

SLAC-PUB-13518

January 2009

# Time Reversal Violation

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**Abstract.** This talk briefly reviews three types of time-asymmetry in physics, which I classify as universal, macroscopic and microscopic. Most of the talk is focussed on the latter, namely the violation of T-reversal invariance in particle physics theories.

*Talk presented at Discrete '08 Conference,  
Valencia, Spain  
December 11, 2008  
SLAC-PUB-13518*

*Published in the Journal of Physics: Conference Series*

*This work is supported by the Department of Energy under contract number  
DE-AC03-76SF00515.*

## 1. Three $t$ -asymmetries

I was asked to talk about T-Violation. In this conference there are also talks on CPT Violations, Lorentz Violations and CP Violations, so there are very likely some overlaps. Fortunately, mine is the first talk, so I am not at risk of repeating what others have to say, and I can defer to later talks the examination of the interesting issues that have to do with how to compare tests of things that have no self-consistent theoretical basis, such a CPT non-invariance and Lorentz violations. Thus throughout this talk I will be considering the physics as it is seen from the perspective of local field theories, all of which have CPT symmetry as a consequence of their basic locality, Lorentz Invariance and Hermiticity [1]

I will briefly discuss two observed  $t$ -asymmetries, asymmetries under a reversal of the time variable, which I call Universal and macroscopic, before I focus down on T-invariance and its violations in the microscopic laws of physics. The three type of  $t$ -asymmetry are, as far as I can tell, fundamentally unrelated. I include the first two simply because I find them interesting.

### 1.1. Universal $t$ -asymmetry

There is no doubt that we live in a Universe that is expanding, indeed we even have evidence that the rate of that expansion is increasing with time. It also appears that our Universe began its history with a period of exponentially rapid expansion known as inflation. All this is clearly a violation of symmetry under  $t$  goes to  $-t$ . Indeed we also observe a preferred frame within our Universe, the frame in which the cosmic microwave background radiation has the same temperature coming from all directions, modulo the tiny fluctuations about that universal average value. All of this it is completely compatible with underlying laws of physics that have an intrinsic  $t$  goes to  $-t$  symmetry, and indeed all the Lorentz symmetries of general relativity. Such a Universe is a possible solution of Einstein's equations. These same equations have another solution that has the opposite time evolution, but since any Universe that fulfils that solution would be completely disconnected from (and thus unobservable from) our Universe, the symmetry between these two solutions is a matter of mathematical rather than physical interest.

In an Inflationary Big Bang theory an initial small space-like volume expanded to become the observable Universe. An observable relic of that expansion is found in the cosmic background radiation, both its uniform average value and its fluctuations. The frame in which this radiation is seen to be the same temperature coming from all directions, up to fluctuations that are a few parts in a million, is presumably determined by the initial space-like patch that inflated to become our Universe. Beautiful maps of the fluctuations have been produced by experiments, culminating in the most recent results from WMAP [2]. Ongoing studies are seeking to refine our knowledge of the map of polarization in this radiation. The concordance of the interpretation of these maps with data from a number of very different types of measurements, such as studies of supernova spectra, Lyman-alpha "forests", deep structure surveys, etc. is a triumph for scientific cosmology. All are consistent with a solution of Einstein's equations of the Universe after it emerged from an initial inflationary epoch, a flat space with a tiny cosmological constant that today dominates over its matter and dark matter content. This concordance is, to me, a beautiful and convincing demonstration that we can measure these basic properties of the Universe with remarkable precision.

### 1.2. Macroscopic $t$ -asymmetry

A second type of  $t$ -asymmetry, often called the "arrow of time", is the thermodynamic law of increase of entropy. Initially ordered systems become more disordered over time – and that indeed is our usual experience of the physical world. However, in systems with a limited number of degrees of freedom we find cycles, ordered states may give way to apparently disordered ones, but if you watch the system long enough it actually goes through a cycle and the initial ordered state reappears periodically. As the number of coupled degrees of freedom in the system

increases, the typical time for such a cycle gets longer. Eventually, with enough degrees of freedom, the thermodynamic description can be applied; rigorously speaking it applies for an isolated infinite system. [3]

