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Plasmonic resonant detection of WIMP

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Theoretical works showed the existence of neutrino flux with energy below eV, the detection of these low energetic neutrino can shed light on Dark Matter problem along with the improvement of the Standard Model; the detector used nowadays are not able to detect such energies, in this thesis we propose a technique to detect slow flux of massive neutrino by plasmon generation. Through the semiclassical approximation of the Weak Interaction, we derived the force felt by a plasma due to the neutrino distribution, and vice-versa; therefore, by the Kinetic description with linear perturbation approach, we studied the interaction of electron-plasma with neutrino flux. The long lifetime of plasmon in graphene structures oriented us to study bidimensional (2D) electron systems; the weak interaction, between neutrino and ungated electron solid-state plasma, leads to a feature alike the beam-plasma instability, raising the possibility to have a growth rate. The generated plasmon has wavevector dependent on the neutrino velocity and spectral width function of the neutrino's density and mass; the instability was considered in an effective tridimensional (3D) metamaterial obtained by graphene heterostructure, the resulting Signal to Noise ratio (SN) is mainly dependent on the length of the device. Larger growth rates are found for lower neutrino energy and larger density: with detector size in the order of centimeters, the detection of neutrino with energy μeV is ensured for flux above 10^5cm^{2}s^{-1} with SN about 10 dB, for meV neutrino the same SN is ensured for flux above 10^{12}cm^{2}s^{-1}.

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1. Introduction

The scientific community is facing problems as the extension of the Standard Model, the unknown Dark Matter, Cosmogenesis and many other. One promising benchmark is studying the neutrino properties [1]. In 2020 it was proposed the neutrino spectra that reaches the Earth, the result shows a large flux at energy below the electron volt [2], those neutrino are not detected by any present technology. The scope of this work is to explore a way to detect those neutrinos with energy in the range of meV − μeV. Being inspired by the supernova neutrino instability, we seek for a scheme to make the neutrino flux interacts with the electron plasma. We decide to work with graphene [3] thanks to the high plasmon quality.

2. Metamaterial

Looking for a metamaterial with high conductivity and low plasmon decay we started by graphene. We then consider a bi-Layer graphene as basic element since it ensures an constant effective e^- mass. To be able to tune the plasma properties we use several bi-layer graphene (thick a ≈ 0.3 nm) stacked keeping a buffer layer (thickness d ≈ 1 μm) between each other. The MetaMaterial (MM) dispersion relation is then calculated by considering the mutual interaction, increasing the number of layer wee see a convergence of the modes as depicted in Fig.1, We notice that in the short-wavelength limit the modes resemble a single bi-layer graphene while in the long-wavelenght limit there are an optical and an acoustic mode. We are interested in the optical mode

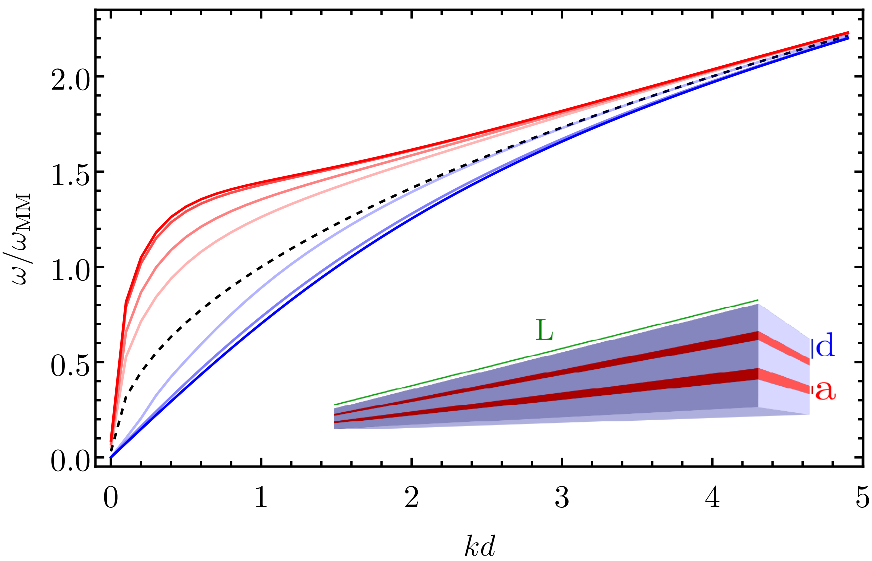

Figure 1: The evolution of the modes from single bi-layer graphene (dashed black line) to metamaterial, the red curve is the optical mode while in blue the acoustic; in the inset a pictorial representation of the MM with only 2 layers.

