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On the effects on a Landau-type system for an atom with no permanent electric dipole moment due to a Coulomb-type potential

Abinael B. Oliveira, Knut Bakke *

Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970, João Pessoa, PB, Brazil

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ABSTRACT

We analyse the bound states for a Landau-type system for an atom with no permanent electric dipole moment subject to a Coulomb-type potential. By comparing the energy levels for bound states of the system with the Landau quantization for an atom with no permanent electric dipole moment (Furtado et al., 2006), we show that the energy levels of the Landau-type system are modified, where the degeneracy of the energy levels is broken. Another quantum effect investigated is a dependence of the angular frequency of the system on the quantum numbers associated with the radial modes and the angular momentum. As examples, we obtain the angular frequency and the energy levels associated with the ground state and the first excited state of the system.

1. Introduction

Coulomb-type potentials have been reported as being in the interests of several areas of Physics [1–3]. In the context of condensed matter physics, studies have worked with 1-dimensional systems [4–8], molecules [9–11], pseudo-harmonic interactions [12,13], position-dependent mass systems [14–16], the Kratzer potential [17] and topological defects in solids [18–22]. Other studies have dealt with Coulomb-type potential in the propagation of gravitational waves [23], quark models [24], atoms

* Corresponding author.
E-mail address: kbakke@fisica.ufpb.br (K. Bakke).

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with electric quadrupole moment [25–27] and magnetic quadrupole moment [28], neutral particle with permanent magnetic dipole moment [29] and relativistic quantum mechanics [30–33].

The objective of this paper is to analyse the quantum effects on the Landau system associated with an atom with no permanent electric dipole moment due to the presence of a Coulomb-type potential. The Landau quantization for an atom with no permanent electric dipole moment has been proposed in Ref. [34] based on the interaction of the induced electric dipole moment of the atom with a field configuration of crossed electric and magnetic fields. It is motivated by cold atoms technology that has allowed the simulation of several solid-state effects by using atoms and quantum optics techniques [35–42]. At present days, several effects are known in the literature that stem from the interaction between the electric dipole moment of atoms and external fields [43–46]. In particular, geometric quantum phases have attracted a great deal of work [47–61]. In Ref. [62], it has been shown that an analogue of the Aharonov–Bohm effect for bound states [63] and persistent currents [64] can be obtained for an atom with an induced electric dipole moment confined to a quantum ring and a quantum dot. In [65], the Landau-type quantization for an atom with an induced electric dipole moment was investigated in a two-dimensional quantum ring. Thereby, we analyse the bound states solutions to the Schrödinger equation that describes a Landau-type system for an atom with no permanent electric dipole moment subject to a Coulomb-type potential. In particular, we discuss a dependence of the angular frequency of the system on the quantum numbers associated with the radial modes and the angular momentum, where we calculate the angular frequencies and the energy levels associated with the ground state and the first excited state of the system as examples.

This paper is organized as follows: in Section 2, we make a brief introduction of the analogue of the Landau quantization associated with an atom with no permanent electric dipole moment, and thus investigate the quantum effects on this Landau-type system subject to a Coulomb-like potential; in Section 3, we present our conclusions.

2. Landau-type system subject to a Coulomb-like potential

In this section, we make a brief review of the Landau quantization associated with an atom/molecule with no permanent electric dipole moment, and thus investigated the effects of a Coulomb-like potential on this Landau-type system. In the rest frame of the atom or in the laboratory frame, the electric dipole moment of an atom can be considered to be proportional to the electric field: $\vec{d}=\alpha\,\vec{E}$, where α is the dielectric polarizability of the atom/molecule [59,66]. However, if the atom is moving with a velocity $\vec{v}$ ($v\ll c$), then, it interacts with an electric field $\vec{E}'$ determined by the Lorentz transformation. By applying the Lorentz transformation of the electromagnetic field up to terms of order $\mathcal{O}\left(v^2/c^2\right)$, we have that the electric field $\vec{E}'$ must be replaced with $\vec{E}'=\vec{E}+\vec{v}\times\vec{B}$, the fields $\vec{E}$ and $\vec{B}$ correspond to the electric and magnetic fields in the laboratory frame, respectively [66]. Therefore, the dielectric polarizability of the atom can be written as $\vec{d}=\alpha\left(\vec{E}+\vec{v}\times\vec{B}\right)$. Thereby, the Lagrangian of the system must be written in terms of the electric $\vec{E}'=\vec{E}+\vec{v}\times\vec{B}$ as

$$\mathcal{L}=\frac{1}{2}\left(M+\alpha\,B^2\right)\,v^2+\vec{v}\cdot\left(\vec{B}\times\alpha\,\vec{E}\right)+\frac{1}{2}\,\alpha\,E^2-V,\tag{1}$$

where V is a scalar potential. Note that there is an effective mass in the Lagrangian (1) given by $m=M+\alpha\,B^2$, where M is the mass of the neutral particle [59]. Let us work by assuming that $B^2=$ constant, hence, after simple calculations, the Schrödinger equation that describes this system is [62] (with the units $c=\hbar=1$):

$$i\frac{\partial\psi}{\partial t}=\frac{1}{2m}\left[\vec{p}+\alpha\left(\vec{E}\times\vec{B}\right)\right]^2\psi-\frac{\alpha}{2}\,E^2\,\psi+V\,\psi.\tag{2}$$

According to Ref. [61], the term $\alpha\,E^2$ is very small compared with the kinetic energy of the atoms, therefore we can neglect it without loss of generality from now on. Recently, Aharonov–Bohm-type effect for bound states [63] for a moving atom has been investigated in quantum rings and quantum dots in Refs. [62,65].