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Time reversal violation for entangled neutral mesons

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Abstract. A direct evidence for Time Reversal Violation (TRV) means an experiment that, considered by itself, clearly shows TRV independent of, and unconnected to, the results for CP Violation. No existing result before the recent BABAR experiment with entangled neutral B mesons had demonstrated TRV in this sense. There is a unique opportunity for a search of TRV with unstable particles thanks to the Einstein-Podolsky-Rosen (EPR) Entanglement between the two neutral mesons in B, and PHI, Factories. The two quantum effects of the first decay as a filtering measurement and the transfer of information to the still living partner allow performing a genuine TRV asymmetry with the exchange of "in" and "out" states. With four independent TRV asymmetries, BABAR observes a large deviation of T-invariance with a statistical significance of 14 standard deviations, far more than needed to declare the result as a discovery. This is the first direct observation of TRV in the time evolution of any system.

1. Introduction

I was asked by the organizers to report about the recent discovery of Time Reversal Violation (TRV) in the Entangled Neutral B-system and the conceptual basis for such observation. This subject has had an important impact in the scientific community and media. Under the title "The arrow of time", The Economist devoted its central page on Science and Technology in the number of September 1st 2012 [1] to TRV, as shown in figure 1. In particle physics one expects that not all processes run in the same

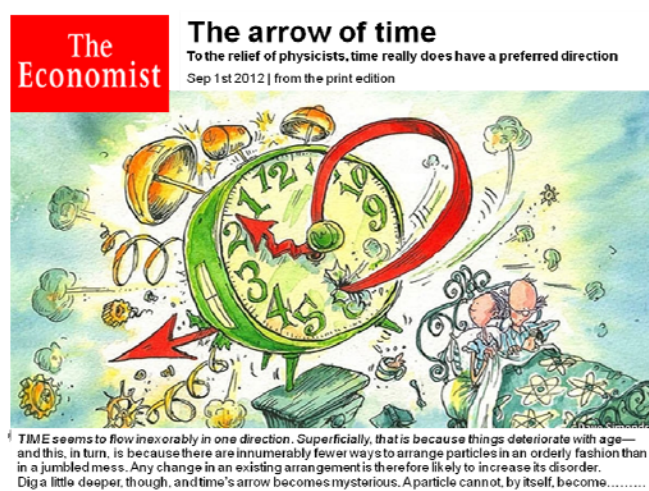


Figure 1. Illustration of “The Economist” for discussing the observed asymmetry for motion reversal of a neutral B-meson in a transition between two definite states: going forwards is thus not the same as going backwards.

way forwards in time as they do backwards. The direct observation of this phenomenon by the BABAR Collaboration was reported [2] in November 2012 with a high significance result, and the journals Nature [3] and Physics Today [4] presented it stating, as shown in figures 2 and 3, that

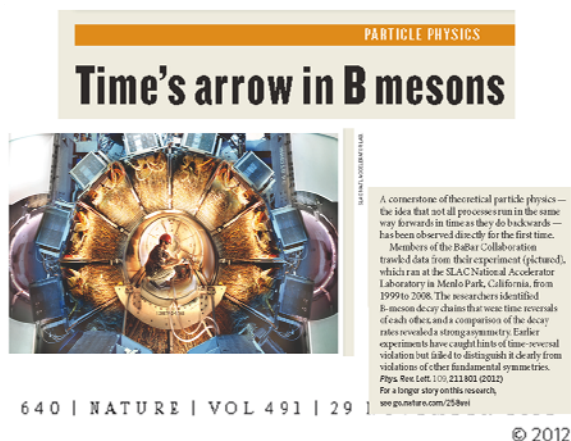


Figure 2. Nature 491,640(2012) reports that a cornerstone of theoretical particle physics -the idea that not all processes run in the same way forwards in time as they do backwards- has been observed directly for the first time.

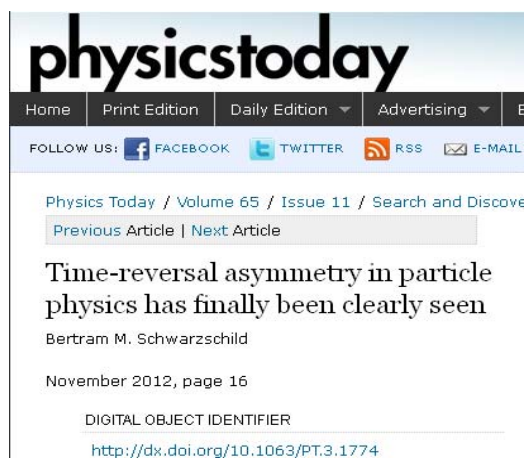
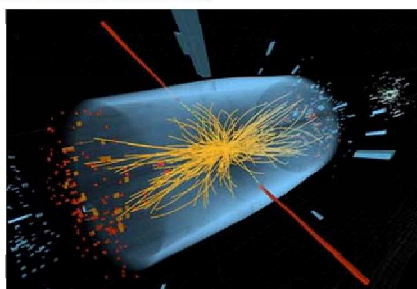


Figure 3. This report in Physics Today emphasizes that, in transitions between neutral B states not connected by CP, BABAR finds transition rates that depend on temporal direction in a way that can only be attributed to T violation.

TRV has finally been clearly seen. Additionally, Physics World revealed its top breakthroughs for physics in 2012 and the first three results appear to be [5] the Higgs-like boson discovery at CERN, a Majorana fermion excitation in solid state physics and Time-Reversal Violation, as shown in figure 4.

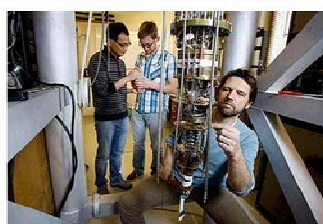
<http://physicsworld.com/cws/article/news/2012/dec/14/physics-world-reveals-its-top-10-breakthrough>.

CERN discovers Higgs-like boson



One of many proton-proton collisions at CMS

Majorana fermions



Looking for Majorana fermions in a solid

Time-reversal violation

"To the BaBar collaboration for making the first direct observation of time-reversal violation by measuring the rates at which the B^0 meson changes quantum states."



