We study the generation of an electromagnetic current in monolayer graphene immersed in a weak perpendicular magnetic field and radiated with linearly polarized monochromatic light. Such a current emits Bremsstrahlung radiation with the same amplitude above and below the plane of the sample, in the latter case consistent with the small amount of light absorption in the material. This mechanism could be an important contribution for the reflexion of light phenomenon in graphene.

Keywords: Graphene; Bremsstrahlung radiation; induced electromagnetic currents.

Graphene [1, 2] continues to provide an excellent laboratory to explore fundamental physics, let alone its technological applications (see, for instance, Ref. [3]). The gapless pseudo-relativistic Dirac nature of it charge carriers at low energies is responsible for many of the outstanding properties of this 2 dimensional (2D) crystal that has given rise to a new era of materials science [4]. High electric and thermal conductivities, stiffness and flexibility of graphene flakes are a few examples in this connection. On top of these properties, the transparency of its membranes is remarkable: Only 2.3% of visible light is absorbed by a single membrane [5]. This rate has been verified under a number of experimental conditions [6]. On the other hand, many theoretical approaches have been used in the past to explain the rate of light absorption in graphene including quantum field theoretical methods [7–12]. It is interesting to point out that modeling graphene from a thin film to a monolayer can give different predictions of this rate [13]. Yet, the underlying mechanism that explains light absorption is less transparent. In this communication, we explore the possibility for such a mechanism to be explained in terms of Bremsstrahlung radiation. The issue of Bremsstrahlung in graphene has recently been addressed [14–16]. Here we consider the situation where a graphene membrane is located in the \( z = 0 \) plane and is subjected to a weak magnetic field of strength \( B \) oriented perpendicularly to the sample, and then is radiated with an electromagnetic plane-wave, monochromatic (frequency \( \omega \)) and linearly-polarized, traveling from the top \(( z > 0)\).

The vector potential describing this plane-wave is

\[
A_\mu(r,t) = -g_\mu \frac{E_0}{i\omega} e^{i(kz + \omega t)},
\]

such that the electric field \( E \) (intensity \( E_0 \)) is oriented in the \( y \) direction. We use the metric tensor \( g = \text{diag}(1, -1, -1, -1) \) and units where \( \hbar = c = 1 \) and, therefore, \( k = \omega \) in vacuum.

In this form,

\[
E = E_0 \hat{y} e^{i\omega(z + t)}, \quad B = E_0 \hat{x} e^{i\omega(z + t)}. \tag{2}
\]

The electric current generated in the graphene sample induced by the external electromagnetic wave is defined through the polarization tensor as

\[
j_\mu(r) = \int d^4r' \Pi_{\mu\nu}(r - r') A^\nu_{pl}(r'). \tag{3}
\]

Here, \( A_{pl}(r) = A^*(r) \delta(z) \) is the conjugated vector potential constrained to the plane, and \( \Pi \) is the polarization tensor, also constrained to the membrane. For weak external magnetic fields, it is defined in momentum space as [10] \( \Pi_{\mu\nu}(p) = i \frac{\sqrt{p^2}}{v_F^2} \frac{\alpha}{2} \eta_{\mu\alpha} \)

\[
\times \left\{ \frac{1}{\left[ 1 + \left( \frac{eB}{p^2} \right)^2 \left( 1 - \frac{p_\perp^2}{p^2} \right) \right]} \left( g^{\alpha\beta} - \frac{\vec{p}_\perp \cdot \vec{p}_\perp}{p^2} \right) \right. \\
+ 2 \frac{eB}{p^2} \left( \left( 1 - \frac{p_\perp^2}{p^2} \right) \left( g^{\alpha\beta} - \frac{\vec{p}_\perp \cdot \vec{p}_\perp}{p^2} \right) \right) \left( \eta_{\mu\nu} \right), \tag{4}
\]

where \( \vec{p}^\alpha = \eta^{\alpha\mu} p_\mu \) and \( g^{\alpha\beta} = \eta^{\alpha\mu} \eta^{\beta\nu} \), being the projector matrix \( \eta_{\alpha\mu} \) is

\[
[\eta]_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\
0 & v_F & 0 & 0 \\
0 & 0 & v_F & 0 \end{pmatrix}. \tag{5}
\]

Notice that \( \eta \) slightly differs from the definition in [7–11]. Here, it also acts as a projector in Lorenz indexes into the...
The membrane we use is a graphene plane. In our conventions, along the graphene plane, the potential in the real axis in the form shown in Fig. 1. After the integration of these equations in Lorentz gauge \(\partial^2 A_{\mu}^{rad}(r) = j_{\mu}(r)\), which in Fourier space correspond to \(-p^2 A_{\mu}^{rad}(p) = j_{\mu}(p)\). The radiated electromagnetic field vector potential \(A_{\mu}^{rad}\) is then the inverse Fourier transformation of \(-j_{\mu}(p)/p^2\). The integral involved to obtain it is ill-defined, as it contains poles on the real axis. In accordance to the prescription of retarded boundary conditions, we consider displacing the poles slightly from the real axis in the form shown in Fig. 1. After the integration in the \(p_0, p_x\) and \(p_y\) components, the radiation vector potential is

\[
A_{\mu}^{rad}(r) = -g_{\mu 2} E \int \frac{dp_z}{2\pi} \frac{e^{i(p_z z - \omega t)}}{p_z^2 - \omega^2 - i\epsilon}.
\]

Furthermore, selecting the contour of integration as shown in Fig. 1, integrations over momentum components are readily done. We thus can identify the emitted radiation above (+) and and below (−) the plane as

\[
A_{\mu}^{rad}(\pm)(r) = g_{\mu 2} \frac{E}{2i\omega} e^{i\omega(\pm z - \epsilon t)}.
\]

The corresponding emitted electromagnetic fields are, therefore,

\[
E_+ = (E/2) \hat{y} e^{i\omega(z-t)}
\]

\[
B_+ = (E/2) \hat{\epsilon} e^{i\omega(z-t)+i\epsilon},
\]

\[
E_- = (E/2) \hat{y} e^{-i\omega(z+t)},
\]

\[
B_- = (E/2) \hat{\epsilon} e^{-i\omega(z+t)}.
\]

We can straightforwardly see that the emitted wave below and above the plane carry half of the re-emitted intensity. Thus, the total radiated energy density is \(\mathcal{E} = E^2/2\). Although the electric component of the wave emission is the same in the lower side, the magnetic component of the emitted wave acquires a phase shift of \(\pi\). The radiated emission diminishes as the external magnetic field strength increases, reflecting the tendency of the magnetic field to deflect charged-particles trajectories.

The experimental measurements of perpendicularly incident light on graphene [5, 6] as well as the theoretical description [7–11] coincide in that the order of the opacity rate is \(\alpha^2\). The experimentally arranged light is basically radiation from the top, detection from the bottom, and comparison between them (transparency). The theoretical description, in turn, accounts for the absorption rate. But none of these assumptions make explicit reference to the reflection rate. In this work we describe the re-emission of light by Bremsstrahlung, half transmitted and half reflected. The reflected amount is of order \(\alpha^2\), much lower than the experimental detection of light opacity. However, there is not much done in order to detect perpendicular reflection and theoretical estimations [18] reproduce null reflection when the incident beam is perpendicular to the graphene layer. Bremsstrahlung at the moment could be the main mechanism responsible for perpendicular light reflection.

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