If we prepare a many variable system, such a gas of atoms in an initial ordered, and hence non-equilibrium, state (but not a pure state in the quantum sense) then it will evolve to become less ordered, asymptotically approaching thermal equilibrium, which is an equipartition of energy among the available modes. The chance that we will observe an apparently disordered system evolve towards order is infinitesimal. Nothing in the microscopic laws of physics provides this asymmetry, every specific evolution sequence has a physically possible inverse evolution sequence. However, while we can in various ways prepare a relatively ordered system and watch it evolve, it is difficult to prepare and observe the precisely time-reversed situation. In particle physics, particle decays are an example of a time-asymmetric experience. If we start with an initial collection of identical but unstable particles we arrive after decay at a large collection of final states, many possible outcomes, populated by laws of probability that we may understand. But there is little if any chance of any collection of such states evolving to become a set of identical unstable particles. Once again this macroscopic asymmetry has nothing to do with T-violation in the underlying laws of physics; it would be so even in a theory where T-invariance is an exact symmetry of the microphysics. Process by process, the laws of physics that allow particle decay also allow the inverse process of particle creation. It is just more difficult to arrange the circumstances in which it can be observed. For example we produce flavored particles in pairs in strong interaction processes, but observe their weak decays. This mismatch tells us nothing about whether there is or is not an underlying microscopic symmetry in the laws of physics.

Is there any connection between the macroscopic and the Universal t-asymmetries? They are quite separate effects, and do not have common underlying causes. However our relatively recent understanding of the Inflationary Universe does help solve one of the issues that has puzzled those who think about entropy increase in the Universe as a whole. If the Universe is an isolated system, then the its entropy should be always increasing. The puzzle then is that it must have started in a relatively ordered state, a relatively improbable initial condition. The whole question of the probability of the initial condition that gave rise to our Universe is one that is fraught with logical dangers, as one sees when reading the recent string theory literature on landscapes –the question of the measure by which one defines such probabilities remains a vexing one. However, the state of the Universe that emerges from an inflationary epoch in which it has undergone something of the order of sixty e-foldings of expansion is a relatively ordered one, simply because all high frequency excitations of the initial patch have been inflated into long wave-length smooth features of the resulting expanded Universe. Inflation apparently fixes the entropy problem, in the same way that it fixes the horizon and flatness problems of the Universe, by expanding away almost all the initial details. However there follows a rapid increase in entropy, in a process known as reheating, which produces a hot dense plasma of matter and antimatter.

### *1.3. Microscopic T-violation*

Now I turn to the T-violation in the laws of physics. We know there is such an effect in the Standard Model or any field theoretic extension of it. These theories must contain CP violating effects to match observations. In the context of theories that have CPT symmetry, as all field theories do, there is an automatic connection between ant CP-violation and a related T-violation. T-violation, in this context means an asymmetry, not only under the reversal of the sign of  $t$  in the equations of motion, but also under the interchange of in-states and out states. At the microscopic level we study specific initial and final states, so this second aspect is as important as the first in discussing T-violation. There are effects in particle physics that are odd under  $t$  to  $-t$ , but are not T-violation, because they have do not correspond to an interchange of in states for

out states. These kind of t-asymmetries, like the macroscopic and the Universal t-asymmetry, can occur in theories which have an exact T-symmetry in the microscopic physics. I will not talk further about them.

## 2. Strong T- and CP-violation

One of the mysteries of the Standard Model, and an ongoing challenge for any extended theory that incorporates it, is how to insulate the strong interaction sector from developing CP and T violating effects, once we know such effects are indeed present in the weak interactions. The small upper limit on the electric dipole moment of the neutron [5] indicates that any such effect is small. Indeed it is one of the strongest constraints on models for new physics that we have. Even for the Standard Model it raises an issue.

Within QCD there is possible a CP (P) and T violating operator,  $\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$ , that can appear as a term in the effective Lagrangian, multiplied by an arbitrary angular parameter, usually denoted by  $\theta$ . This parameter is not strictly speaking a new coupling, but rather it is a boundary condition that tells us how the multiple gauge equivalent but non-trivial winding number “vacuum states”  $|n\rangle$  are added together to give a well-defined physical vacuum  $|\theta\rangle = \sum_n e^{in\theta}|n\rangle$ . The smallness of the neutron dipole moment requires that this parameter theta be small, of the order  $10^{-10}$  or less[4]. Why is this parameter so small? Is there a mechanism that protects it from developing a larger value?