Figure 4. Together with the Physics World award for the 2012 Breakthrough of the Year to the discovery of a Higgs-like particle at the LHC, the journal includes the first evidence of the elusive Majorana fermion in a solid and the first direct observation of Time Reversal Violation.

The main point associated to a genuine test of T-invariance is that one needs an interchange between in-states and out-states for a given process, a request particularly difficult to accomplish for particles that decay. The interest in the unstable neutral meson $K^0 \rightarrow \bar{K}^0$ and $B^0 - \bar{B}^0$ systems stems from the fact that Violation of CP invariance (CPV) has been observed for them [6]. By virtue of the CPT theorem [7], as imposed by any local quantum field theory with Lorentz invariance and Hermiticity, one then expects that T violation should also appear in those systems. A direct evidence for TRV would mean an experiment that, considered by itself, clearly shows TRV independent of, and unconnected to, the results for CPV. No existing result before the BABAR experiment [2] had clearly demonstrated TRV in this sense. For particles in a decaying state, T-transformation is not defined, because the image under T is not a physical state. It looks like the decay prevents a true test of T-symmetry. What is the conceptual basis that is able to bypass this argument? Everything started with the papers [8] that used the quantum Einstein-Podolsky-Rosen (EPR) [9] Entanglement to transfer the information, lost in the irreversible decay of one particle, to its still living orthogonal partner. This correlation allows the preparation, in the quantum mechanical sense, of the state of the second neutral meson as a filtering measurement does. These ideas were scrutinized by several authors, including Wolfenstein [10], Quinn [11] and many others, with the conclusion that "it appears to be a true TRV effect".

The original ideas and calculations [8] were more recently transformed into a definite experimental proposal [12] and its feasibility was demonstrated by a full simulation using the realistic statistics available in the B Factories. In this presentation I discuss the conceptual basis, the methodology and the experimental results leading to the direct evidence of TRV in the time evolution of the neutral B meson in the interval between the two decays to definite flavour and definite CP of the decay products, for the entangled B meson system produced by the Y(4S) decay. In Section 2 the fundamental distinction between the "arrow of time" for complex systems and the TRV in the fundamental laws of Physics is discussed. Section 3 is devoted to the problematics of unstable systems to be used for a test of T-symmetry, and its solution by means of the EPR-Entanglement for the transfer of information to the still living meson at the time of the first decay. The foundations of the experimental analysis are presented in Section 4, whereas the results and the T-violating asymmetries are given in Section 5. Section 6 summarizes the main conclusions.

2. T symmetry in the laws of physics

We are interested in Microscopic T-symmetry Violation. Effects in particle physics odd under the change of sign of time $t \leftrightarrow -t$ are not necessarily T-violating. These observables can occur in theories with exact T-symmetry and are called T-odd effects, like those induced by absorptive components of the transition amplitude. On the other hand, for complex physical systems, well known time asymmetries are the Universe t-asymmetry and the macroscopic t-asymmetry called the "arrow of time". But none of these t-asymmetries is a test of TRV in the fundamental Laws of Physics.

T-Violation exists in the Standard Model or any field theoretic extension of it. All local quantum field theories with Lorentz invariance and Hermiticity satisfy the CPT theorem [7], so that they establish an automatic connection between CP Violation (CPV) and a related TRV. CPV has been observed in the $K^0 \rightarrow \bar{K}^0$ and $B^0 - \bar{B}^0$ systems [6]. All experimental results are in agreement with the Standard Cabibbo-Kobayashi-Maskawa (CKM) mechanism in the ElectroWeak Theory. As a consequence, one also expects to have TRV in these neutral meson systems. How to observe it? T and CPT symmetries are implemented by Antiunitary Operators in Quantum Mechanics, with the algebraic commutation rules left invariant. **A genuine TRV Observable means an Asymmetry under the interchange of in \leftrightarrow out states**. The antiunitary character, rather than unitary, introduces many intriguing subtleties.

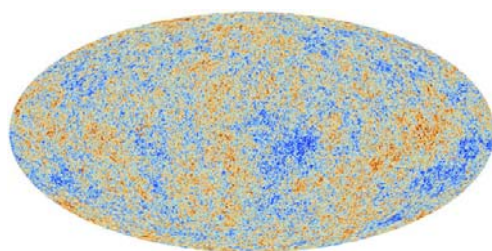


Figure 5. This Map tracing the oldest light in the sky has been produced by Europe's Planck Surveyor satellite [13].

There is no doubt that the Universe is expanding, even accelerating at present cosmological age. This natural t -asymmetry $t \leftrightarrow -t$ is perfectly compatible with fundamental laws of physics that are Time Reversal-symmetric. It is due to the initial condition for our Universe, like Inflation. This asymmetry is similar to the fact that in our Universe we have a privileged reference frame, the one associated with the Cosmic Microwave Background (CMB) radiation at a definite temperature with fluctuations. In figure 5 we show the result that allows fundamental measurements of cosmological parameters, compatible with the Λ CDM Model. The CMB radiation has a thermal black body spectrum at a temperature of 2.725 K, as shown in Figure 6. The spectrum peaks in the microwave range frequency of 160.2 BHz, corresponding to a 1.9 mm wavelength, in the intensity per unit frequency. This privileged reference frame in our Universe does not mean a violation of Lorentz invariance in the fundamental laws of physics. Similarly for the Universe time-asymmetry: it does not mean a violation of Time Reversal invariance in the fundamental laws of physics.

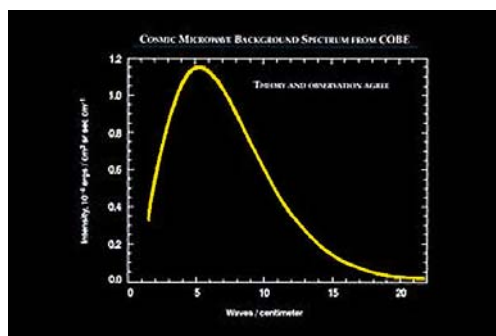


Figure 6. Graph of cosmic microwave background spectrum, the most precisely measured black body spectrum in nature.

