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Thermodynamical properties of graphene in noncommutative phase–space

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ABSTRACT

We investigated the thermodynamic properties of graphene in a noncommutative phase–space in the presence of a constant magnetic field. In particular, we determined the behaviour of the main thermodynamical functions: the Helmholtz free energy, the mean energy, the entropy and the specific heat. The high temperature limit is worked out and the thermodynamic quantities, such as mean energy and specific heat, exhibit the same features as the commutative case. Possible connections with the results already established in the literature are discussed briefly.

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1. Introduction

Carbon, in its allotropic forms like graphite and diamond, takes up a prominent place in different branches of science. In particular, graphite can be thought as composed by stacking one-atom thick layers of carbon, called *graphene*. The physics of graphene has attracted attention from theoretical scientific community since experimental observations revealed the existence of electrical charge carriers that behave as massless Dirac quasi-particles [1–4]. The reason for this is due to the unusual molecular structure of graphene. The Carbon atoms are arranged in a hexagonal lattice, similar to a honeycomb structure [5]. It was observed that the low-energy electronic excitations at the corners of graphene

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Brillouin zone can be described by a 2 + 1 Dirac fermions with linear dispersion relation (massless) [3,4]. This effect offers the prospect of testing several aspects of relativistic phenomena, which usually requires large energy, in experiments of the condensed matter physics such as chiral tunnelling and Klein paradox [6,7].

On the other side, the study of quantum systems in a noncommutative (NC) space has been the subject of much interest in last years, assuming that noncommutativity may be, in fact, a result of quantum gravity effects [8]. In these studies, some attention has been given to the models of noncommutative quantum mechanics (NCQM) [9]. The interest in this approach lies on the fact that NCQM is a fruitful theoretical laboratory where we can get some insight on the consequences of noncommutativity in field theory by using standard calculation techniques of quantum mechanics. In this context, several types of noncommutativity have been considered [10] and one case of particular importance is the so called noncommutative phase–space. This specific formulation is necessary to implement the Bose–Einstein statistics in the context of NCQM [11,12].

The NC phase–space is based on the assumption that the spatial coordinates $\hat{x}_i$ and the conjugate momenta $\hat{p}_i$ are operators satisfy a deformed Heisenberg algebra, which in its simplest form can be described by the commutation relations:

$$\begin{aligned} &[\hat{x}_i, \hat{x}_j] = i\theta_{ij}, \qquad [\hat{p}_i, \hat{p}_j] = i\eta_{ij}, \\ &[\hat{x}_i, \hat{p}_j] = i\hbar\left(\delta_{ij} + \frac{\theta_{ik}\eta_{jk}}{4\,\hbar^2}\right), \quad \text{with } i, j, k = 1, \ldots \mathrm{d}, \end{aligned} \tag{1}$$

where the deformation parameters $\theta_{ij} = \theta\epsilon_{ij}$ and $\eta_{ij} = \eta\epsilon_{ij}$ are real and antisymmetric constants matrices. These commutation relations can be explicitly implemented by means of coordinate transformations [13]:

$$\hat{x}_i = x_i - \frac{\theta_{ij}}{2\hbar}p_j, \qquad \hat{p}_i = p_i + \frac{\eta_{ij}}{2\hbar}x_j, \tag{2}$$

where x_i and p_i are commutative variables that satisfy ordinary Heisenberg commutation relations,

$$[x_i, x_j] = 0, \qquad [p_i, p_j] = 0, \qquad [x_i, p_j] = i\hbar\delta_{ij}. \tag{3}$$

Recently, graphene in the framework of NCQM was studied by Bastos et al. [14], where the authors determined the Hamiltonian and the associated energy spectrum. It was shown that the electron states close to the Dirac points (K and K' points at the corners of graphene Brillouin zone) in a NC phase–space, subject to an external constant magnetic field, can be described by a massless $2D$ Dirac equation with only momenta noncommutativity. Otherwise, we would have a gauge symmetry breaking, which it is not observed in the graphene lattice [13].

These results, in association with suitable experimental data, may be used to investigate the role of noncommutativity in the graphene system and improve bounds on the magnitude of the corresponding noncommutative parameters. For instance, the issue concerning the thermodynamic properties of graphene modified by this kind of theory has not been addressed. Thus, using an approach similar to the cases of Dirac and Kemmer oscillators studied in Refs. [15,16], we propose to evaluate the main thermodynamic functions that describe the thermal behaviour of this system in both cases; commutative and noncommutative. One such study with a focus on graphene is particularly interesting because this material has numerous applications for thermal industry, and it may be important in the understanding of heat conduction in low dimensions [17–19].

This work is outlined as follows. In Section 2, we summarize the key results of Ref. [14] which we will use in the sequel. In Section 3, the solution for the energy levels is utilized to calculate the partition function, and then all thermodynamic quantities that describe the thermal physics of NC graphene. The methodology used closely follows that developed in Refs. [15,16]. Finally, in Section 4, we present the conclusion and final remarks.

2. Graphene in a noncommutative phase–space

Before studying the thermal properties of graphene, let us first recall the fundamentals on the graphene physics in a NCQM approach. Here, we follow the steps described in Ref. [14]. The basic

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