TIME REVERSAL VIOLATION FOR ENTANGLED NEUTRAL MESONS

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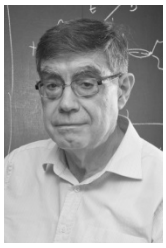

Abstract. A direct evidence for Time Reversal Violation (TRV) means an experiment that, considered by itself, clearly shows TRV independent of, and unconnected to, the results for CP Violation. No existing result before the recent BABAR experiment with entangled neutral B mesons had demonstrated TRV 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.

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 had an important impact in the scientific community and journals. 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. In particle physics one expects that not all processes run in the same 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, that 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.

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 $K^0 \to \overline{K}^0$ and $B^0 - \overline{B}^0$ 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.

DIRECT EVIDENCE FOR TRV IN UNSTABLE PARTICLES

We are interested in Microscopic T-symmetry Violation. Effects in particle physics odd under the change of sign of time t ↔ -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[13)] and the macroscopic t-asymmetry called the "arrow of time"[14)]. But none of these t-asymmetries is a test of TRV in the fundamental Laws of Physics.

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 ↔ out states**. The antiunitary character, rather than unitary, introduces many intriguing subtleties. Two types of experiments can demonstrate TRV:

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 $\varepsilon_{\mu\nu\tau\sigma} F^{\mu\nu} F^{\tau\sigma}$ 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 ↔ 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 $K^0 \to \bar{K}^0$ 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 $\bar{K}^0 \to K^0$ vs $K^0 \to \bar{K}^0$ 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[18)] on several facts associated with this flavour-flavour transition with an asymmetry proportional to ΔΓ. In the WW approach[19)] the entire effect comes from the overlap of the non-orthogonal "stationary" K_L, K_S states.

Not all tests of T-symmetry are ruled out for particles that decay, as long as ΔΓ 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↔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. At the moment of the $\Upsilon(4S) \to B^0 \bar{B}^0$ decay, the neutral meson system is in the antisymmetric state

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

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.

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. 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 considerer 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

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

The main question is now: If B_- is the B-state filtered by the CP = - decay J/ψ 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 <u>single weak phase</u>. The state B_+ is that filtered by the CP = + decay in the same system J/ψ 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/ψ K_S decay and B_+ with J/ψ K_L decay.

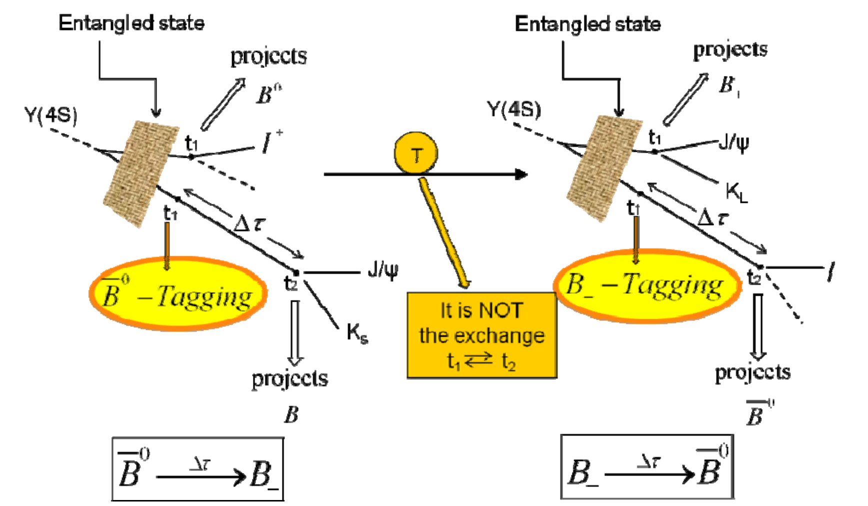

FIGURE 1. Scheme of the experimental observation of the time ordered (l^+, J/ψ K_S) and (J/ψ K_L, l^-) decays for performing the study of the time evolution of the transition $\overline{B}^0 \underline{\Delta\tau} B_-$ and its T-reverse $B_- \underline{\Delta\tau} \overline{B}^0$

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 fig. 1 for the comparison between $\overline{B}^0 \underline{\Delta\tau} B_-$ and $B_- \underline{\Delta\tau} \overline{B}^0$ transitions. As seen, for the first transition one has to observe the decays (l^+, J/ψ K_S) in this time ordering, whereas the T-reversed transition corresponds to (J/ψ K_L, l^-) for the two decays. This nontrivial T-reversal is thus <u>not</u> given by the t-reversal exchanging the two decays. <u>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</u>. The problem of particle unstability for a T-symmetry test has been bypassed. Experimentally, we need a very good time resolution for disentangling the ordering of the two decays.