For complex systems, their t -asymmetric behaviour is in the nature of Thermodynamics. As discussed by Eddington [14], figure 7, the “arrow of time” is a property of entropy alone, as a measurement of the disorder. It says that time is asymmetric with respect to the amount of order in isolated systems. **The arrow indicates the direction of progressive increase of the random element.** There is probably a connection between the cosmological t -asymmetry and the “arrow of time” for complex systems: it would say that the initial condition in the evolution of the Universe was more ordered and thus highly improbable.



Figure 7. The “arrow of time” is a concept developed in 1927 by Arthur Eddington involving the one-way direction of asymmetry of time. At the macroscopic level there is an obvious flow of time generated by entropy alone.

None of these t -asymmetries is related to a fundamental TRV of the physical laws.

3. Direct evidence for TRV in unstable particles?

A direct evidence for TRV means an experiment that, considered by itself, clearly shows TRV independent of, and unconnected to, the results for CPV. Two types of experiments can do it:

- 1) A non-zero expectation value of a T-odd operator for a non-degenerate stationary state. This is the case for an electric dipole moment, which is a P-odd, C-even, T-odd quantity. It can be generated by either strong T-violation, with the non-perturbative θ -term $\mathcal{E}_{\mu\nu\tau\sigma} F^{\mu\nu} F^{\tau\sigma}$ of the tensor gluon field with its dual, unless it is rotated away by a Peccei-Quinn symmetry [15] leaving the axion as remnant, or by T-violation in weak interactions. In the standard model, with the CKM mechanism, a non-vanishing electric dipole moment of the neutron only appears to three loop amplitudes. The present experimental status is summarized in [16].
- 2) For transitions, as discussed before, the antiunitary character of the T-operator demands an asymmetry under the in \leftrightarrow out exchange, i.e., the comparison between $\langle f | S | i \rangle$ and $\langle -i | S | -f \rangle$, where $|-i\rangle, |-f\rangle$ indicate the T-transformed of $|i\rangle, |f\rangle$ respectively. Transitions in the $K^0 \rightarrow \bar{K}^0$ and $B^0 - \bar{B}^0$ systems have demonstrated the existence of CPV. It is then natural to search for TRV in those systems.

The Kabir asymmetry $K^0 \rightarrow \bar{K}^0$ vs $\bar{K}^0 \rightarrow K^0$ was measured in 1998 by the CPLEAR experiment [17] at CERN with a non-vanishing value and a statistical significance near 4 standard deviations. But the interpretation of this observable as a direct evidence of TRV has generated some controversy. It is based on several facts associated with this flavour-flavour transition:

- Taking $K^0 \rightarrow \bar{K}^0$ as Reference, and calling (X,Y) the observed decays at times t_1 and t_2 , with $\Delta t = t_2 - t_1 > 0$, which tag the flavour for initial and final states, the CP, T and CPT transformed transitions, as well as the Δt -reversal of the observed decays, are given in Table 1:

Table 1. Symmetry transformations applied to $K^0 \rightarrow \bar{K}^0$

Transition	$K^0 \rightarrow \bar{K}^0$	$\bar{K}^0 \rightarrow K^0$	$\bar{K}^0 \rightarrow K^0$	$K^0 \rightarrow \bar{K}^0$	$K^0 \rightarrow \bar{K}^0$
(X,Y)	(I, I)	(I ⁺ , I ⁺)	(I ⁺ , I ⁺)	(I, I)	(I, I)
Transformation	Reference	CP	T	CPT	Δt

As a consequence, assuming that T can be defined for these transitions, there is no way to distinguish it from CP, they are experimentally identical. Even if CPT is violated, there is no way to observe it in this transition.

- The Kabir asymmetry, as a consequence of being associated to flavour mixing transitions, needs the interference of CP mixing im_{CP} with the “initial state interaction” to generate the effect which is proportional to $\Delta\Gamma$, as shown in the diagrams of figure 8. **The decay plays then an essential role.** For decaying states, the T-operator is not defined: its time reverse is not a physical state [18].

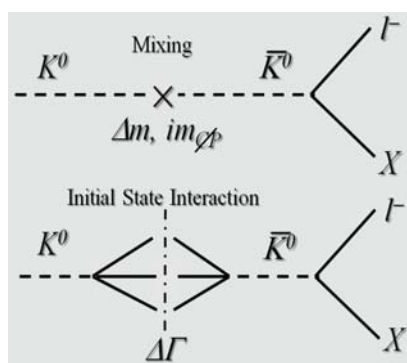


Figure 8. The CP mixing asymmetry for $K^0 \rightarrow \bar{K}^0$ is generated by the interference of CP-violation in the mass matrix with the “initial state interaction” given by $\Delta\Gamma$.

- The time evolutions of $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ are in fact equal and the asymmetry becomes time independent. In the Weisskopf-Wigner approach [19], the entire effect comes from the overlap of the non-orthogonal “stationary” K_L , K_S states. If the stationary states were orthogonal, the asymmetry vanishes.

All these arguments hint to the claim [18] by Wolfenstein that “it is not as direct a test of TRV as one might like”.

The previous reasoning is not ruling out all tests of T-symmetry for particles that decay, as long as $\Delta\Gamma$ is not needed for the observable asymmetry. This is the situation when the interference which leads to an asymmetry is taking place for amplitudes with and without mixing. The corresponding transition is associated with flavour and CP decay products. But still we have the problem of the in \leftrightarrow out exchange required for a genuine test of T-symmetry. The fact that particles decay looks like it prevents performing such an exchange.

The solution arises [8] from the Quantum Mechanical Entanglement imposed by the EPR correlation between the neutral mesons produced in the B, or Φ , Factories. This idea will give us the opportunity to have separate tests of CP, T and CPT-symmetries, depending on the selection of the decay channel.

The $B^0 - \bar{B}^0$ EPR-Entanglement is due to Particle Identity, because $B^0 \bar{B}^0$ are two states of a unique (complex) field. These two states are connected by charge conjugation C, so that the symmetry requirement for bosons implies $C\mathcal{P} = +$, where \mathcal{P} is the permutation operation. In B-Factories, $B^0 \bar{B}^0$ are produced by the Y(4S)-decay, with J = 1, S = 0, L = 1 quantum numbers. For this particle-antiparticle system, C = - is well defined, so we conclude that $\mathcal{P} = -$: the wave function has to be antisymmetric.