Roberto Peccei and I addressed this question more than thirty years ago and came up with an answer, now generally known as Peccei-Quinn symmetry [6]. Let me share a little of the thinking that led us to this answer. It was well known that, in a theory with any massless quark, the theta parameter is physically irrelevant, because it can be rotated away by a chiral redefinition of that quark field. The actual physical parameter is  $\theta_{eff}$  the difference between the theta coefficient defined above and the phase of the determinant of the quark mass matrix. Roberto and I were confused by the fact that, in the hot early Universe, quarks are all massless. So, we asked one another, can't the theta parameter be removed then –but if so, how can it become relevant later? The resolution is to ask what remembers the effect of chiral rotations in the high temperature phase of a Higgs-type theory. The answer is the phases of quark-Higgs couplings. This then gave us the idea that we could arrange a naturally small  $\theta_{eff}$  value by adding a global U(1) symmetry to these couplings arranged such that, when the Higgs fields do get a non-zero vacuum value, the minimum of the potential is that which gives  $\theta_{eff} = 0$ . The symmetry is a pseudo-symmetry, it is broken by the theta term, which tips the potential in just such a way that the minimum is the CP and T conserving solution. One consequence of this pseudo-symmetry is a pseudo-Goldstone boson, the axion. Roberto and I failed to notice this. We did not investigate the phenomenology of the model we used to illustrate our idea. We knew that that model was probably too simple to survive, and indeed it has since been ruled out by experiment. However we should have noticed that the existence of the axion, though not its detailed properties, is a direct consequence of the pseudo-symmetry and will occur in any model that achieves a small theta parameter by this mechanism. Weinberg and Wilzcek, separately, soon pointed this out.[7]) Modified Peccei-Quinn type theories, called “invisible axion” models[8] add further extra Higgs multiplets, including an weak SU(2) singlet, and thereby avoid the bounds that ruled out our initial example model. These bounds come both from direct particle searches and from considering the astrophysical consequences of a new light and weakly interacting particle, for example as a transport mechanism that would change the cooling rate of red giant stars.

Interestingly, the “invisible” axion is a possible dark matter candidate. It is a light and very weakly interacting particle. It manages to be a cold dark matter despite its tiny mass if the axion population is dominated by the relics of a primordial coherent axion field that existed prior to the QCD phase transition that gives the axion its mass, rather than by thermally produced axions. Searches for this particle are an interesting complement to searches that look

for more massive dark matter candidates known as WIMPS. To the best of my knowledge, only one set of axion search experiments reaches into the interesting range of sensitivity, where, if “invisible” axions dominate the dark matter of our galaxy, the experiments might be able to detect them in the coming few years. That is the experiment at LLNL led by Carl Van Bibber and Leslie Rosenberg. [9] I think it is important to pursue such searches, as a complement to the WIMP search experiments that tend to get more attention because of the possible relationship of WIMPs to particles that may be detected at the LHC.

All this strays a little from the issue of T-violation – clearly I have a bias about axions as a possible, and to my mind somewhat neglected, dark matter candidate. My excuse in discussing them here is that they arise from a mechanism to avoid a T-violating effect. Other approaches to this problem, such as theories where the Lagrangian is required to be CP invariant and all CP violation arises by spontaneous symmetry breaking, are, to my mind, less attractive, because I find the models developed to fit the large CKM CP violation via a spontaneous symmetry breaking effect to be somewhat contrived. However, as always, beauty is in the eye of the beholder, others may respond that invisible axion theories are likewise contrived.

### 3. Weak Interaction T- and CP-violation

The mechanism of weak interaction CP violation arises from the single physically relevant phase in the three generation CKM matrix. This has been validated by the past ten years of experiments probing CP violation, particularly the studies of the decays of neutral B mesons. This success of the three-generation theory has been recognized by the award of a share of this year’s (2008) Nobel prize in physics to Kobayashi and Maskawa, who pointed out that a third generation was needed to incorporate CP violation in a Standard Model theory with a single Higgs multiplet.[10] (Weinberg showed that additional Higgs multiplets offered another way to allow CP-violating phases, but, we now know that this is not the dominant mechanism responsible for the observed CP violation effects in K and B mixing and decays.[7] Clearly since the Standard Model theory is CPT invariant it predicts T-violation effects in parallel to each CP-violation effect that arises due to the phase differences of different weak couplings.