GENUINE OBSERVABLES NOT NEEDING ΔΓ

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 $\overline{B}^0$, 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

$$\mathrm{I}_i(\Delta\tau) \sim e^{-\Gamma\Delta\tau} \left\{ C_i \cos(\Delta m \Delta\tau) + S_i \sin(\Delta m \Delta\tau) + C'_i \cosh(\Delta\Gamma\Delta\tau) + S'_i \sinh(\Delta\Gamma\Delta\tau) \right\} \tag{3}$$

where Γ is the average width. For a genuine test of a symmetry, one has to compare the I_i (Δt) of a transition with its transformed by the symmetry operation. We proceed now to study the effects of the three symmetry operations CP, T and CPT separately:

1) Take $B^0 \to B_+$ 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 1, as well as the so-called Δt-operation (not a symmetry!) exchanging X↔Y

TABLE 1. Symmetry Transformations applied to $B^0 \to B_+$

Transition	$B^0 \to B_+$	$\overline{B}^0 \to B_+$	$B_+ \to B^0$	$B_+ \to \overline{B}^0$	$B_- \to \overline{B}^0$
(X,Y)	(l^-, J/ΨK_L)	(l^+ ,J/ΨK_L)	(J/ΨK_S, l^+)	(J/ΨK_S, l^-)	(J/ΨK_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 $B^0 \to B_-$ as the Reference transition. The CP, T and CPT transformed transitions are given in Table 2

TABLE 2. Symmetry Transformation applied to $B^0 \to B_-$

Transition	$B^0 \to B_-$	$\overline{B}^0 \to B_-$	$B_- \to B^0$	$B_- \to \overline{B}^0$	$B_+ \to \overline{B}^0$
(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 $B_- \to \overline{B}^0$ 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 $B_+ \to \overline{B}^0$ 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. 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 $B^0 - \overline{B}^0$ system, we will take $\Delta\Gamma = 0$. In our notation for $S^{\pm}_{\alpha,\beta}(C^{\pm}_{\alpha,\beta})$, 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

$$\Delta S^+_T = S^-_{l^-,K_L} - S^+_{l^+,K_S} \qquad \Delta C^+_T = C^-_{l^-,K_L} - C^+_{l^+,K_S}$$
$$\Delta S^-_T = S^+_{l^-,K_L} - S^-_{l^+,K_S} \qquad \Delta C^-_T = C^+_{l^-,K_L} - C^-_{l^+,K_S} \tag{4}$$

Similarly for the asymmetry parameters $\Delta S^{\pm}_{CP}$ ($\Delta C^{\pm}_{CP}$) and $\Delta S^{\pm}_{CPT}$ ($\Delta C^{\pm}_{CPT}$) 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 fig. 2 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 $\Delta t>0$ ($\Delta t<0$).

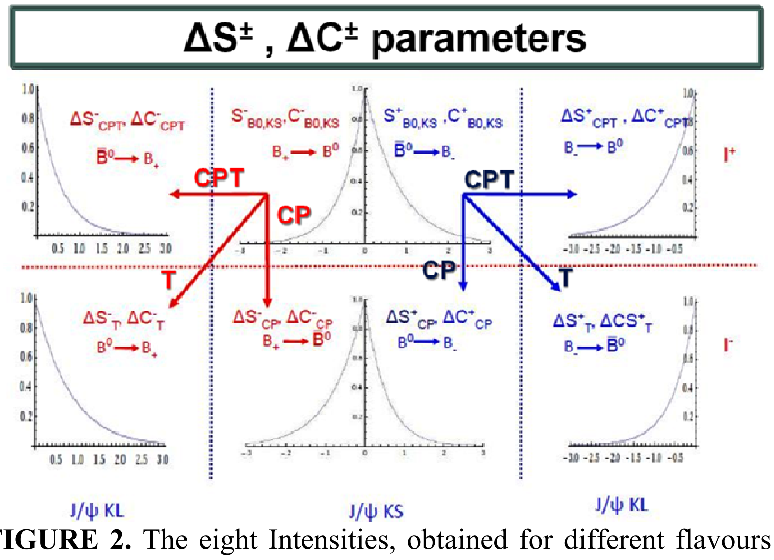

FIGURE 2. The eight Intensities, obtained for different flavours $l^{\pm}$, different CP eigenstates $J/\psi\ K_S$ (K_L) and different sign of Δt, are connected by the symmetry transformations CP, T and CPT. There are two sets of asymmetry parameters.