At the moment of the $Y \rightarrow B^0 \bar{B}^0$ decay, the neutral meson system is in the state

$$|i\rangle = \frac{1}{\sqrt{2}} [B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] \quad (1)$$

where the states 1, 2 are defined by the time ordering of the decays, with $t_1 < t_2$. The times t_1 and t_2 in equation (1) are not time dependences, but labels to characterize the states. The antisymmetric character of equation (1) is crucial for the time evolution of $|i\rangle$ when the mixing $B^0 - \bar{B}^0$ is included. In spite of the mixing, only terms $B^0 \bar{B}^0$ appear at any time. This behaviour is perfect for a Flavour-Tag mechanism. As it is well known, the observation of the decay of one meson to a positive lepton l^+ , for example, at time t_1 , signals that the (still living) partner meson state at this time is the B-state not decaying to l^+ , i.e., \bar{B}^0 . The decay has filtered the B^0 -state, and the orthogonal state \bar{B}^0 is then tagged at time t_1 . For $t > t_1$, we have a single state time evolution from \bar{B}^0 .

But, for the entangled state of the two mesons, the individual state of each neutral meson is not defined before its collapse as a filter imposed by the observation of the decay. This quantum mechanical entanglement was in fact argued by EPR [9] as being against local realism and, as such, that the quantum theory was not “complete”. This epistemological EPR “paradox” was later converted to physics by John Bell and it is now the foundation of quantum information and quantum computing.

One can rewrite the same $|i\rangle$ state in equation (1) in terms of any other pair of orthogonal states of the individual neutral B-mesons: a linear combination of B^0 and \bar{B}^0 , and its orthogonal. One may consider the states B_+ and B_- of the neutral mesons, where B_+ is the state not decaying to the decay product $J/\psi K_+$ and K_+ is the neutral K-meson filtered by its decay to $\pi\pi$. The orthogonal state B_- is thus the neutral B-meson filtered by the decay to the CP = - final state. The observation of the decay to this CP-eigenstate at time t_1 generates an automatic transfer of information to the (still living) partner meson. We may call the quantum preparation of the initial state at t_1 , using the filter imposed by a first observation of this decay, a “CP-tag” [20]. The same entangled state is then better to write it as

$$|i\rangle = \frac{1}{\sqrt{2}} [B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)] \quad (2)$$

The main question is now: If B_- is the B-state filtered by the $CP = -$ decay $J/\psi K_+$, what is the orthogonal state B_+ experimentally? For these CP-eigenstate decay products, the condition to filter a definite state is [12] that the decay amplitude has a single weak phase. The state B_+ is that filtered by the $CP = +$ decay in the same system $J/\psi K_-$, where K_- is the neutral K-meson filtered by its decay to $\pi^0 \pi^0 \pi^0$. If, for the B-system, one neglects the small CP-violation of the K-system, one can associate B_- with $J/\psi K_S$ decay and B_+ with $J/\psi K_L$ decay.

This last association is the foundation of the experimental performance of the Time-Reversal Transformation for a transition of the neutral B-meson between a first flavour decay and a second decay to a CP-eigenstate. This T-transformation is illustrated in figure 9 for the comparison between $\bar{B}^0 \xrightarrow{\Delta\tau} B_-$ and $B_- \xrightarrow{\Delta\tau} \bar{B}^0$ transitions. As seen, for the first transition one has to observe the decays (I^+ , $J/\psi K_S$) in this time ordering, whereas the T-reversed transition corresponds to ($J/\psi K_L$, I^-) for the two decays. This nontrivial T-reversal is thus not given by the t-reversal exchanging the two decays. Entanglement has been essential for the quantum preparation of the initial state of the neutral B-meson in one transition and its T-reverse transition. The problem of particle instability for a T-symmetry test has been bypassed. Experimentally, we need a very good time resolution for disentangling the ordering of the two decays.

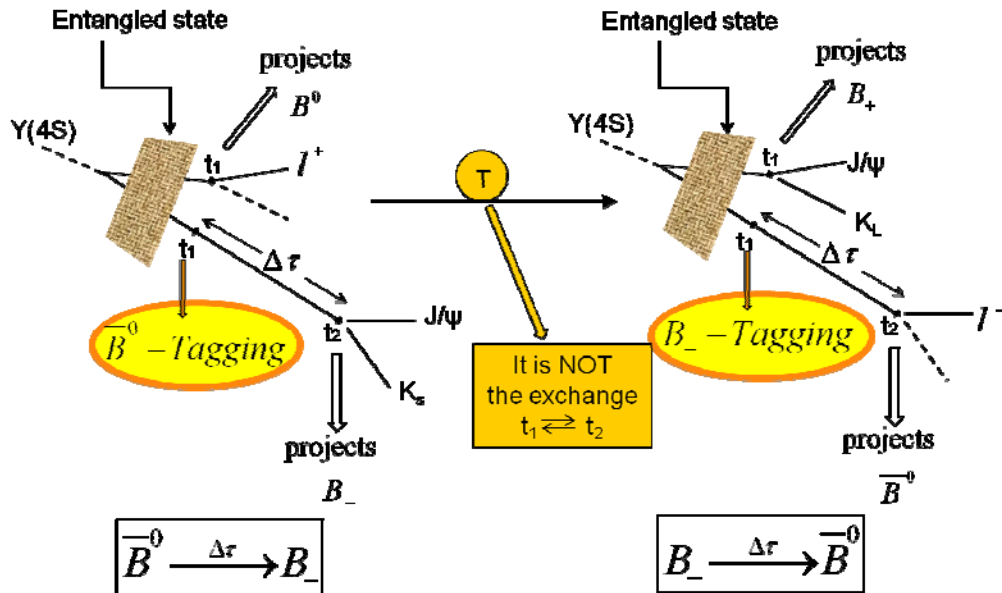


Figure 9. Scheme of the experimental observation of the time ordered (I^+ , $J/\psi K_S$) and ($J/\psi K_L$, I^-) decays for performing the study of the time evolution of the transition $\bar{B}^0 \xrightarrow{\Delta\tau} B_-$ and its T-reverse $B_- \xrightarrow{\Delta\tau} \bar{B}^0$.