One can classify three ways in which CP violation manifests itself in 3 generation Standard Model physics. These are: CP violation in decays (sometimes called “direct” CP violation); CP violation in the mixing of neutral states to form mass eigenstates that are not possible CP eigenstates; and CP violation that arises from an interference between decay with and without mixing. All have been observed. For each, given the CPT theorem, there must be a corresponding type of T-violating effect. In the rest of this lecture I will summarize the observational status on each type.

#### 3.1. CP Violation in decays

T-violation matched to a CP-violation in decay is expected but not observed, simply because the observations are too difficult to attempt. For any unstable particle we observe both production and decay processes, but, as mentioned above, we rarely have a chance to match the rates for a particular decay process with a measured rate for the inverse production process; it is just too difficult to prepare the initial state. Let us look at the example of B decays to a K plus pion. This is a rare decay, branching fraction of order  $10^{-5}$ . However, because we can produce millions of B mesons in B-factory facilities, we do observe it, and indeed have measured it precisely enough to clearly establish a CP violating rate asymmetry. There is a difference between the rate  $R_1$  for  $B^0 \rightarrow K^+ \pi^-$  and the rate  $R_2$  for the CP conjugate process  $\bar{B}^0 \rightarrow K^- \pi^+$ [11]. CPT tells us that rates for the inverse processes have rates  $R_1$  for  $K^+ \pi^- \rightarrow \bar{B}$  and  $R_2$  for  $K^- \pi^+ \rightarrow B^0$ . Comparing each process with its own inverse we expect a T-violation that is a direct partner of the CP violation. However there is very little chance that anyone will actually measure these inverse rates and check this expectation.

### 3.2. CP Violation in Mixing

The manifestation of CP violation in the mixing of two neutral but flavored mesons, say  $K^0$  and  $\bar{K}^0$ , is that the mass eigenstates  $K_L$  and  $K_S$  are not CP eigenstates. If we write  $K_L = \frac{pK^0 + q\bar{K}^0}{\sqrt{p^2 + q^2}}$  and  $K_S = \frac{pK^0 - q\bar{K}^0}{\sqrt{p^2 + q^2}}$  it is clear that, no matter what phase convention you choose, if  $|q/p|$  is not equal to unity, these two states are not CP eigenstates. The observation of the decay of  $K_L$  to two pions was the first observed CP violation.[12] It indicates a non-zero value for  $1 - |q/p|$ . (As will probably be discussed later in this conference, no evidence for CPT violating terms in the mixing have been seen for either neutral kaon or for neutral B-decays; these would correspond to the need to introduce a different value of  $q/p$  for the heavy and light mass eigenstates.)

Can we see a related T-invariance violation? Here there is indeed a possible experiment, we can ask whether the rate for a particle tagged at its production as a  $K^0$  to decay in a way that identifies it as a  $\bar{K}^0$  is equal to the rate for a particle tagged at its production as a  $\bar{K}^0$  to decay in a way that identifies it as a  $K^0$ . My difference is clearly both CP violating and T violating. This experiment has been done, by CP-LEAR.[13] To no-one's surprise it yielded a T-violating difference in these rates. Indeed such a difference is a consequence of the parameters that define the mass eigenstates in terms of the flavor eigenstates, and these parameters had been quite well determined by measurements on a variety of decays. Since this is all an old story I do not present the details here.

### 3.3. CP Violation interference of decays with and without mixing

The by-now classic example of this effect is the time-dependant CP asymmetry between the rate  $B^0 \rightarrow J/\psi K_S$  (or  $J/\psi K_L$ ) and the CP conjugate rate for  $\bar{B}^0$  to decay to the same CP-eigenstate final state. In the case of the  $B^0$  mesons  $|q/p|$  is indeed unity, or so close to it that the as-yet unobserved deviation can be ignored for the purposes of this discussion. However a CP violation arises because the phase of this quantity minus the phase of the ratio of amplitudes for the decay and its CP conjugate (also a quantity of absolute value 1) does not vanish. In the Standard Model this phase difference is predicted to be proportional to one of the angles of the CKM unitarity triangle, known as either  $\beta$  or  $\phi_1$ . The decay of the  $\Upsilon_{4s}$  produces an antisymmetric coherent state of two B mesons. Events of interest for this measurement are those where one neutral B meson decays in a way that defines its flavor, and the other decays to the CP eigenstate of interest here. The time parameter  $\Delta t$  is the time difference between these two decays. Experiments have now reached very high precision.[14] The data clearly shows an asymmetry with respect to the sign of this time parameter, an asymmetry which reverses sign which is reversed between the  $B^0$  and  $\bar{B}^0$  tagged events, and between  $J/\psi K_S$  and  $J/\psi K_L$  events with the same tag. All of this is the expected CP-violating effect. However, since there is no reversal of in and out states this time asymmetry cannot directly be interpreted as a T-invariance violation

