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Topological and non inertial effects on the interband light absorption

Moises Rojas [a,*], Cleverson Filgueiras [a], Julio Brandão [b], Fernando Moraes [c,1]

[a] Departamento de Física, Universidade Federal de Lavras, Caixa Postal 3037, 37200-000, Lavras, Minas Gerais, Brazil
[b] Instituto Federal de Educação, Ciência e Tecnologia do Sertão Pernambucano, Campus Salgueiro, 56000-000, Salgueiro, PE, Brazil
[c] Departamento de Física, Universidade Federal Rural de Pernambuco, 52171-900, Recife, PE, Brazil

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ABSTRACT

In this work, we investigate the combined influence of the nontrivial topology introduced by a disclination and non inertial effects due to rotation, in the energy levels and the wave functions of a noninteracting electron gas confined to a two-dimensional pseudoharmonic quantum dot, under the influence of an external uniform magnetic field. The exact solutions for energy eigenvalues and wave functions are computed as functions of the applied magnetic field strength, the disclination topological charge, magnetic quantum number and the rotation speed of the sample. We investigate the modifications on the light interband absorption coefficient and absorption threshold frequency. We observe novel features in the system, including a range of magnetic field without corresponding absorption phenomena, which is due to a tripartite term of the Hamiltonian, involving magnetic field, the topological charge of the defect and the rotation frequency.

1. Introduction

Quantum dots are often referred to as artificial atoms because of their atom-like electron energy spectrum. They are alluring to a wide range of optoelectronic applications [1], due to their optical properties, similar to those of atoms [2]. They are able to emit light at specific frequencies if either electricity or light is applied to them. The emitted frequency may be precisely tuned by a careful choice of the size of the dot and/or its shape and composition. In Ref. [3], an exactly soluble model to describe quantum dots, antidots, one-dimensional rings and straight two-dimensional wires in the presence of external fields, was proposed.

An extra ingredient that may influence the tuning of these emission frequencies is a topological defect [4]. Defects, in general, are a nuisance since they impair the electronic properties of the materials. Nevertheless, recent works [5–11] have pointed out that topological defects can in fact be used to tailor specific electronic transport properties. Besides the dynamics of carriers, investigations on how topological defects affect the electronic bound states, may also be of importance for the improvement of electronic technology. A step forward in this direction was done in Ref. [12].

Rotation, as well, has its effects on quantum systems, like in the celebrated Barnett effect [13]. For instance, in [14,15], the low-energy electronic states of rotating fullerene were investigated within a continuum model, motivated by the experimental evidence of rapidly rotating C_{60} molecules in fullerite. In Ref. [16], it was shown that rotating effects modify the cyclotron frequency and breaks the degeneracy of the analogue Landau levels for an atom with a magnetic quadrupole moment. The semiclassical kinetic theory of Dirac Fermions in the presence of external electromagnetic fields and global rotation was established in [17]. It is clear then, that rotation may be used as an additional tool to manipulate the electronic structure of charge carriers in low dimensional systems as discussed in [18,19].

As mentioned above, the interband frequency of absorption/emission by a quantum dot can be tuned with slight changes in parameters like size, shape and composition, for instance. In this paper, we add two more ingredients: a topological defect called *disclination* and rotation. We investigate how the quantum dots and antidots, with the pseudoharmonic interaction and under the influence of external magnetic field, are affected by a combination of non inertial and topological influences. Under these circumstances, we obtain exact analytical expressions for the energy spectrum and wavefunctions of a noninteracting two-dimensional electron gas (2DEG) confined in a quantum dot. The modifications in the light absorption coefficient is examined and the influences

* Corresponding author.
E-mail addresses: moises.leyva@dfi.ufla.br (M. Rojas), cleverson.filgueiras@dfi.ufla.br (C. Filgueiras), julio.brandao@ifsertao-pe.edu.br (J. Brandão), fernando.jsmoraes@ufrpe.br (F. Moraes).
[1] Also at Departamento de Física, CCEN, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970, João Pessoa, PB, Brazil.

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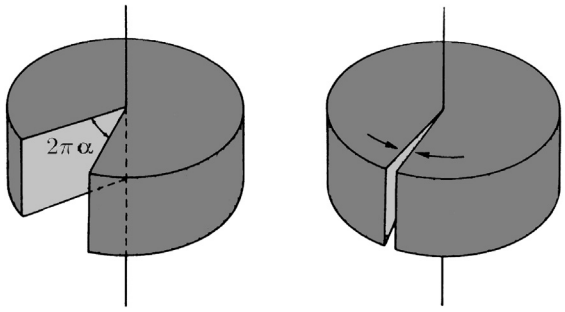

Fig. 1. Volterra process for a disclination: from an infinite elastic medium, we cut an infinite wedge with the angle $2\pi\alpha$. In the next step, the boundaries of the cut are symmetrically moved one to another and glued together.

in the threshold frequency value of the absorption coefficient are addressed. Separately, rotation [19] and disclination [14] couple to the angular momentum, as does the magnetic field. We will see that, when they act together with a magnetic field on a free 2DEG, a new coupling is found involving all of them simultaneously. This makes the energy levels as function of the magnetic field to bend from the usual straight lines and a range of magnetic field without emission/absorption will be observed.

The plan of this work is the following. In Sec. 2, we derive the Schrödinger equation for the 2DEG in a rotating sample, with a disclination, in the presence of an external magnetic field and of a two-dimensional pseudoharmonic potential. Then, we investigate how such physical conditions affect the electronic energy levels. In reality, we consider the 2DEG confined to a flat interface so that we can discuss our results in the context of a (quasi) two-dimensional electron gas. This permits the inclusion of a disclination, since in three-dimensional systems, the very high elastic energy cost forbids the existence of such a defect. In Sec. 3, we investigate the modifications due to the topological defect as well as the non inertial effects on the light interband absorption coefficient and absorption threshold frequency. The conclusions are outlined in Section 4.