4. Genuine Observables not needing $\Delta\Gamma$

We may now proceed to a partition of the complete set of events into four categories, defined by the tag in the first decay at time t_1 : B_+ , B_- , B^0 or \bar{B}^0 , so we have eight different Decay-Intensities at our disposal, as function of $\Delta t = t_2 - t_1 > 0$. Each one of these eight Flavour-CP transitions has an Intensity given by

$$I_i(\Delta\tau) \sim e^{-\Gamma\Delta\tau} \{ C_i \cos(\Delta m \Delta\tau) + S_i \sin(\Delta m \Delta\tau) + C'_i \cosh(\Delta\Gamma \Delta\tau) + S'_i \sinh(\Delta\Gamma \Delta\tau) \} \quad (3)$$

where Γ is the average width.

For a genuine test of a symmetry, one has to compare the $I_i(\Delta t)$ of a transition with its transformed by the symmetry operation. For the case of T, one builds the in \leftrightarrow out exchange asymmetry.

We notice that the Intensities (3) contain terms independent of $\Delta\Gamma$, in such a way that these asymmetries, contrary to Kabir symmetry, do not need a non-vanishing $\Delta\Gamma$ associated to the decay properties. In fact, the interference in the time evolution between the two decays is built between mixing and no mixing.

Up to now, for CPV analyses in B-factories, BABAR & BELLE had assumed CPT-invariance and $\Delta\Gamma = 0$. In this case, there is a theorem which is operating [21]: Then $\Delta t \leftrightarrow -\Delta t$ exchange, i.e., the exchange of the two decay products at t_1 and t_2 , which is not a T-symmetry operation, becomes equivalent to T in the sense that one invariance implies the other. In this case, as $CP \sim T \sim \Delta t$ are theoretically connected, only two independent Intensities remain to be compared. Alternatively, one may establish $S_i \neq 0$ for a single transition, proving that it is Δt -asymmetric. The coefficients C_i and S_i are then related for the eight transitions. In the Standard Model (SM), the CKM Mixing Matrix [22] conveys the fact that the quarks with definite properties under charged current weak interactions are linear combinations of the quark mass eigenstates. For three families, the unitarity conditions are represented by triangles in the complex plane. For the $B^0 - \bar{B}^0$ system, the unitarity triangle is given by

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \quad (4)$$

and its consistency with all existing experimental results on Flavour Mixing and CP Violation is shown in Figure 10

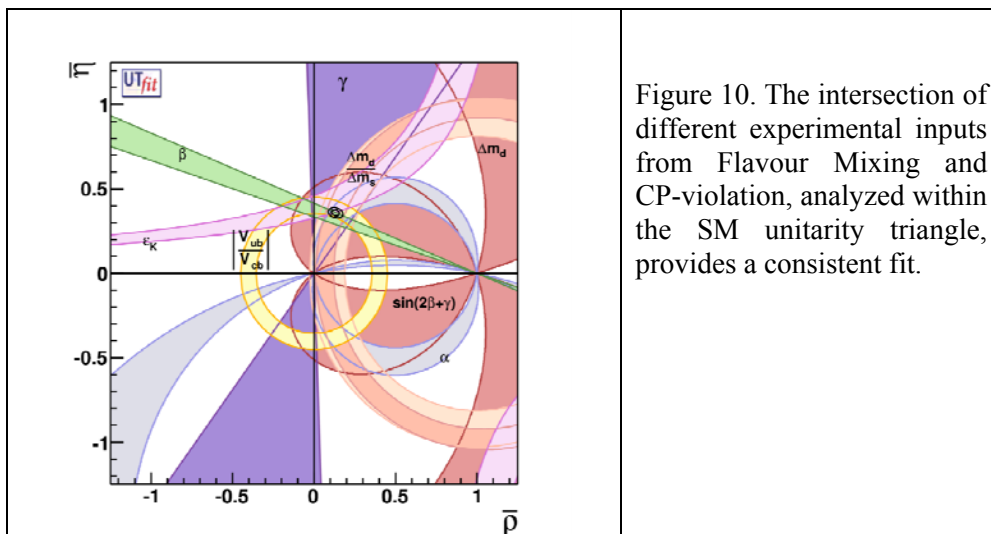


Figure 10. The intersection of different experimental inputs from Flavour Mixing and CP-violation, analyzed within the SM unitarity triangle, provides a consistent fit.

For our selected transitions with the associated interference of Mixing x Decay, with the two decays to Flavour and CP eigenstates for $b \rightarrow c\bar{c}s$, all the 8 S_i coefficients in equation (3) are related to a single value $\sin(2\beta) = 0.67 \pm 0.02$, where β is the CP-phase between the t- and c-sides of the unitarity triangle (4).

The SM connection is not followed here for the study of observables and, in a general context using quantum mechanics only, the eight Intensities (3) are experimentally independent. We proceed now to study the effects of the three symmetry operations CP, T and CPT separately:

- 1) Take $B^0 \rightarrow B_+$ as the Reference transition and call (X,Y) the observed decay products at times t_1 and t_2 , respectively. The CP, T and CPT transformed transitions are given in Table 2, together with the so-called Δt -operation (not a symmetry!) exchanging $X \leftrightarrow Y$

Table 2. Symmetry Transformations applied to $B^0 \rightarrow B_+$

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

As you may check, all transitions are experimentally independent. It is important to point out that the two sets of events, called sometimes “ $\Delta t > 0$ ” and “ $\Delta t < 0$ ”, for the same two decay products l^- and $J/\Psi K_L$, experimentally included in the same sample of events, are not connected by any symmetry.

- 2) Take $B^0 \rightarrow B_-$ as the Reference transition. The CP, T and CPT transformed transitions are given in Table 3

Table 3. Symmetry Transformation applied to $B^0 \rightarrow B_-$

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

Therefore a second Asymmetry for each of the 3 symmetry transformations can be built. Again the result of the Δt -operation is a different transition from the other four transitions connected by the symmetries.

