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On the influence of a Rashba-type coupling induced by Lorentz-violating effects on a Landau system for a neutral particle

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HIGHLIGHTS

- Landau system from crossed electric and magnetic fields and fixed time-like vector.
- Analogues of the Rashba coupling, the Zeeman term and the Darwin term.
- Lorentz symmetry breaking effects on a two-dimensional quantum ring.
- Upper bound for the Lorentz symmetry breaking parameters.

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ABSTRACT

We study a possible scenario of the Lorentz symmetry violation background that allows us to build an analogue of the Landau system for a nonrelativistic Dirac neutral particle interacting with a field configuration of crossed electric and magnetic fields. We also discuss the arising of analogues of the Rashba coupling, the Zeeman term and the Darwin term from the Lorentz symmetry breaking effects, and the influence of these terms on the analogue of the Landau system confined to a two-dimensional quantum ring. Finally, we show that this analogy with the Landau system confined to a two-dimensional quantum ring allows us to establish an upper bound for the Lorentz symmetry breaking parameters.

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1. Introduction

The Lorentz symmetry principle, with the development of quantum mechanics, provided a guide for the formulation of a theory which describes the behaviour of elementary particles: the Standard Model. The search for a fundamental theory has brought the notion of symmetry, phase transition and spontaneous symmetry breaking. The mechanism suggested by Higgs et al. consolidated these concepts in the scope of the Weinberg–Salam–Glashow model. Despite of the tremendous success of the Standard Model, it fails to incorporate gravity as a fundamental interaction, therefore, the description of neutrinos consists in massless particles. In view of these limitations, there are some proposals for extensions of the Standard Model. In this work, we focus our study on a line that extends the spontaneous breaking of symmetry by tensorial fields.

The study of the symmetry breaking for relativistic systems can be extended by considering a background given by the spacetime indices of a tensor with rank $n \geq 1$. In magnetic systems, it is well-known that the spontaneous breaking of symmetry is performed by a vector background, where the symmetry group $SO(3)$ is spontaneously broken. A natural extension of this violating background is thinking in a four-vector or tensor background. The background field, in this situation, breaks the symmetry $SO(1, 3)$ instead of the symmetry $SO(3)$. This line of research is known in the literature as the spontaneous violation of the Lorentz symmetry [1–3]. This new possibility of spontaneous violation was first suggested in 1989 in a work of Kostelecky and Samuel [1] indicating that, in the string field theory, the spontaneous violation of symmetry by a scalar field could be extended. This extension has an immediate consequence: a spontaneous breaking of the Lorentz symmetry. In the electroweak theory, a scalar field acquires a nonzero vacuum expectation value which yields mass to gauge bosons (Higgs Mechanism). Similarly, in the string field theory, this scalar field can be extended to a tensor field. Nowadays, these theories are encompassed in the framework of the Standard Model Extension (SME) [4] as a possible extension of the minimal Standard Model of the fundamental interactions. For instance, the violation of the Lorentz symmetry is implemented in the fermion section of the Standard Model Extension by two CPT-odd terms: $a_\mu \overline{\psi}\gamma^\mu\psi$ and $b_\mu \overline{\psi}\gamma_5\gamma^\mu\psi$, where a_μ and b_μ correspond to the Lorentz-violating vector backgrounds. From these fixed vector field backgrounds, Lorentz symmetry breaking effects have been investigated in quantum Hall effect [5], self-adjoint extension [6–8], bound states solutions [9–11] and geometric quantum phases [12–18].

Our interest in this work is to study the nonrelativistic quantum dynamics of a Dirac neutral particle interacting with a field configuration of crossed electric and magnetic fields which stems from Lorentz symmetry breaking effects. We discuss the arising of analogues of the Rashba coupling, the Zeeman term and the Darwin term from the Lorentz symmetry breaking effects. Moreover, we study a possible scenario of the Lorentz symmetry violation background that allows us to obtain an analogue of the Landau system, and discuss the influence of the analogues of the Zeeman energy and the Rashba effect [19–26] on this Landau system confined to a two-dimensional quantum ring [27]. Finally, we show that this analogy with the Landau system confined to a two-dimensional quantum ring [27] allows us to establish an upper bound for the Lorentz symmetry breaking parameters.

The structure of this paper is: in Section 2, we discuss the nonrelativistic limit of the Dirac equation by applying the Foldy–Wouthuysen approximation [28,29], and show the arising of a Rashba-like coupling, a Zeeman-like term and a Darwin-like term induced by Lorentz symmetry breaking effects; in Section 3, we study a possible scenario of the Lorentz symmetry violation background that allows us to build an analogue of the Landau system for a nonrelativistic Dirac neutral particle interacting with a field configuration of crossed electric and magnetic fields, and the influence of the analogues of the Zeeman energy and the Rashba effect on this Landau system confined to a two-dimensional quantum ring [27]; in Section 4, we present our conclusions.

2. Rashba-like coupling, Zeeman-like term and Darwin-like term induced by a Lorentz symmetry violation background

In this section, we discuss the nonrelativistic quantum dynamics of a Dirac neutral particle interacting with a field configuration of crossed electric and magnetic fields induced by Lorentz symmetry breaking effects. Furthermore, we show that Lorentz symmetry breaking effects can induce