Cavity-Mediated Electron-Electron Interactions: Renormalizing Dirac States in Graphene

Hang Liu
Francesco Troisi, Hannes Hübener, Simone Latini, Angel Rubio
Max Planck Institute for the Structure and Dynamics of Matter and Center for Free-Electron Laser Science, Luruper Chaussee 149, 22761, Hamburg, Germany
hang.liu@mpsd.mpg.de

Embedding materials in optical cavities has emerged as an alternative strategy for tuning material properties [1,2]. Accurate simulations of electrons in materials interacting with photons within dark cavities are crucial for understanding and predicting cavity-induced phenomena. In this article, we develop a non-perturbative quantum electrodynamical approach based on a photon-free self-consistent Hartree-Fock framework to model the coupling between electrons in crystalline materials and cavity photons. We apply such a theoretical approach to investigate graphene coupled to the vacuum field fluctuations of different types of cavity photon modes. The nonlocality of photon-mediated interactions, originating from the quantum nature of light, plays a crucial role in the renormalization of the Dirac bands in graphene. In contrast to the case of graphene coupled to a circularly polarized photon mode, where a topological Dirac gap emerges, for a linearly polarized mode nonlocal electron-photon interactions break the lattice symmetry and induce a topologically trivial Dirac gap with a flat band feature. When two symmetric cavity photon modes are introduced, Dirac cones remain gapless, but a Fermi velocity renormalization yet indicates the relevant role of nonlocal interactions. This new self-consistent theoretical framework paves the way for the accurate simulation of strongly coupled light-matter systems beyond perturbation theory, and allows a more comprehensive discovery of novel cavity-induced quantum phenomena.

References

[1] J. Bloch, A. Cavalleri, V. Galitski, M. Hafezi, and A. Rubio, Nature 606, 41 (2022).
[2] H. Hübener, U. De Giovannini, C. Sch¨afer, J. Andberger, M. Ruggenthaler, J. Faist, and A. Rubio, Nature Materials 20, 438 (2021).

Figures

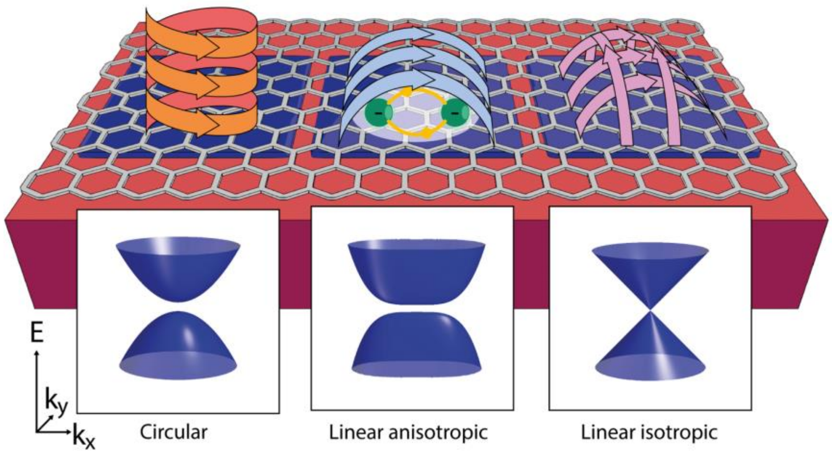

Figure 1: Illustration of the renormalized Dirac cones of monolayer graphene coupled to cavity photon modes of different polarizations.