since it will be the one who can exchange energy with the neutrino flux. We focus on the low wavevector limit and we obtain

$$\omega^{(\mathrm{O})} \simeq \omega_{\mathrm{MM}} \left[a_0\, kd + a_1 \left(1 - e^{-a_2\sqrt{kd}}\right)\right] \equiv \omega_{\mathrm{MM}}\alpha(k), \tag{1}$$

where $a_0 = 0.199$, $a_1 = 1.255$ and $a_2 = 2.724$ are some coefficients and $\omega_{\rm MM} = \sqrt{N_{\rm MM} e^2/m_e \epsilon_0}$ denotes the effective MM plasma frequency, with $N_{\rm MM} = N_e/d$ being the homogenized MM density in terms of the 2D electron density N_e [4].

3. Weak Interaction

The neutrino (ν) is a chargeless lepton with a mass that has to be defined yet although experimental data constrains its value to be $m < 1$eV [5]; the only way the neutrino can interact with the electron is by the Weak Interaction, it couples the lepton through the Fermi constant $G_{\rm F}$. The interaction is described in the Quantum Field Theory by the [6] Lagrangian which can be reduced to the semiclassical Lagrangian by the formal substitutions $\bar{\psi}\gamma_\mu\psi \to \{n; n\,\boldsymbol{v}/c\}$ and $\bar{\psi}\gamma_\mu(1-\gamma_5)\psi \to \{n; n\,\boldsymbol{v}/c\}$ where n ($\boldsymbol{v}$) is the classical density (velocity) of the species previously described by the field ψ:

$$L^{\rm int} = -\frac{G_{\rm F}}{\sqrt{2}}\bar{\psi}_e\gamma^\mu\left[(1-\gamma_5)+(C_{\rm V}-C_{\rm A}\gamma_5)\right]\psi_e\bar{\psi}_\nu\gamma_\mu(1-\gamma_5)\psi_\nu = \tag{2}$$

$$= -\frac{G_{\rm F}}{\sqrt{2}}(C_{\rm V}+1)\left[n_e n_\nu - \frac{(n_e\boldsymbol{v}_e)\cdot(n_\nu\boldsymbol{v}_\nu)}{c^2}\right]. \tag{3}$$

Using the free Lagrangian for an electron and a neutrino, along with the $L^{\rm int}$, we can derive the Hamiltonian governing the interaction. It allows to calculate the force experienced by an electron due to the distribution of neutrinos, the result is [6]

$$\boldsymbol{F}_e^W = -\tilde{G}_{\rm F}\left[\boldsymbol{\nabla} n_\nu + \frac{\partial}{\partial t}\frac{(n_\nu\mathbf{u}_\nu)}{c^2} + \frac{\mathbf{u}_e\times\boldsymbol{\nabla}\times(n_\nu\mathbf{u}_\nu)}{c^2}\right], \tag{4}$$

where we introduced $\tilde{G}_{\rm F} = G_{\rm F}(C_{\rm V}+1)/\sqrt{2}$. The force felt by the neutrinos ($\boldsymbol{F}_\nu^W$) is obtained by sweeping the e and ν labels. We must remember that the electron has a charge therefore it feels also the presence of EM, therefore we will consider the $\boldsymbol{F}_e^{EM} = e\boldsymbol{\nabla}\phi$ where ϕ is the sum of the external and self-consistent electric potential. to describe the neutrino-plasma dynamics, we make use of a kinetic theory governing the evolution of the phase-space distribution function for the $j-$th species, $f_j(\mathbf{r},\mathbf{p},t)$, as

$$\begin{gathered}\frac{\partial f_e}{\partial t} + \mathbf{u}_e\cdot\boldsymbol{\nabla} f_e + \left(\frac{\mathbf{F}_e^{(\rm weak)}}{m_e} + \frac{e\boldsymbol{\nabla}\phi}{m_e}\right)\cdot\boldsymbol{\nabla}_{\mathbf{p}} f_e = 0,\\ \frac{\partial f_\nu}{\partial t} + \mathbf{u}_\nu\cdot\boldsymbol{\nabla} f_\nu + \frac{\mathbf{F}_\nu^{(\rm weak)}}{m_\nu}\cdot\boldsymbol{\nabla}_{\mathbf{p}} f_\nu = 0.\end{gathered} \tag{5}$$

