen Mary University of London