2. The Schrödinger equation for the system

We consider a 2DEG around a disclination, which is a topological defect [4] associated to the removal of a wedge of material with the subsequent identification of the loose ends (Volterra process, see Fig. 1). This introduces an angular deficit, changing the boundary condition on the angular variable from $\phi \to \phi + 2\pi$ to $\phi \to \phi + 2\pi\alpha$. Here, $\alpha < 1$ expresses the removed wedge angle of $2\pi(1-\alpha)$. Conversely, if a wedge is added, $\alpha > 1$. This new boundary condition can effectively be incorporated into the theory if we work out in the background space with line element

$$ds^2 = dr^2 + \alpha^2 r^2 d\phi^2 + dz^2 \,. \tag{1}$$

The topological charge of the defect is given by its Frank vector f, which is the curvature flux associated to the defect [4]. Since the above line element corresponds to a space with a curvature scalar given by [20]

$$R = 2\left(\frac{1-\alpha}{\alpha}\right)\frac{\delta(r)}{r} \,, \tag{2}$$

its flux is therefore

$$\oint R r dr d\phi = 4\pi\left(\frac{1-\alpha}{\alpha}\right) = f \,. \tag{3}$$

This result still holds for a two-dimensional flat interface (a quasi 2DEG) with a disclination, as well as for a conical surface. A word of caution about the singularity: its role here is topological instead of geometrical. To clarify this we use as example the well known honeycomb structure of graphene. To put a disclination on the graphene sheet corresponds to substituting one of the hexagons by a pentagon. If the structure is left to relax into the third dimension, it results in a carbon nanocone. In fact, a truncated cone without the apex and therefore, without the curvature singularity. The curvature now is distributed on the circle which defines the truncation and circumscribes the pentagon. Elsewhere, the truncated cone surface has zero Gaussian curvature, behaving locally like the Euclidean plane. Globally, it is something else. The curvature flux still goes through any loop around the pentagon and, like in the Aharonov–Bohm effect, has its influence on the quantum dynamics of particles on the truncated cone (see for example Ref. [21]). Alternatively, the effect of the curvature flux can be seen as a change in boundary conditions: by making the azimuthal angle $\phi \in [0, 2\pi]$ into $\theta = \alpha\phi$, the metric (1) turns into the Euclidean metric $ds^2 = dr^2 + r^2 d\theta^2 + dz^2$ with the new boundary condition that $\theta \in [0, 2\pi\alpha]$.

The Hamiltonian, in cylindrical coordinates, of a charged particle in a disk rotating with angular velocity $\vec{\Omega} = \Omega\hat{z}$, in the presence of a magnetic field $\vec{B} = B\hat{z}$, can be written as [19]

$$H = \frac{[\vec{p} - q\vec{A} - m(\vec{\Omega}\times\vec{r})]^2}{2m} - \frac{m(\vec{\Omega}\times\vec{r})^2}{2} + \\ + qV + V_{ext} \,, \tag{4}$$

where V and $\vec{A}$ are the scalar and vector electromagnetic potentials. They are given by

$$V = -\frac{\Omega B r^2}{2}, \tag{5}$$

$$\vec{A} = (0, \frac{Br}{2\alpha}, 0) \,. \tag{6}$$

The electric field associated to the scalar potential appears from the transformation of the applied magnetic field to the rotating frame. The disclination factor, α, appearing in the vector potential compensates the change $\phi \to \alpha\phi$, giving the correct value of the magnetic flux through a circle of radius r in the plane. That is, $\oint A_\phi ds = \oint \frac{Br}{2\alpha} r\alpha d\phi = \pi r^2 B$, where $ds = \alpha r d\phi$ comes from the metric (1) with $z = const.$, $r = const.$ In the same reasoning, we write the angular momentum operator as $\vec{p}_\phi = -\hat{\phi}\frac{i\hbar}{\alpha r}\frac{\partial}{\partial\phi}$.

A scalar pseudoharmonic interaction is incorporated into the system by the potential

$$V_{\text{conf}} = V_0\left(\frac{r}{r_0} - \frac{r_0}{r}\right)^2, \tag{7}$$

with $r_0 = (a_1/a_2)^{1/4}$ and V_0 being the average radius and the chemical potential [22], respectively. The choice of the values for the parameters a_1 and a_2 specifies the particular system under study, as will be seen below. The model given by Eq. (7) (see also Ref. [3,23]) was proposed to describe quantum dots, anti-dots, one-dimensional rings and straight two-dimensional wires in the presence of a magnetic field. Some of its properties are: a) the potential (7) has a minimum, $V(r) = 0$, at $r = r_0$; b) for $r \to r_0$, the potential of the ring has a parabolic form, $V(r) \simeq \mu\omega_0^2 (r - r_0)^2/2$, with $\omega_0 = \sqrt{8a_2/m}$ being the angular frequency characterizing the strength of the transverse confinement. Another important feature of potential (7) is that we can control its "shape" such that both the radius and the width of the ring can be adjusted independently by suitably choosing a_1 and a_2. Then, we can study a $1D$ ring, by choosing $r_0 =$ constant and $\omega_0 \to \infty$, a straight 2D wire, by making $\omega_0 =$ constant and $r_0 \to \infty$, a quantum dot, by making $a_1 = 0$ and an isolated anti-dot, by making $a_2 = 0$. The particular limits

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