By performing a linearization around spatially homogeneous distributions, $f_j(\mathbf{r},\mathbf{p},t) \simeq N_j g_{0,j}(\mathbf{p}) + f_{1,j}(\mathbf{r},\mathbf{p},t)$, by assuming the electrons initially at rest and neutrinos streaming with momentum $\mathbf{p}_{0,\nu} = \gamma_{0,\nu}m_\nu\mathbf{u}_{0,\nu}$, such that $g_{0,e}(\mathbf{p}) = \delta(\mathbf{p})$ and $g_{0,\nu}(\mathbf{p}) = \delta(\mathbf{p}-\mathbf{p}_{0,\nu})$, and identifying the equilibrium density of the electrons with that of the metamaterial, $N_e = N_{\rm MM}$, we obtain after some algebra

$$1 - \frac{\omega_{\rm MM}^2\alpha(k)^2}{\omega^2} - \frac{\Gamma_{\rm MM}k^4}{(\omega-\mathbf{k}\cdot\mathbf{u}_{0,\nu})^2\omega^2} = 0, \quad \Gamma_{\rm MM} = \tilde{G}_{\rm F}^2\frac{N_\nu N_{\rm MM}c^2(\gamma_{0,\nu}^2+\gamma_{0,\nu}-1)}{m_e\mathcal{E}_{0,\nu}}, \tag{6}$$

with $\mathcal{E}_{0,\nu}$ denoting the incident neutrino energy, related to its velocity as $V_{0,\nu} = c\sqrt{1-m_\nu^2c^4/\mathcal{E}_{0,\nu}^2}$.

4. Projection of ν-detector

The solution of the Eq.(6) are the mode which can be exited in the plasma-neutrino system. In Fig. 2 we see how the MM optimal mode $\omega^{(O)}$ and the linear neutrino mode bend on the crossing point due to the Weak Interaction. The consequence is an imaginary part on the frequency which correspond to an instability.

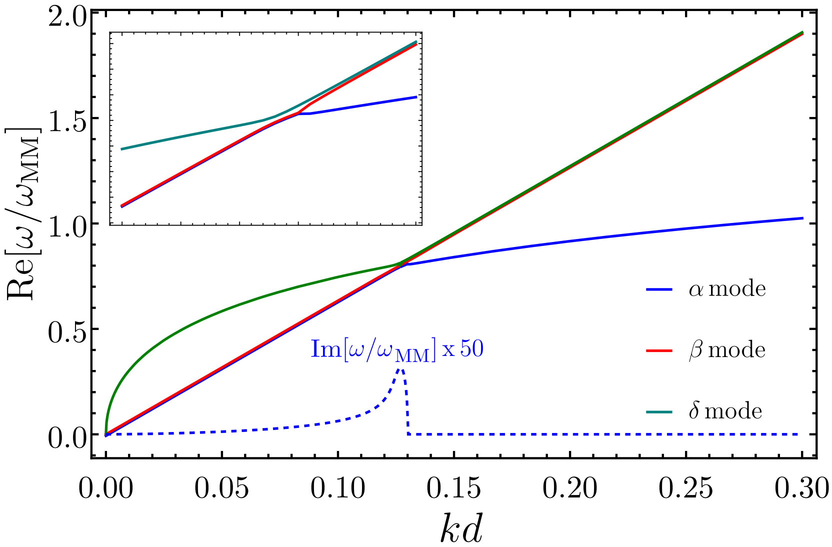

Figure 2: Neutrino-plasma joint dispersion relation in the graphene metamaterial, with a magnified growth rate for the imaginary part of the α mode (blue dashed line). These modes are obtained considering $N_{\mathrm{MM}} = 5 \times 10^{20}\,\mathrm{m}^{-3}$, $\Phi_\nu = 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathcal{E}_{0,\nu} = 1.0$ meV and $m_\nu = 0.01$ eV. Upper inset: details of the crossing point, putting in evidence the bending and coalescence of the bare modes.

The growth rate, $\gamma = \mathrm{Im}(\alpha\,\mathrm{mode})$, is responsible of the exponential amplification of the plasmon. We focus on the resonant plasmon (i.e. larger growth rate) with wavevector k_{C} and frequency given by $\omega_R + i\gamma_{\mathrm{m}}$. Therefore the plasma density not only oscillates but also grows exponentially as

$$n_e(x,t) = n_{th} \exp[i(k_C x - \omega_R t)] \exp(\gamma_{\mathrm{m}} t), \tag{7}$$

where n_{th} is the amplitude given by the thermal noise. To actually evaluate the availability to detect the neutrino we define the Signal-to-Noise ratio as