However, there is a way to observe a related T-violating quantity. The opportunity arises from the quantum mechanical properties of the antisymmetric coherent state of two neutral B mesons. Bose statistics demands that these two mesons are in orthogonal states. One can use this orthogonality, as is done in the CP-violation studies, by tagging the flavor the state of one of the mesons by its decay process, to infer the flavor state the other B is in (or would have to be in had it not already decayed) at the instant of the flavor tagging decay. However, as was pointed out by Banuls and Bernabeu. [15] one can equally well define and tag any pair of orthogonal states. In particular they define what they call a "CP-tagged" state, namely the state that decays to the (odd) CP eigenstate  $J/\psi K_S$  and the orthogonal or conjugate state that is forbidden to decay in that way but that does decay (with close to equal rate) to the opposite CP eigenstate  $J/\psi K_L$ .

This observation allows one to construct measurements that compare, for example the rate for a  $B^0$  to evolve to the CP-eigenstate  $B - odd$  that decays to  $J/\psi K_S$  (negative lepton flavor

tag decay first, odd CP-eigenstate decay second) with the rate for the CP-eigenstate  $B - odd$  to evolve to  $B^0$  (even CP eigenstate decay ( $J/\psi K_L$ ) first, positive lepton flavor tag decay second). The dominant effect in this difference is T-invariance violating. This effect is proportional to  $\sin 2\beta$ , matching the observed CP violation that occurs in the  $J/\psi K_S$  and (with opposite sign) in  $J/\psi K_L$  decays. In my talk in Valencia I referred here to the paper of Alvarez and Szykman, [16] but the essential idea is contained in the earlier work. Alvarez and Szykman develop the test suggested by Banuls and Bernabeu, and used data published since the original work to demonstrate that it gives a T-violating effect. However, the test requires separating events with the flavor-tagging decay before or after the CP-tagging decay, whereas the published data uses a single fit to all t-values to determine the best fit coefficient of the  $\sin(\Delta m \Delta t)$  term in the rates. It is then not quite legitimate to say that fit describes the separated positive and negative  $\Delta t$  behavior. It would be worthwhile for the BaBar and Belle experiments to perform the time-separated fits that will cleanly demonstrate this T-violating effect. Corrections due to any possible lifetime difference of the two  $B$  mass eigenstates, to possible direct CP violation in the decay  $B^0 \rightarrow J/\psi K_S$  (or  $K_L$ ), or to CP violation in K-decays are small corrections to the dominant T-violating effect that can be observed here.

This test makes no assumption about CPT invariance – it is a test for T-violation based on purely quantum mechanical statements about matrix elements and their T-conjugate. CPT comes into the picture in the relationship between the T-violating quantity described here and the CP-violating quantities usually evaluated from this same data. One can thus also devise tests of CPT from this data, however I do not think they are as sensitive as other CPT tests in B decays, which I assume will be discussed in later lectures in this conference.

#### 4. Conclusion

In sum tests of microscopic T-invariance, or observations of its violation, are limited by the fact that, while we can measure many processes, only in very few cases can we construct a matched pair of process and inverse process and observe it with sufficient sensitivity to make a test. In both the cases discussed here we can achieve an observable T violation making use of flavor tagging, and in the second case also using the quantum properties of an antisymmetric coherent state of two B mesons to construct a CP-tag. Both these tagging properties depend only on very general properties of the flavor and/or CP quantum numbers and so provide model independent tests for T-invariance violations.

The microscopic laws of physics are very close to T-symmetric. There are small effects that give CP- and T-violating processes in three-generation-probing weak decays. Where a T-violating observable can be constructed we see the relationships between T-violation and CP-violation expected in a CPT conserving theory. These microscopic effects are unrelated to the “arrow of time” that is defined by increasing entropy, or in the time direction defined by the expansion of our Universe.

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