Research Plan

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Overview

My research interests focus on collective phenomena throughout a number of condensed matter systems, including multi-component Fermi liquids, superconductors, Dirac-like systems, and charge-density wave systems. In particular, I am interested in how these collective modes hybridize with each other and with external modes such as photons as well as the impact of quantum geometry on the behavior and observability of these modes.

Research Experience

Cavity-Superconductor systems — Drawing inspiration from the seminal work of Ivlev, Lisistyn, and Eliashberg on enhancement of superconductivity via microwave stimulation [1], I have studied how superconductivity can be strengthened by coupling to cavity photons [2]. Using the Keldysh non-linear sigma model of a disordered supercondutor, I calculated corrections to the BCS gap equation due to coupling with a microwave cavities. In this work, I considered coupling a superconducting thin-film to a bath of microwave cavity photons and the resulting effect on the Bogoliubov quasi-particle distribution function. Our results provide a general framework for deriving the modification of superconductivity in a thin film due to coupling with an arbitrary photonic cavity.

Subsequently, I considered the formation of superconductor-polaritons in a cavity system [3]. The goal of this study was to understand how the collective modes of superconductors can hybridize with light to form new types of excitations. While the study of hybrid light-matter excitations dates back to at least 1958 when Hopfield first considered exciton-polaritons [4], recent years have seen enormous success in the field of *cavity* exciton-polaritons, observing exciton-polariton condensation up to room temperature [5]. Extending such techniques to work with superconductors presents rich opportunities. An impediment is that coupling of photons to collective excitations in superconductors, with the exception of the phason, is generally weak. This can be circumvented by driving a supercurrent [3], a fact which was only appreciated a few years ago [6]. Expaning upon this, we showed that the use of a supercurrent allows one to engineer significant hybridization between properly tuned microwave cavity photons and the Bardasis-Schrieffer mode of a superconductor [3], a Bogoliubov quasi-particle analog of an exciton [7].

In a following work I extended the idea of superconductor-polaritons to the hybridization of cavity photons and the Higgs (amplitude) mode of dirty superconducting thin films. Using the supercurrent induced coupling discussed above we obtained a linear hybridization term between photons and the Higgs mode. Because disorder is necessary for such a coupling to be non-vanishing, the hybridization process is most straightforwardly understood as being mediated by diffusive modes of the superconductor.

Geometric effects in kinetics — Recently I have studied the collective behavior of multi-component Fermi liquids [8, 9], concretely using the Fermi liquid state of single layer graphene as a well established test bed. Using a kinetic formalism, I demonstrated the absence of sound modes in the spin and valley channels of Fermi liquid graphene [8]. The main force of the work consisted of deriving approximate expressions for the Landau interaction functions of such a system, and then solving the Landau-Silin kinetic equation for collective mode dispersions in the neutral channels (i.e. all channels but the charge channel, which is simply the plasmon). In the collisional regime, we found that transport in the neutral channels is always diffusive due to the lack of spin/valley current conservation laws. While in the collisionless regime, all neutral sound was found to be destroyed by Landau damping. It is therefore evident that spin and valley transport is diffusive, and I subsequently obtained expressions for the diffusion constants in these channels.

While there are no gapless collective modes in the spin $SU(2)$ symmetric case, in the presence of an applied Zeeman field and/or extrinsic spin-orbit coupling, well-defined oscillatory modes appear in the spin and valley-staggered spin channels [9]. I derived such modes for a model of graphene on a transition metal dichalcogenide, as well as their signature in the optical conductivity. Of particular interest in the case of graphene is that the non-Abelian Berry (Wilczek-Zee) connection plays an important role in the kinetics, necessitating a transport equation which properly captures the band geometric effects. In deriving the aforementioned spin-valley modes, I therefore made use of a Berry-gauge invariant kinetic formalism [10], which allows to straightforwardly and transparently include band-geometric effects in the calculation of transport phenomena. Notably, coupling of light to the valley-staggered spin mode in graphene is mediated by the non-abelian Berry curvature of the quasi-degenerate bands.

