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Cavity effects on the Fermi velocity renormalization in a graphene sheet

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Abstract

Recently, in the literature, it was shown that the logarithmic renormalization of the Fermi velocity in a plane graphene sheet (which, in turn, is related to the Coulombian static potential associated to electrons in the sheet) is inhibited by the presence of a single parallel conducting plate. In the present paper, we investigate the situation of a suspended graphene sheet in a cavity formed by two conducting plates parallel to the sheet. The effect of a cavity on the interaction between electrons in the graphene is not merely the addition of the effects of each plate individually. From this, one can expect that the inhibition of the renormalization of the Fermi velocity generated by a cavity is not a mere addition of the inhibition induced by each single plate. In other words, the simple addition of the result for the inhibition of the renormalization of the Fermi velocity found in the literature for a single plate could not be used to predict the exact behavior of the inhibition for the graphene between two plates. Here, we show that, in fact, this is what happens and calculate how the presence of a cavity formed by two conducting plates parallel to the suspended graphene sheet amplifies, in a non-additive manner, the inhibition of the logarithmic renormalization of

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the Fermi velocity. In the limits of a single plate and no plates, our formulas recover those found in the literature.

1. Introduction

In 1993, Marino [1] proposed an effective and complete description in $2+1$ dimensions for electronic systems moving on a plane, but interacting as particles in $3+1$ dimensions,

$$\mathcal{L}_{\rm PQED} = \frac{1}{2}\frac{F_{\mu\nu}F^{\mu\nu}}{(-\Box)^{1/2}} + \mathcal{L}_{\rm D} + j^\mu A_\mu - \frac{\xi}{2}A_\mu \frac{\partial^\mu\partial^\nu}{(-\Box)^{1/2}}A_\nu, \tag{1}$$

where $\Box$ is the d'Alembertian operator, $\mathcal{L}_{\rm D}$ stands for the Dirac's Lagrangian while the last term corresponds to the gauge fixing term. The model given by Eq. (1), denominated pseudo-quantum electrodynamics (PQED), was recently used in the description of several graphene properties [2–7].

From Eq. (1), one obtains the free photon propagator in Euclidean space,

$$\Delta^{(0)}_{\mu\nu}(k) = \frac{1}{2\sqrt{k^2}}\left[\delta_{\mu\nu} - \left(1-\frac{1}{\xi}\right)\frac{k_\mu k_\nu}{k^2}\right], \tag{2}$$

where $k_\mu = (k_0, \mathbf{k})$ and $\mathbf{k} = (k_1, k_2)$. In the nonretarded regime, considering the Feynman gauge ($\xi = 1$), it becomes

$$\Delta^{(0)}_{\mu\nu}(k_0 = 0, |\mathbf{k}|) = \frac{1}{2|\mathbf{k}|}\delta_{0\mu}\delta_{0\nu}, \tag{3}$$

which leads to the Coulombian potential for static charges (instead of the peculiar logarithmic one from QED in $2+1$ dimensions),

$$V(|\mathbf{r}|) = \frac{e}{4\pi}\frac{1}{|\mathbf{r}|}. \tag{4}$$

In this regime, the electron self-energy in a graphene sheet was calculated in Ref. [8] (see also Refs. [9–12]), and the result in one-loop order is

$$\Sigma_0(\mathbf{p}) = -\frac{e^2(\mathbf{p}\cdot\boldsymbol{\gamma})}{16\pi}\ln\frac{\Lambda}{|\mathbf{p}|}, \tag{5}$$

where e is the nonrenormalized coupling constant, $\gamma^\mu = (\gamma^0, \boldsymbol{\gamma})$ stands for the Dirac matrices, and Λ is an ultraviolet cutoff introduced in the momentum integrals. From Eq. (5), the renormalized Fermi velocity $v_F^R(|\mathbf{p}|)$ with external momentum p reads [8]

$$v_F^R(|\mathbf{p}|) = v_F\left(1 + \frac{\alpha_F}{4}\ln\frac{\Lambda}{|\mathbf{p}|}\right), \tag{6}$$

where $\alpha_F = e^2/(4\pi v_F)$ is the graphene fine structure constant. Experimental results [13] are in good agreement with the theoretical prediction shown in Eq. (6).

The understanding of interaction effects between electrons in graphene is important from theoretical and experimental points of view, since the Fermi velocity is renormalized by these interactions, and it is connected with some transport properties of graphene. For instance, the

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