- 3) Select now as Reference the $B_- \rightarrow \bar{B}^0$ transition, obtained by the choice (Y, X) of decay products in the Reference 1) and proceed with the symmetry transformations.
 4) Select as Reference the $B_+ \rightarrow \bar{B}^0$ transition, obtained by the choice (Y, X) of decay products in the Reference 2), and proceed with the symmetry transformations.

We thus conclude that there are 4 Model-Independent Asymmetries for each of the 3 symmetry transformations CP, T and CPT. They are now explicitly written as

-Genuine CPV-Asymmetries

$$\begin{aligned}
 A_{CP,1} &= \frac{\Gamma(l^-, J/\Psi K_L) - \Gamma(l^+, J/\Psi K_L)}{+} \\
 A_{CP,2} &= \frac{\Gamma(l^-, J/\Psi K_S) - \Gamma(l^+, J/\Psi K_S)}{+} \\
 A_{CP,3} &= \frac{\Gamma(J/\Psi K_L, l^-) - \Gamma(J/\Psi K_L, l^+)}{+} \\
 A_{CP,4} &= \frac{\Gamma(J/\Psi K_S, l^-) - \Gamma(J/\Psi K_S, l^+)}{+}
 \end{aligned} \tag{5}$$

-Genuine TRV-Asymmetries

$$\begin{aligned}
& \xrightarrow{\Delta t} A_{T,1} = \frac{\Gamma(l^-, J/\Psi K_L) - \Gamma(J/\Psi K_S, l^+)}{+} \\
& A_{T,2} = \frac{\Gamma(l^-, J/\Psi K_S) - \Gamma(J/\Psi K_L, l^+)}{+} \\
& \xrightarrow{\Delta t} A_{T,3} = \frac{\Gamma(J/\Psi K_L, l^-) - \Gamma(l^+, J/\Psi K_S)}{+} \\
& A_{T,4} = \frac{\Gamma(J/\Psi K_S, l^-) - \Gamma(l^+, J/\Psi K_L)}{+} \xrightarrow{\Delta t}
\end{aligned} \tag{6}$$

-Genuine CPTV-Asymmetries

$$\begin{aligned}
& \xrightarrow{\Delta t} A_{CPT,1} = \frac{\Gamma(l^-, J/\Psi K_L) - \Gamma(J/\Psi K_S, l^-)}{+} \\
& A_{CPT,2} = \frac{\Gamma(l^-, J/\Psi K_S) - \Gamma(J/\Psi K_L, l^-)}{+} \\
& A_{CPT,3} = \frac{\Gamma(l^+, J/\Psi K_L) - \Gamma(J/\Psi K_S, l^+)}{+} \\
& A_{CPT,4} = \frac{\Gamma(l^+, J/\Psi K_S) - \Gamma(J/\Psi K_L, l^+)}{+} \xrightarrow{\Delta t}
\end{aligned} \tag{7}$$

In equations (5), (6) and (7) the asymmetries connected by Δt -exchange are pointed out.

These Asymmetries in the time dependent decay rates for any pair of symmetry-conjugated transitions would be apparent through differences between the corresponding coefficients S_i or C_i in equation (3). In the analysis for the $B^0 - \bar{B}^0$ system, we will take $\Delta\Gamma = 0$. In our notation for $S_{\alpha,\beta}^\pm$ ($C_{\alpha,\beta}^\pm$), α will indicate the flavour decay l^+ or l^- and β the CP-eigenstate decay $J/\psi K_L$ or $J/\psi K_S$. The superindex “+” is for time ordering (Flavour, CP), whereas “-” is for the opposite time ordering of the two decays. For T-symmetry, a measure of TRV in the time evolution between the two decays is given by the asymmetry parameters

$$\begin{aligned}
\Delta S_T^+ &= S_{l^-, K_L}^- - S_{l^+, K_S}^+ & \Delta C_T^+ &= C_{l^-, K_L}^- - C_{l^+, K_S}^+ \\
\Delta S_T^- &= S_{l^-, K_L}^+ - S_{l^+, K_S}^- & \Delta C_T^- &= C_{l^-, K_L}^+ - C_{l^+, K_S}^-
\end{aligned} \tag{8}$$

Similarly for the asymmetry parameters ΔS_{CP}^\pm (ΔC_{CP}^\pm) and ΔS_{CPT}^\pm (ΔC_{CPT}^\pm) which measure CPV and CPTV, respectively. The $\Delta S^\pm, \Delta C^\pm$ parameters for the three symmetries CP, T and CPT are represented in figure 11 on top of the Intensities for the 8 independent transitions we are considering. These transitions are characterized by the flavour l^\pm , the CP eigenstate $J/\psi K_S$ (K_L) and the time ordering $\Delta t > 0$ ($\Delta t < 0$).

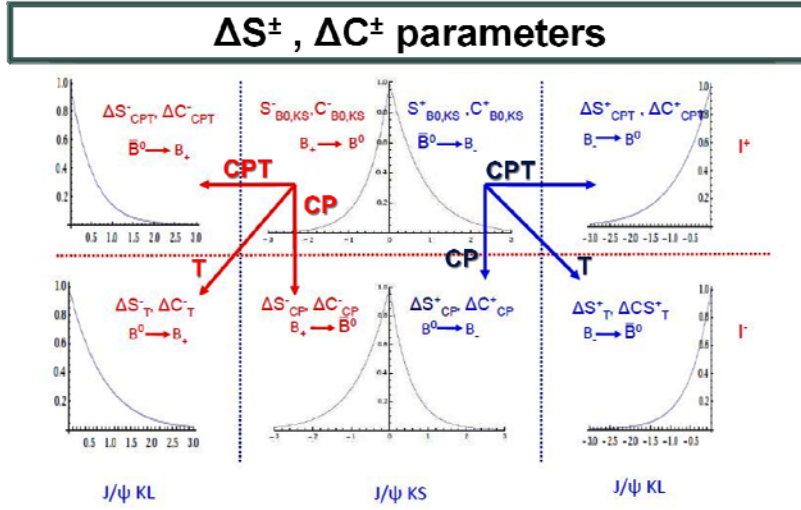


Figure 11. The eight Intensities, obtained for different flavours I^\pm , different CP eigenstates $J/\psi K_S (K_L)$ and different sign of Δt , are connected by the symmetry transformations CP, T and CPT. There are two sets of asymmetry parameters.

