

Quasiparticle theory of collective electron excitations in graphene

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M. Akbari-Moghanjoughi 

AFFILIATIONS

Faculty of Sciences, Department of Physics, Azarbaijan Shahid Madani University, 53745-406 Tabriz, Iran

*Author to whom correspondence should be addressed: massoud2002@yahoo.com

ABSTRACT

In this paper, we develop a new approach for analyzing collective quantum excitations in graphene, based on the quantum multistream model. We explore a range of phenomena, including the energy band structure of collective modes, linear and nonlinear excitations, statistical characteristics, and the linear dielectric response of quasiparticle excitations in graphene. A modified Wigner quasiprobability distribution is derived, enabling the study of phase-space dynamics for linear excitations. Our results reveal that quasiparticle excitations of massless Dirac fermions are governed by three distinct characteristic wavenumbers. Notably, we identify a broad energy bandgap associated with the collective effects, below which quasiparticle excitations become unstable. The thermodynamic analysis, encompassing internal pressure and heat capacity, uncovers several intriguing deviations from the behavior of a conventional Fermi electron gas. Furthermore, we demonstrate that massless Dirac fermions in graphene can sustain both large-amplitude cnoidal waves and solitary structures. By examining the dielectric response within the Lindhard framework, incorporating a quasiparticle energy dispersion that accounts for both single-particle and wave-like contributions, we gain new insights into the frequency-dependent response, loss-function spectrum, and static charge screening, highlighting key differences from the ordinary Fermi gas. This theory offers a unified approach to capturing both the particle-like and wave-like aspects of massless Dirac Fermion excitations, clearly distinguishing their individual contributions to various physical properties. It also extends beyond the conventional many-body theories incorporating the mean field approximations by appropriately linking the single-electron dynamics to collective behavior through the hybrid nature of quasiparticle matter-wave dispersion.

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1. INTRODUCTION

Collective excitations play a fundamental role in determining the physical properties of all phases of matter. They are a central focus of research across numerous interdisciplinary fields,^{1–6} spanning from opto- and nano-electronics^{7–9} to plasmonics.^{10–12} These phenomena emerge from the effective coupling between an interaction potential and single-particle oscillations. In ionized matter, for instance, electrostatic coupling among charged particles gives rise to a rich variety of collective behaviors in plasmas, including localized structures and intricate density patterns.¹³ Such effects are critical for understanding the plasma dynamics in both laboratory settings^{14–16} and astrophysical environments.^{17–21} Collective excitations also underlie various instabilities and mechanisms of wave-particle energy exchange, such as collisionless damping, where energy is transferred without direct particle collisions. The strength

and nature of the collective response are typically governed by thermodynamic parameters, most notably, electron number density and temperature, which together define the equation of state (EoS) of the system. This connection allows for the predictive modeling of plasma behavior based on its thermodynamic profile. Remarkably, it has been shown that collective excitations can impose their own EoS, determined by the excitation level of individual electrons into collective bands.^{22–24} This distinctive feature leads to novel physical properties in plasmas, metals, and semiconductors, including modifications in conductivity and magnetic behavior.^{25–28} Despite these advances, a major challenge remains: the development of accurate many-body theories and computational methods capable of capturing the full complexity of collective phenomena. Traditional approaches often rely on simplifying assumptions, such as the mean-field (MF) and random-phase approximations (RPAs),^{29–31} which can limit their validity under extreme or non-equilibrium

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