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Response to Bryan Roberts: A new perspective on *T* violation

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ABSTRACT

It is surprising that the *fundamental, microscopic* laws of Nature are not invariant under time reversal. In his article, *Three Merry Roads to T-Violation*, Dr. Bryan Roberts provided a succinct summary of the theoretical frameworks normally used to interpret the results of the experiments that established this fact. They all rely on the detailed structure of quantum mechanics. In this 'response' to Dr. Robert's talk, I will show that these experiments can be interpreted using a *much* more general framework. Consequently, should quantum mechanics be eventually replaced by a new paradigm, e.g., because of quantum gravity, these experiments could still be used to argue that the microscopic laws violate *T* invariance.

1. Preamble

Dr. Roberts has provided a lucid account (Roberts, 2013a) of the conceptual arguments that have been used to show that the *fundamental, microscopic* laws of Nature fail to be invariant under the time-reversal operation, *T*. His clear presentation led me to sharpen my own understanding of the theoretical constructs that have been used to analyze experiments in this area. This response is the result of that re-examination. I have attempted to make it reasonably self-contained but, to fully appreciate its content, it would be helpful if the reader has already gone through Dr. Robert's paper.

I will focus on the two approaches to *T*-violation—referred to as the *Curie and the Kabir principle* in Roberts (2013a) and recalled below—that have already been used to analyze experiments. However, following this workshop, Dr. Roberts has also extended the third approach, based on Wigner's non-degeneracy principle, to the general setting presented in this article (Roberts, 2013b).[1]

To interpret any experiment, one needs a theoretical paradigm. For *T*-violation experiments, the standard choice has been the mathematical framework of quantum physics. This is natural because the best available description of the electro-weak interactions is based on local quantum field theory. However, in this response, I will show that one can in fact analyze the *T*-violation experiments in a *much* more general setting. Classical mechanics, quantum mechanics and quantum field theory provide only specific examples of this general framework. As is often the case, because this framework has much less structure, the analysis becomes significantly simpler. As a result, aspects of quantum physics that are truly essential for interpreting experiments on *CP* and *T*-violation are brought to the forefront. They are clearly separated from other features which, though not central, have generally been treated in the literature as being equally significant. More importantly, the conceptual structure that is essential to the interpretation of experiments is so weak that, even if quantum physics were to be replaced by some more general framework—e.g., because of its unification with general relativity—the current experiments will still, in all likelihood, enable us to conclude that the fundamental laws of Nature fail to be invariant under time reversal.

The issue of time-reversal has two distinct facets: microscopic and macroscopic. The microscopic *T*-violation discussed in Roberts (2013a) and in the present communication is quite distinct from the manifest arrow of time we perceive in our everyday life and, more generally, in the physics of large systems. Since Dr. Roberts mentioned the macro-world only in passing, before entering the

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[1] Perhaps the most promising experiments to realize this idea are the measurements of the electric dipole moment of elementary particles, such as neutrons. However, the dipole moment fails to be invariant also under the parity operation *P*. Therefore, even if one were to observe a non-zero electric dipole moment, one would need to cleanly remove the parity contribution before one can draw definitive conclusions about *T* violation. Consequently this route to experimentally demonstrating *T*-violation has been quite difficult.

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main discussion, let me begin with a brief detour to explain this point. For simplicity, I will use the framework of classical physics because the core of the argument is not sensitive to the distinction between classical and quantum mechanics. Consider a large box with a partition that divides it into two parts, say, the right and the left half. Suppose that there is some gas in the left half and vacuum in the right. Once the equilibrium is reached, the macroscopic state of this gas is described by the volume it occupies, V_i; the pressure it exerts on the walls of the box, P_i; and its temperature, T_i; where i stands for 'initial'. If we open the partition slowly, the gas will fill the whole box and its macro-state in equilibrium will be described by new parameters, V_f, P_f, T_f. Thus, there has been a transition from the initial macro-state (V_i, P_i, T_i) to the final state (V_f, P_f, T_f). Our common experience tells us that the time reverse of this process is *extremely* unlikely. However, we also know that the microscopic variables for the system are the positions and momenta of some 10^{23} molecules in the box. These are subject just to Newton's laws which are *manifestly invariant under the time-reversal operation* T! Therefore, if we were to reverse the momentum $\vec{p}_{(\alpha)}(t)$ of each molecule (labeled by α) at a late time t, keeping the positions $\vec{x}_{(\alpha)}(t)$ the same, time evolution would indeed shift the gas back from its final macroscopic state to the initial one, confined just to the left half of the box. But in practice it is very difficult to construct this time-reversed initial state. Thus, there is indeed a macroscopic arrow of time but its origin is *not* in the failure of the microscopic laws to be invariant under T but rather in the fact that the initial conditions we normally encounter are very special. Specifically, in our example, there are vastly fewer micro-states compatible with the initial macro-state (V_i, P_i, T_i) than those that are compatible with the final macro-state (V_f, P_f, T_f).[2] Put differently, the entropy of the initial macro-state is much lower than that in the final macro-state. This is the arrow of time, commonly discussed in the literature.

It is clear from the simple example that the fact that there is an obvious arrow of time in the macro-world does *not* imply that the microscopic or fundamental laws have to break T-invariance. Indeed, as Dr. Roberts emphasized in the beginning of his article (Roberts, 2013a), it was common to assume that the fundamental laws *are* invariant under the time-reversal operation T. It came as a shock that the weak force violates this 'self-evident' premise!