One should notice that a genuine test of T implies the comparison of: 1) “Opposite Δt sign”, i.e., $\text{in} \leftrightarrow \text{out}$; 2) Different CP eigenstates, $J/\psi K_L$ vs. $J/\psi K_S$; and 3) Opposite flavor states, B^0 vs. \bar{B}^0 .

In the SM, all 8 coefficients are related as a consequence of CPT invariance and $\Delta\Gamma = 0$, and given by the value of $\sin(2\beta)$

$$S = S_{I^+, K_S}^+ = -S_{I^-, K_S}^+ = -S_{I^+, K_S}^- = S_{I^-, K_S}^- = -S_{I^+, K_L}^+ = S_{I^-, K_L}^+ = S_{I^+, K_L}^- = -S_{I^-, K_L}^- \approx 0.67 \quad (9)$$

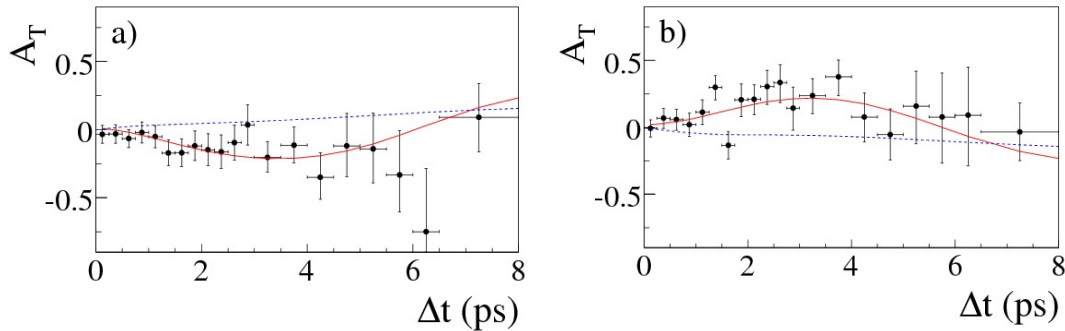
$$C = C_{I^+, K_S}^+ = -C_{I^-, K_S}^+ = C_{I^+, K_S}^- = -C_{I^-, K_S}^- = C_{I^+, K_L}^+ = -C_{I^-, K_L}^+ = C_{I^+, K_L}^- = -C_{I^-, K_L}^- \approx 0$$

5. Experimental Results

The details of the experimental analysis by the BABAR Collaboration may be consulted in reference [2]. For the $\bar{B}^0 \rightarrow B^-$ transition, neglecting reconstruction effects, we have for the TRV asymmetry

$$A_T(\Delta t) \approx \frac{\Delta S_T^+}{2} \sin(\Delta m \Delta t) + \frac{\Delta C_T^+}{2} \cos(\Delta m \Delta t) \quad (10)$$

The other three T-violating asymmetries can be written similarly. Figure 12 shows the four observed asymmetries, overlaid with the projection of the best fit results to the Δt distribution with and without the eight T-invariance restrictions: $\Delta S_T^+ = \Delta C_T^+ = 0$, $\Delta S_{CP}^+ = \Delta S_{CPT}^+$ and $\Delta C_{CP}^+ = \Delta C_{CPT}^+$.



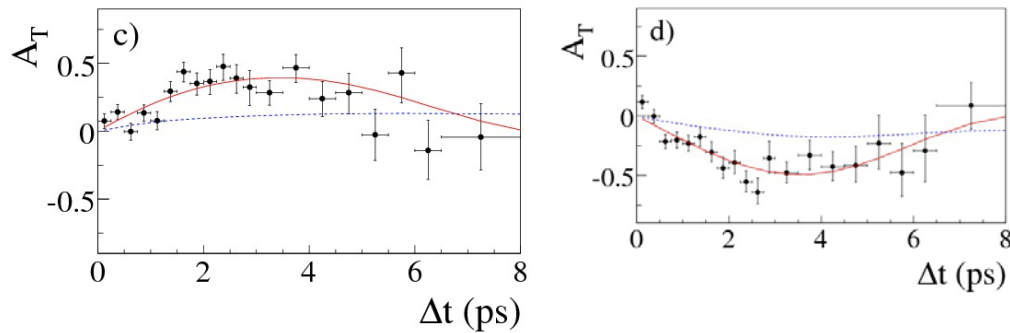


Figure 12. Experimental results for the four raw time dependent asymmetries associated with TRV.

The measured values of the T, CP and CPT-asymmetry parameters are given in Table 4, together with the values of reference coefficients of the time dependent intensities (at the bottom).

Table 4. Measured values of the asymmetry parameters $\{\Delta S^\pm, \Delta C^\pm\}$ for each of the three symmetries T, CP and CPT.

Parameter	Final result	SM expected val.
ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$	-1.34
ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$	1.34
ΔC_T^+	$0.10 \pm 0.14 \pm 0.08$	0.
ΔC_T^-	$0.04 \pm 0.14 \pm 0.08$	0.
ΔS_{CP}^+	$-1.30 \pm 0.11 \pm 0.07$	-1.34
ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$	1.34
ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$	0.
ΔC_{CP}^-	$0.08 \pm 0.10 \pm 0.04$	0.
ΔS_{CPT}^+	$0.16 \pm 0.21 \pm 0.09$	0.
ΔS_{CPT}^-	$-0.03 \pm 0.13 \pm 0.06$	0.
ΔC_{CPT}^+	$0.14 \pm 0.15 \pm 0.07$	0.
ΔC_{CPT}^-	$0.03 \pm 0.12 \pm 0.08$	0.
$S_{\ell^+, K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$	0.67
$S_{\ell^+, K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$	-0.67
$C_{\ell^+, K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$	0.
$C_{\ell^+, K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$	0.

The first uncertainty is statistical and the second systematic. In the last column, the SM expected value is also given, with such a good precision that its error is well below the present experimental uncertainty.

