






Energy of plasmon-mediated boson-fermion pair condensate in high temperature superconductors

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Highlights

- We study the electronic boson-fermion interactions in the Bose-Einstein Condensate (BEC) state under plasmon mediation.
- The collective excitation of electronic BFP condensates is anisotropic.
- The magnitude of collective excitation of electronic BFP condensates is in the order of energy gaps of high temperature superconductors.
- Plasmons can sufficiently mediate boson-fermion coherence over 10^{-9} m.

Abstract

Interaction between particles in condensate state is nontrivial in understanding charge pairing that defines high-temperature superconductivity. A Bose-Einstein Condensate (BEC) of a non-zero-momentum Cooper pair constitutes a composite boson. A two-component electronic BEC - bosons and fermions - harbours some properties that are closely related to those of high temperature superconductors. We demonstrated that quantum coherence of a boson-fermion condensate is controlled by plasmons. A binary electronic system has an associated response function, given by the zero of longitudinal dielectric function. The response function has both long and short-wavelength branches, at least in layered superconductors. Coulomb screening of bosons by the electron cloud, in the long-wavelength branch, drives plasmon mediation in boson-fermion (BF) pairing. This study reveals that: the attractive potential in boson-fermion pair condensate (BFPC) is anisotropic, the magnitude of collective BEC excitations is in the order of an energy gap and that boson-fermion coherence under plasmon-mediation occurs at 10^{-9} m.

Introduction

Understanding the mechanism underlying high temperature superconductivity has been a major encumbrance to achieving room temperature superconductivity [1,2]. However, it remains undisputed that a Cooper pair plays a central role in high temperature superconductivity [3]. Previously, research has divulged the coexistence between zero- and finite-momentum Cooper pairs [4]. The existence of finite-momentum Cooper pairs (electronic composite bosons) alludes to a possible boson-electron interaction. A system that embodies an electronic boson interacting with a fermion in Bose-Einstein condensate (BEC) state was first proposed by Tomalchev [5]. Atypical from ultracold-atom systems, a mixture of bosons and fermions undergo first order transition from the nematic (BCS) state to BEC state at T_c that is much higher than absolute zero [[6], [7], [8]]. It has been demonstrated that the Bardeen-Cooper-Schrieffer-to-Bose-Einstein-Condensate (BCS-BEC) crossover of an electron system, distinct from an atomic system, has desirable properties related to high temperature superconductivity [7]. For instance, electronic systems favour the coexistence between antiferromagnetism and d-wave superconductivity, but ultracold-atom systems favour s-wave superconductivity [9]. Furthermore, the presence of Fermi arcs in the pseudogap state has also been associated with the binary mixture of fermions [10]. Maximum quasi-particle excitations of electronic system condensates can be attained by tuning relevant parameters such as boson-fermion mass ratio and boson-fermion number density ratio while the pairing potential can be manipulated by means of chemical composition such as hole doping [11,12].

Recent studies have explored fermion- and atom-mediated pairing between BEC systems [11,13]. The strength of pairing in high temperature superconductors is determined by unusual electronic excitations [14]. A binary electronic system has an associated charge- and pair-response functions given by the zero of the longitudinal dielectric function $\epsilon(\mathbf{k}, \omega)$ [15]. In the low-frequency plasmon branch, Coulomb screening by Thomas-Fermi method may be considered because the wave-vector \mathbf{k} is less than its critical value \mathbf{k}_c (and \mathbf{k}_c is slightly less than the wavevector \mathbf{k}_F of the Fermi surface) [16].

Ufrecht et al. [17] argue that under some conditions, attraction between a boson and a fermion is possible. During B-F interaction, the boson-fermion separation shrinks to weaken the pair breaking ability of the Coulomb effect, which vanishes at T_c [18]. Since the excitation of a Cooper pair is in the order of $k_B T_c$ [16], the total energy due to boson-fermion interaction is maintained at or below $k_B T_c$ to keep the boson from breaking up. A pseudogap occurs simultaneously as pre-formed finite-momentum Cooper pairs, which were neglected in entirety by the conventional BCS theory [8]. The phenomenon of high temperature superconductivity is driven by the collective behaviour of boson-fermion pairs rather than a single-particle-like behaviour of the condensate [19].


Accordingly, we study a Boson-Fermion interaction system mediated by a plasmon in which the second electron in the boson (excited by phonons) excites a plasmon in the electron cloud. This phenomenon leads to coupling between the boson and a fermion. Odhiambo et al. [3] attempted to determine the ground state energy of the system, though not exhaustively. In this paper, we investigate energy of the system both at ground and excited states and the implications thereof to high temperature superconductivity.

The paper is organized as follows: first, the Boson-Fermion interactions are probed to determine the total energy of boson-fermion pairs both at ground and excited states. Next, we look at how the plasmonic energy compares with the attractive potential of the system and the consequences thereof. Finally, the

results are discussed and conclusion made in the framework of the energies so determined in relation to the phenomenon of high temperature superconductivity.

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Section snippets

The boson-fermion interaction

The Hamiltonian H of the system is the sum of the Bloch energy (H_0) of individual particles (fermion and boson) and the interaction term (H_I). The Hamiltonian of the system is expressed as

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}}^f c_{\mathbf{k}\sigma}^\dagger c_{\mathbf{k}\sigma} + \sum_{\mathbf{K}} \epsilon_{\mathbf{K}}^b b_{\mathbf{K}}^\dagger b_{\mathbf{K}} + \sum_{\mathbf{K}, \mathbf{k}} V_{\mathbf{K}, \mathbf{k}} c_{\mathbf{k}'\sigma}^\dagger b_{\mathbf{K}}^\dagger b_{\mathbf{K}} c_{\mathbf{k}\sigma}$$
 Where $\epsilon_{\mathbf{k}}^f$ is the kinetic energy of a fermion in state \mathbf{k} , $\epsilon_{\mathbf{K}}^b$ is the kinetic energy of a boson in state \mathbf{K} , $c_{\mathbf{k}\sigma}^\dagger$ and $c_{\mathbf{k}\sigma}$ are fermion creation and annihilation operators, $b_{\mathbf{K}}^\dagger$ and $b_{\mathbf{K}}$ are boson creation and annihilation operators, $\sigma = \uparrow$ or \downarrow is the fermion spin-up or ...

Results and discussion

A curve of collective excitation as a function of temperature is shown in Fig. 4.

A similar curve was also obtained by Loram et al. [24] while studying the energy gap in Y1236. The magnitude of the excitation energy above the ground state of BFP condensate is in the order of the energy gap of cuprate superconductors [[25], [26], [27], [28], [29]]. The attractive potential is sensitive to change in direction of the applied voltage and predominantly accounts for anisotropy at the ground state of ...

Conclusion

Both the ground state and excited states of the BFP condensates are anisotropic. The anisotropy arises from Coulomb interactions and excitation of the BFP condensates. Increased hole content produces weak BFP condensates that form at a higher temperature while reduced hole content produces stronger BFP pairs that form at a lower temperature. The collective excitation of the BFP condensates is in the order of the energy gap of a cuprate superconductor. It's also noted that the plasmonic energy ...

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Author statement

Abel Mukubwa: Conceptualization, Methodology, software, Data curation, Writing- Original draft preparation. Visualization, investigation, Validation John Makokha: Supervision, Writing- Reviewing and Editing. ...

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ...

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