The rest of this article will focus on the T violation at the fundamental, microscopic level.

2. Weak interactions and the Curie principle

As Dr. Roberts has explained, what the Cronin–Fitch experiment (Christenson, Cronin, Fitch, & Turlay, 1964) establishes directly is that the weak interactions are not invariant under CP, i.e., under the simultaneous operations of charge conjugation C and reflection through a mirror, P. As normally formulated, the parity operation is meaningful only if the underlying space–time is flat, i.e., represented by Minkowski space–time. This means that one ignores curvature and therefore gravity. One further assumes that physics is described by a local quantum field theory on this Minkowski space, for which individual physical fields transform covariantly under the action of the Lorentz group, and dynamics is generated by a self-adjoint Hamiltonian obtained by integrating a scalar density (or a 3-form), constructed locally from the physical fields. Then, one has the *CPT theorem* that guarantees that the product *CPT* of charge conjugation, C, parity, P and time reversal, T, is an exact *dynamical* symmetry.[3] Therefore, although the Cronin–Fitch experiment does not *directly* imply T-violation, as Dr. Roberts explained, if we assume that weak interactions are described by a local quantum field theory in Minkowski space, then the observed breakdown of CP invariance implies that they violate T invariance as well. In the rest of this section, I will focus on just the *CP* symmetry and its violation observed in the Cronin–Fitch experiment. Thus, I will not need to refer to the CPT at all.

In the current analysis of *CP* violation, one uses the following form of the Curie principle: If an initial state σ_i is in variant under *CP* but its time-evolved final state σ_f is not, then dynamics cannot be *CP* invariant. As explained in Section 2.5 of Roberts (2013a), the analysis has the remarkable feature that it does not assume a specific Hamiltonian H. Therefore, the argument will remain unchanged should we discover that the currently used Hamiltonian H in electro-weak interactions has to be modified, e.g., to accommodate future experiments, or to unify them with strong interactions.

However, the standard analysis *does* make a crucial use of the detailed kinematical structure of quantum physics (summarized below). If a future quantum gravity theory were to require that this structure has to be modified—e.g., by removing the emphasis on linearity—then the standard analysis cannot be used to conclude that the Cronin–Fitch experiment implies a violation of *CP* invariance in weak interactions. *The main point of this section is to show that this specific kinematical framework of Hilbert spaces and operators is not really necessary.* The Curie principle can be extended to a much more general framework than that offered by quantum physics.

Let us begin by introducing this framework, which we will call *general mechanics*. It will incorporate quantum as well as classical mechanics, but only as specific special cases. The basic assumptions of *general mechanics* are

- (i) We have a set $\mathcal{S}$ of states.
- (ii) There is a 1–1, onto dynamical map S—the 'S-matrix'—from $\mathcal{S}$ to itself. This S could refer to finite time evolution, say from time t_1 to t_2 or, alternatively, to the time evolution in the infinite past to the infinite future. In practice is it convenient to consider two copies $\mathcal{S}_i$ and $\mathcal{S}_f$ of $\mathcal{S}$, representing initial and final states, and regard S as a map from $\mathcal{S}_i$ to $\mathcal{S}_f$
$$S : \mathcal{S}_i \to \mathcal{S}_f; \quad S(\sigma_i) = \sigma_f, \quad \forall \sigma_i \in \mathcal{S}_i \tag{2.1}$$
- (iii) Potential symmetries are represented by a 1–1, onto map $R : \mathcal{S} \to \mathcal{S}$, from $\mathcal{S}$ to itself. We will first consider the case in which R maps $\mathcal{S}_i$ to itself and $\mathcal{S}_f$ to itself. This is the case if R is, for example, the discrete symmetry represented by C, or P or CP.

Note that the framework is truly minimalistic. *The space $\mathcal{S}$ of states is just a set*; no further structure is needed. To draw the contrast, let me summarize the structure we use in classical and quantum mechanics.[4] In classical mechanics, $\mathcal{S}$ is the phase space which is assumed to be a smooth, even dimensional differentiable

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[2] This is primarily because the volume V_f allowed for *each* molecule in the final macro-state is twice as large as V_i, allowed in the initial macro-state. Consequently, the number of microscopic configurations compatible with the final macroscopic state is about $2^{10^{23}}$ times the number of microscopic states compatible with the initial macroscopic configuration.

[3] This is a summary of the discussion one finds in quantum field theory text books (see, e.g., Weinberg, 1995). More rigorous versions based on Wightman axioms (Streater & Wightman, 1964, chap. 4) and the algebraic approach (Yngvason & Borchers, 2000) are also available in the literature. However, the self-adjoint Hamiltonian required in the text book version is not rigorously defined in four dimensions beyond the quantum theory of free fields. Similarly, we still do not have a single example of a 4-dimensional, interacting quantum field theory satisfying either the Wightman axioms or the axioms of the algebraic quantum field theory. Thus, there is a curious mis-match between the mathematical statements of CPT theorems and theories of direct physical interest.

[4] But the material till the end of this paragraph can be skipped without loss of continuity. It brings to forefront the intricacy of the structure underlying classical and quantum mechanics, in contrast to *general mechanics*.