The significance of the T-violation signal is obtained from the CL contours shown in figure 13

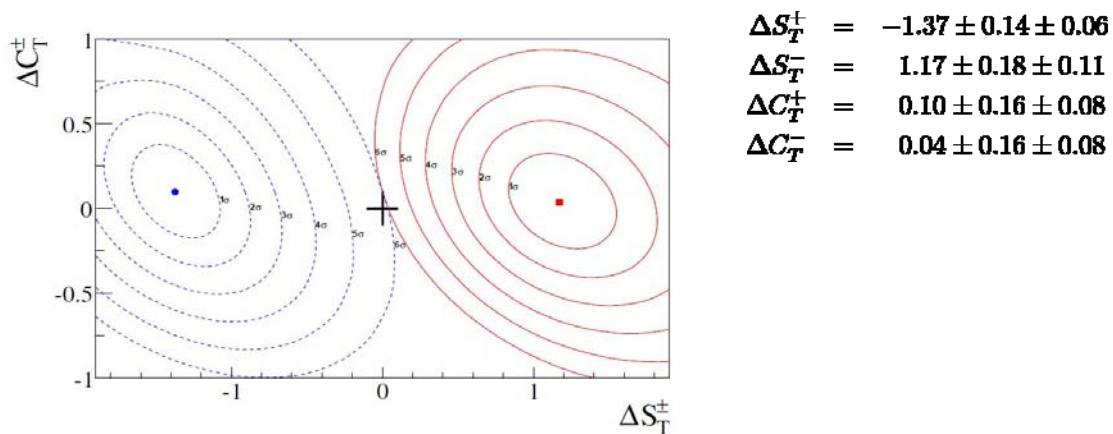
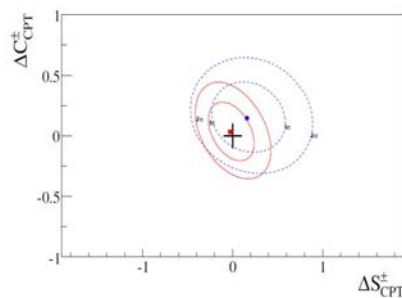
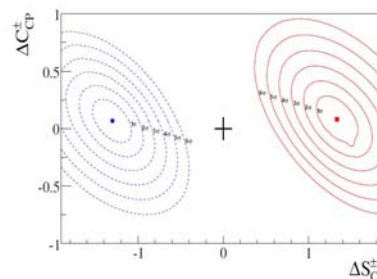


Figure 13. Confident Level (CL) contours for the T-asymmetry parameters $\{ \Delta S_T^\pm, \Delta C_T^\pm \}$

These CL contours are given in two dimensions for the T-asymmetry parameters $(\Delta S_T^+, \Delta C_T^+)$ and $(\Delta S_T^-, \Delta C_T^-)$. Assuming Gaussian errors, the result corresponds to a significance equivalent to 14 standard deviations, and thus constitutes a direct observation of T violation.

The significance of CP and CPT violation is determined analogously from the CL contours shown in figure 14,

$$\begin{aligned} \Delta S_{CP}^+ &= -1.30 \pm 0.10 \pm 0.07 \\ \Delta S_{CP}^- &= 1.33 \pm 0.12 \pm 0.06 \\ \Delta C_{CP}^+ &= 0.07 \pm 0.10 \pm 0.03 \\ \Delta C_{CP}^- &= 0.08 \pm 0.09 \pm 0.04 \end{aligned}$$



$$\begin{aligned} \Delta S_{CPT}^+ &= 0.16 \pm 0.20 \pm 0.09 \\ \Delta S_{CPT}^- &= -0.03 \pm 0.13 \pm 0.06 \\ \Delta C_{CPT}^+ &= 0.15 \pm 0.17 \pm 0.07 \\ \Delta C_{CPT}^- &= 0.03 \pm 0.14 \pm 0.08 \end{aligned}$$

Figure 14. Confident Level (CL) contours for the CP and CPT asymmetry parameters $\{ \Delta S^\pm, \Delta C^\pm \}$

obtaining a result equivalent to 17 and 0.3 standard deviations, respectively, consistent with CP violation and CPT invariance.

6. Conclusion

We have discussed the conceptual basis, the methodology and the experimental result for a direct evidence of Time-Reversal Violation in the fundamental laws of physics. The observed time-asymmetries in complex systems, like de Arrow of Time, are not T-violating, but a property of Entropy alone.

A genuine TRV means an asymmetry under the exchange in \leftrightarrow out of states in a transition, a requirement which looks impossible to be satisfied for particles that decay. The interest in the

unstable $B^0 - \bar{B}^0$ (and $K^0 - \bar{K}^0$) system originates in the important CP violating effects observed in the Mixing x Decay interference, so that the CPT theorem predicts a related T-violation in those systems.

A unique opportunity for bypassing the problem of T-symmetry tests in unstable particles is provided by the Einstein-Podolsky-Rosen Entanglement between the two neutral mesons in B, and Φ , factories. The information transfer from the first decay, used as a filtering measurement, to the still living partner allows a quantum mechanical preparation, the flavour or CP tag, of the appropriate state for performing the T-symmetry study.

Using the channels for the two decays to Flavour and CP eigenstates, we find 8 different Intensities for the time evolution of the neutral B-meson between the two decays. In appropriate combinations, each CP, T, CPT symmetry can be tested separately using 4 genuine independent Asymmetries between the time dependent Decay Rates. These results have been expressed in terms of independent Asymmetry Parameters ΔS^+ , ΔC^+ for each symmetry transformation.

BABAR has measured the time dependent Asymmetries and has extracted the Asymmetry parameters. The experimental result shows a large deviation of T-invariance with a significance of 14 standard deviations, far more than needed to declare a Discovery. In turn, the results are consistent with CPT invariance in the time evolution of the neutral B-meson between the two decays, connecting CPV and TRV in different transitions.

This experimental result constitutes a direct evidence of Time Reversal Violation in the time evolution of the neutral B-meson.

This discovery was made possible thanks to the spectacular quantum properties of EPR entangled states: the reality of two entangled B's is much more than the sum of two separate B local realities.

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