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Three merry roads to T-violation

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ABSTRACT

This paper is a tour of how the laws of nature can distinguish between the past and the future, or be T-violating. I argue that, in terms of basic analytic arguments, there are really just three approaches currently being explored. I show how each is characterized by a symmetry principle, which provides a template for detecting T-violating laws even without knowing the laws of physics themselves. Each approach is illustrated with an example, and the prospects of each are considered in extensions of particle physics beyond the standard model.

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1. Introduction

Unlike thermal physics, the physics of fundamental particles does not normally distinguish between the past and the future. For example, most classical mechanical systems never do. This dogma once ran so deep that, even after the shocking discovery of Wu, Ambler, Hayward, Hoppes, and Hudson (1957) that parity or "mirror symmetry" is violated, it remained difficult to imagine the violation of temporal symmetry. Many simply considered it to be an unavoidable aspect of quantum field systems, because of the great simplification it provided in the description of weakly interacting particles.[1]

Since then, a great deal of evidence has been accumulated showing that, contrary to the early views of particle physicists, fundamental physics can be *T-violating*—it *does* distinguish between the past and the future! I do not wish to retell that story here. There are many sources,[2] which are really much better than me, that will explain to you all about the gritty and ingenious detections of *T*-violating interactions, the deep and beautiful theory underlying them, and how we can expect that theory to develop from here.

I would like to attempt a different project, to draw out the basic analytic arguments underlying the various approaches to *T*-violation. I would like to cast these arguments into their bare skeletal form; to think about what makes them alike and distinct; and to ask how they may fare as particle physics is extended beyond what we know today. In sum, this will be a cheerful tour—from a birds eye view, if you like—of the existing roads to *T*-violation.

There are, I think, two main benefits to this abstract perspective. The first is to show that there are really only three distinct roads to *T*-violation from where we stand today. Each one is characterized by a symmetry principle, and each is a deductive consequence of quantum mechanics and quantum field theory. The second benefit of the abstract perspective is that it illustrates the powerful generality of our evidence for *T*-violation. We will see in particular that these approaches allow us to test whether the laws of physics are *T*-violating, *even when we don't know what the correct laws of physics are!* Here is a summary of the three approaches to *T*-violation.

1. *T-Violation by Curie's Principle*: Pierre Curie declared that there is never an asymmetric effect without an asymmetric cause. This idea, together with the so-called *CPT* theorem, provided the road to the very first detection of *T*-violation in the 20th century.

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[1] Cf. Weinberg (1958) and Lande, Booth, Impeduglia, Lederman, & Chinowsky (1956). As James Cronin colorfully put it: "It just seemed evident that CP symmetry should hold. People are very thick-skulled. We all are. Even though parity had been overthrown a few years before, one was quite confident about *CP* symmetry" (Cronin & Greenwood, 1982). In the presence of *CPT*-invariance, *CP* symmetry is equivalent to *T* symmetry.

[2] For a book-length overview, try Kabir (1968a), Sachs (1987), Kleinknecht (2003), Sozzi (2008) and Bigi & Sanda (2008).

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2. *T-Violation by Kabir's Principle*: Pasha Kabir pointed that, whenever the probability of an ordinary particle decay $A \to B$ differs from that of the time-reversed decay $B' \to A'$, then we have *T*-violation. This provides a second road.
3. *T-Violation by Wigner's Principle*: Certain kinds of matter, such as an elementary electric dipole, turn out to be *T*-violating because they have an appropriate non-degenerate energy eigenstate.[3] This provides the final road, although it has not yet led to a successful detection of *T*-violation.

In the next three sections, I will explain each of these three roads to *T*-violation. Some of these roads are very exciting and surprising, especially if you have not traveled down them before, and I will try to keep things light-hearted for the newcomer. My explanations will begin with a somewhat abstract formulation of an analytic principle, followed by an illustration of how it provides a way to test for *T*-violation, and then an elementary mathematical treatment. I'll end each section with a little discussion about the prospects for extensions of particle physics beyond the standard model, and in particular extensions in which the dynamical laws are not unitary.

Let's start at the beginning.

2. *T*-violation by Curie's Principle

The first evidence that the laws governing weakly interacting systems are *T*-violating was produced, rather incredibly, in the mid-1960s. This was before the standard model was formulated. It was before a complete understanding of weak interactions. I think it's fair to say that we had little knowledge of the correct laws describing these systems whatsoever, if one takes "the laws" to be given by a Lagrangian or Hamiltonian (together with the Euler-Lagrange or Hamilton equations, respectively). So how could we know the laws are *T*-violating? It was through a clever principle first pointed out by the great French physicist Pierre Curie, and adopted by James Cronin and Val Fitch in their surprising discovery. Here is that story.