One should notice that a genuine test of T implies the comparison of: 1) "Opposite Δt sign", i.e., in ↔ out; 2) Different CP eigenstates, $J/\psi\ K_L$ vs. $J/\psi\ K_S$; and 3) Opposite charged leptons l^+ vs. l^-.

In the SM, all 8 coefficients are related as a consequence[21] of CPT invariance and $\Delta\Gamma = 0$, and given by the value of $\sin(2\beta) = 0.67 \pm 0.02$, when using the CKM Mixing matrix[22],

$$S = S^+_{l^+,K_S} = -S^+_{l^-,K_S} = -S^-_{l^+,K_S} = S^-_{l^-,K_S} = -S^+_{l^+,K_L} = S^+_{l^-,K_L} = S^-_{l^+,K_L} = -S^-_{l^-,K_L} \approx 0.67$$
$$C = C^+_{l^+,K_S} = -C^+_{l^-,K_S} = C^-_{l^+,K_S} = -C^-_{l^-,K_S} = C^+_{l^+,K_L} = -C^+_{l^-,K_L} = C^-_{l^+,K_L} = -C^-_{l^-,K_L} \approx 0 \tag{5}$$

EXPERIMENTAL RESULTS

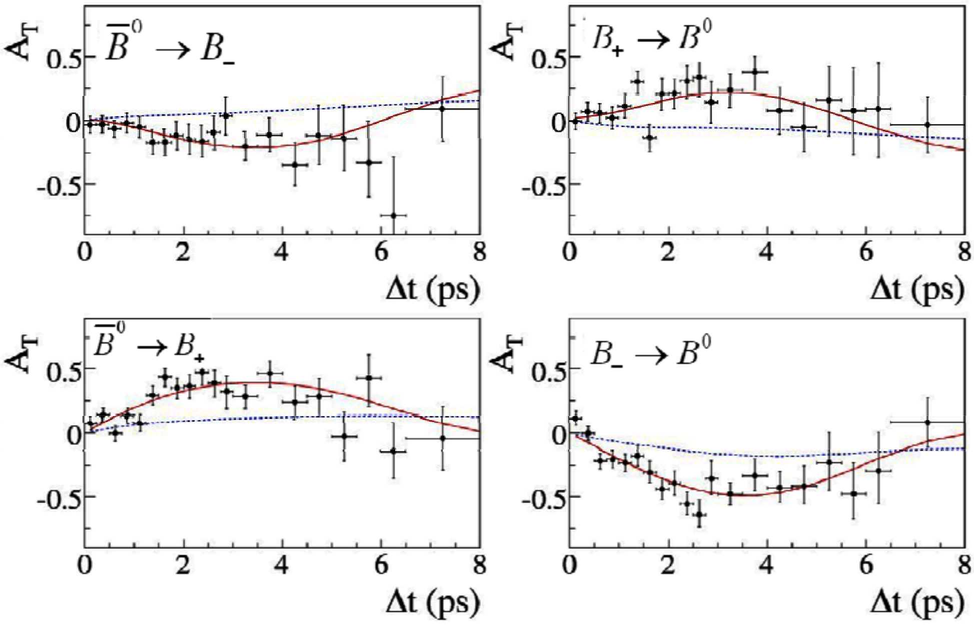

FIGURE 3. Experimental results for the four raw time dependent asymmetries associated with TRV.

TABLE 3. 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_T^-	$0.08 \pm 0.10 \pm 0.04$	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 details of the experimental analysis by the BABAR Collaboration may be consulted in reference[2)].

Fig. 3 shows the four observed TRV asymmetries, overlaid with the projection of the best fit results to the Δt distribution with and without the eight T-invariance restrictions: $\Delta S_T^{\pm} = \Delta C_T^{\pm} = 0$, $\Delta S_{CP}^{\pm} = \Delta S_{CPT}^{\pm}$ and $\Delta C_{CP}^{\pm} = \Delta C_{CPT}^{\pm}$.

The measured values of the T, CP and CPT-asymmetry parameters are given in Table 3, together with the values of reference coefficients of the time dependent intensities (at the bottom).

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 from the global fit is well below the present experimental uncertainty. The significance of the T-violation signal is obtained from the CL contours 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 CL contours, obtaining a result equivalent to 17 and 0.3 standard deviations, respectively, consistent with CP violation and CPT invariance.

CONCLUSION

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, the CP, T, CPT symmetries can be separately tested using 4 genuine independent

Asymmetries between the time dependent Decay Rates. These results have been expressed in terms of independent Asymmetry Parameters $\Delta S^{\pm}, \Delta C^{\pm}$ 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 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.

ACKNOWLEDGMENTS

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