$$\mathrm{SN} = 10 \log_{10}\left[\frac{\mathrm{n_e^2}}{\mathrm{n_{th}^2}}\right] = 10 \log_{10}\left[\exp\left(2\frac{\gamma_{\mathrm{m}}\mathrm{L}}{\mathrm{V}_\nu}\right)\right], \tag{8}$$

where we consider the time-of-flight of the neutrino inside the metamaterial as $t = L/V_{\nu,0}$ The SN is presented in Fig.3 using the quantity $\Phi = N_\nu V_\nu$ to make easier the comparison with the literature.It is straightforward to see that larger flux are more easy to be detected, in the other hands, increasing the energy reduces drastically the SN making virtually impossible to detect neutrino with energy above the eV: this instability detection technique is suitable for low energetic ν.

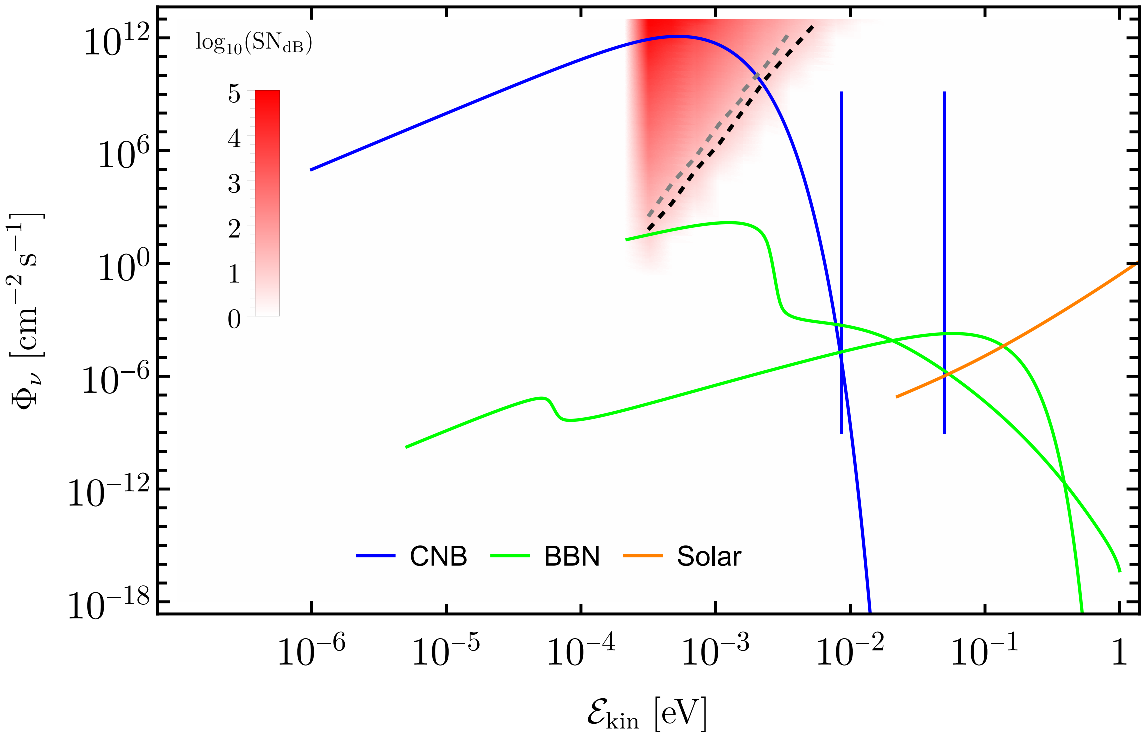

Figure 3: Evolution of the SN for $L = 1$cm, $m = 0.01$eV and for $N_e = 5 \times 10^{20}\,\mathrm{cm}^{-3}$. The colored lines represent the expected neutrino flux in the ultra-low energy range [2]

5. Conclusions and Future

The weak interaction generate a ponderomotive-like force between electron solid state plasma and neutrino flux. Within the semiclassical approximation, we derived the join dispersion relation showing an imaginary component. The resulting instability is able to generate a plasmon. Several assumptions have been made during this presentation. For more information look at the Arxiv paper . So far it seems that our scheme is the first proposal to detect neutrino with energy below the eV and therefore it has large room for improvement. The study of low energetic neutrino can set constrains on the theory beyond the Standard Model, moreover it will helpful to set boundary for the neutrino mass; lastly but not least the proposed detection scheme can apply also to WISP since it rely on Weak interaction, therefore helping in the Dark Matter search.

6. Acknowledgement

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