2.1. Curie's principle

In 1894, Pierre Curie argued that physicists really ought to be more like crystallographers, in treating certain symmetry principles like explicit laws of nature. He emphasized one symmetry principle in particular, which has come to be known as *Curie's principle*:

> When certain effects show a certain asymmetry, this asymmetry must be found in the causes which gave rise to them. (Curie, 1894)

To begin, we'll need to sharpen the statement of Curie's Principle, by replacing the language of "cause" and "effect" with something more precise. An obvious choice in particle physics is to take an "effect" to be a quantum state. What then is a cause? A natural answer is: the *other* states in the trajectory (e.g. the states that came before), together with the law describing how those states dynamically evolve. So, Curie's principle can be more clearly formulated:

> If a quantum state fails to have a linear symmetry, then that asymmetry must also be found in either the initial state, or else in the dynamical laws.

This is a common interpretation of Curie's principle.[4] In fact it can be sharpened even more, and we will do so shortly. But first let's see how it appears in the surprising discovery of Cronin and Fitch.

2.2. Application to CP-violation

The Cronin and Fitch discovery of *T*-violation really goes back to an incredible work by Gell-Mann and Pais (1955), which among other things introduces a version of Curie's Principle. They did not refer to it in this way, but I think you will see that the principle is unmistakably Curie's. Let's start with the example of *charge conjugation* (CC) symmetry, which has the effect of transforming particles into their antiparticles and vice versa. Suppose we have two particle states θ_1 and θ_2; their interpretation is not important for this point.[5] And suppose the state θ_1 is "even" under charge conjugation, in that $C\theta_1 = \theta_1$, while the state θ_2 is "odd," in that $C\theta_2 = -\theta_2$. Then, Gell-Mann and Pais observed,

> according to the postulate of rigorous CC invariance, the quantum number *C* is conserved in the decay; the θ_1^0 must go into a state that is even under charge conjugation, while the θ_2^0 must go into one that is odd. (Gell-Mann & Pais, 1955, p.1389).

Given *C*-symmetric laws, a *C*-symmetric state must evolve to another *C*-symmetric state. Or, reformulating this claim in another equivalent form: if a *C*-symmetric state evolves to a *C*-asymmetric state, *then the laws themselves must be C-violating*. That's a neat way to test for symmetry violation. And it's a simple application of Curie's Principle.

Although Gell-Mann and Pais were discussing *C*-symmetry, the same reasoning applies to any linear symmetry whatsoever. In particular, it applies to *CP*-symmetry, which is the combined application of charge conjugation with the parity (*P*) or "mirror flip" transformation. Cronin later wrote that the Gell-Mann and Pais article "sends shivers up and down your spine, especially when you find you understand it," pointing out that it suggests a statement that is clearly an application of Curie's Principle (although Cronin does not call it that):

> You can push this a little bit further and see how CP symmetry comes in. The fact that CP is odd for a long-lived *K* meson means that K_L could not decay into a π^+ and a π^-. If it does—and that was our observation—then there is something wrong with the assumption that the CP quantum number is conserved in the decay. (Cronin & Greenwood, 1982, p. 41)

Here is that reasoning in a little more detail. When you create a beam of neutral *K* mesons or "kaons," the long-lived state K_L is all that's left after the beam has traveled a few meters.[6] This long-lived state had been discovered eight years earlier in the same laboratory by Lande et al. (1956). And it was known that K_L is *not* invariant under the *CP* transformation, whereas a two pion state $\pi^+\pi^-$ *is* invariant under *CP*. The observation of such the asymmetric decay $K_L \to \pi^+\pi^-$, Cronin points out, could only be the result of a *CP*-violating law (Fig. 1). That's just Curie's Principle.

The Cronin and Fitch experiment of 1964 involved firing a K_L beam into a spark chamber at the Brookhaven National Laboratory, and taking photographs of thousands of particle decay events occurring over the course of about 10^{-10} s. Their "Eureka moment"

[3] An energy eigenstate is *degenerate* if there exists an orthogonal eigenstate with the same eigenvalue. I will discuss this property in more detail below.

[4] C.f. (Earman, 2004; Mittelstaedt & Weingartner, 2005, Section 9.2.4).

[5] Gell-Mann and Pais used θ_1^0 and θ_2^0 to refer to what we know call the neutral kaon states K_1 and K_2, discussed in Footnote 6 below.

[6] The study of strong interactions had led to the identification of kaon particle and antiparticle states K_0 and $\overline{K}_0$ that are eigenstates of a degree of freedom called *strangeness*. When testing for *CP*-violation, it is easier to study the superpositions $K_1 = (K^0 + \overline{K}^0)/\sqrt{2}$ and $K_2 = (K^0 - \overline{K})/\sqrt{2}$, since the lifetime of the latter is orders of magnitude longer. At the time, K_2 was identified as the "long-life kaon state K_L."