The broader import of this work is a general matrix Landau-Fermi liquid description of a multi-band Fermi liquid which automatically includes the effects of Berry curvature in the long-range limit. This can be used to calculate other geometrically dependent quantities as is done e.g. in the non-interacting case for Weyl semi-metals with the chiral kinetic theory, or also to obtain Berry curvature corrections to hydrodynamic parameters by following analogs of the usual kinetic derivation of the linearised Navier-Stokes equation.

Future works

Non-equilibrium superconductivity — Equilibrium statistical mechanics has proven a rich fruitful field of study over the last one hundred and fifty years, underpinning much of modern technology. However, numerous results have demonstrated the existence of a richer variety of phenomena which can occur out of equilibrium. It is, therefore, imperative for the advancement of our technological capabilities that the realm of non-equilibrium states be thoroughly investigated. To that end, I propose to use the techniques employed in my current works to study non-equilibrium superconductivity in the limit where the system strongly hybridizes with light, for example condensation of superconductor-polaritons. Specifically, both Keldysh non-linear sigma model and quasi-classical kinetic treatments of the many body problem are amenable to extension beyond the the regime of thermal equilibrium. Studying these interactions will have implications for the creation or modification of cavity photonic circuit elements given the prevalence of superconductors in such devices. Further, such results would be applicable to proposed cavity photonic quantum computers.

Kinetics of non-abelian Berry systems — The formalism used in my recent work on graphene gives an intuitive avenue to understand the interplay of Berry curvature and fermion kinetics. Using this approach I intend to study collective modes and hydrodynamics in systems with non-abelian Berry curvature and, specifically, channels other than the charge density. As mentioned above, the Berry gauge invariant kinetic equation enables the approach of hydrodynamics of a multi-component system in a manner similar to the conventional case. More broadly, I am interested in geometric formulations (e.g. Ref. [11]) of problems in many-body field theory, both to elucidate the role of anomalous physics (e.g. Berry curvature), as well as to explore how such a description clarifies the analogies with other geometric theories such as classical statistical mechanics and general relativity. The geometric formalism provides a natural means of understanding the relations of the various connections and curvatures in the kinetic equation as well as understanding the nature of the conserved currents.

References

[1] B. I. Ivlev, S. G. Lisitsyn, and G. M. Eliashberg, J. Low Temp. Phys. **10**, 449 (1973).

[2] J. B. Curtis, **Z. M. Raines**, A. A. Allocca, M. Hafezi, and V. M. Galitski, Phys. Rev. Lett. **122**, 167002 (2019).

[3] A. A. Allocca, **Z. M. Raines**, J. B. Curtis, and V. M. Galitski, Phys. Rev. B **99**, 020504 (2019).

[4] J. J. Hopfield, Phys. Rev. **112**, 1555 (1958).

[5] J. D. Plumhof, T. Stöferle, L. Mai, U. Scherf, and R. F. Mahrt, Nature Mater **13**, 247 (2014).

[6] A. Moor, A. F. Volkov, and K. B. Efetov, Phys Rev Lett **118**, 047001 (2017).

[7] A. Bardasis and J. R. Schrieffer, Phys. Rev. **121**, 1050 (1961).

[8] **Z. M. Raines**, V. I. Fal'ko, and L. I. Glazman, Phys. Rev. B **103**, 075422 (2021).

[9] **Z. M. Raines**, D. L. Maslov, and L. I. Glazman, *Spin-valley Silin modes in graphene with substrate-induced spin-orbit coupling*, July 6, 2021, arXiv:2107.02819.

[10] E. Bettelheim, J. Phys. Math. Theor. **50**, 415303 (2017).

[11] T. W. B. Kibble, Commun.Math. Phys. **65**, 189 (1979).