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No contact terms for the magnetic field in Lorentz- and CPT-violating electrodynamics

Karl Schober, Brett Altschul *

Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, United States

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Abstract

In a Lorentz- and CPT-violating modification of electrodynamics, the fields of a moving charge are known to have unusual singularities. This raises the question of whether the singular behavior may include δ-function contact terms, similar to those that appear in the fields of idealized dipoles. However, by calculating the magnetic field of an infinite straight wire in this theory, we demonstrate that there are no such contact terms in the magnetic field of a moving point charge.

1. Introduction

Much of the history of modern physics has involved symmetries that initially appeared to be exact, yet which are actually violated in subtle fashions. Physics beyond the standard model might involve new forms of symmetry breaking. Among the most extreme symmetry violations that might occur in new physics are the breaking of Lorentz and CPT symmetries. These symmetries are related to isotropy, boost invariance, and hermiticity of the Hamiltonian. These features underlie both the standard model and general relativity, but quantum gravity theories could be different. In fact, many schematic theories of quantum gravity appear to have regimes in which Lorentz and CPT symmetries do not hold. Conversely, if evidence of these kinds of fundamental

* Corresponding author.
E-mail address: baltschu@physics.sc.edu (B. Altschul).

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symmetry violations were ever to be uncovered, that would provide powerful evidence about the shape of new physics beyond what we currently understand.

Exotic theories with unusual characteristics can also provide interesting theoretical laboratories for understanding the general structure of quantum field theories. Even if Lorentz and CPT symmetries are exact in nature, such theories may provide fundamental insights about the kinds of behaviors that are permitted in general field theories. The natural formalism for approaching these kinds of problems is effective field theory. The effective field theory that describes Lorentz and CPT violation is known as the standard model extension (SME), and it has been the subject of extensive study. The SME action is constructed from all operators that may be built up from standard model fields [1,2]. Without the requirement of Lorentz invariance, the number of possible operators is exceedingly large. For practical calculations, a standard theory for discussing these broken symmetries is known as the minimal SME; this is the subset of the SME that contains only the finite number of operators that are local, are power counting renormalizable, and respect the gauge symmetries of the standard model. Most experimental bounds on Lorentz violations are formulated in terms of constraints on minimal SME operators.

Some forms of Lorentz and CPT violation have more peculiar properties than others. Possibly the most unusual terms in the minimal SME have what is known as a Chern–Simons form. The electromagnetic Chern–Simons term affects the propagation of left- and right-handed photons differently. At relatively short wavelengths, the differences between the two modes' dispersion relations lead to a polarization rotation during propagation. At sufficiently long wavelengths, the frequency for one of the modes may become imaginary, signaling an instability. These and other unconventional features make the Chern–Simons theory particularly interesting as a tool for understanding how novel quantum field theories may potentially behave.

Because the electromagnetic Chern–Simons term breaks parity and CPT symmetries, the left–right asymmetry in wave propagation speeds would lead to photon birefringence. The distinctive birefringence signature has been searched for and not found, even for waves coming from sources at cosmological distances [3–5]. The lack of birefringence has been used to place exceedingly tight bounds on the coefficient of the real-world Chern–Simons term. Nevertheless, the Chern–Simons theory is still of theoretical interest, because the theory has some very unusual features. For example, the Chern–Simons Lagrange density is not gauge invariant; it changes, but only by a total derivative, under a gauge transformation. This fact makes the determination of the radiative corrections to the Chern–Simons term a very subtle problem, and the topic led to a significant amount of controversy [6–11].

We have previously investigated another peculiar feature in this theory—the possibility of vacuum Cerenkov radiation. Cerenkov processes are normally forbidden in vacuum by Lorentz invariance, but with Lorentz violation, the phase speed of light need not be uniformly 1 for all directions and frequencies. Because the Chern–Simons term affects the dispersion relation for propagating waves, radiation by charges in uniform motion (no matter how slow) becomes kinematically allowed in the theory. However, our investigations have showed that in the case of a timelike Chern–Simons parameter, there is no net radiation loss from a moving charge [12]

In the course of our investigations, we developed an iterative algorithm for determining the electric and magnetic fields of a moving point charge. The geometry of the solution is incompatible with radiation emission, but the structure of the fields is quite unusual, with singularities rather unlike those seen in the conventional electrodynamics of point sources. Since in the standard Maxwell theory, the fields of point dipoles include δ-function contact terms, it is natural to wonder whether there are analogous contact terms in the Chern–Simons theory.