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Magnetic field effects on the superconducting and quantum critical properties of layered systems with Dirac electrons

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Abstract

We study the effects of an external magnetic field on the superconducting properties of a quasi-two-dimensional system of Dirac electrons at an arbitrary temperature. An explicit expression for the superconducting gap is obtained as a function of temperature, magnetic field and coupling parameter (λ_R). From this, we extract the $B \times \lambda_R$, $T \times \lambda_R$ and $B \times T$ phase diagrams. The last one shows a linear decay of the critical field for small values thereof, which is similar to the behavior observed experimentally in the copper doped dichalcogenide Cu_xTiSe_2 and also in intercalated graphite. The second one, presents a coupling dependent critical temperature T_c that resembles the one observed in high-T_c cuprates in the underdoped region and also in Cu_xTiSe_2. The first one, exhibits a quantum phase transition connecting a normal and a superconducting phase, occurring at a critical line that corresponds to a magnetic field dependent critical coupling parameter. This should be observed in planar materials containing Dirac electrons, such as Cu_xTiSe_2.

Keywords: Dirac electrons; Superconductivity; Quantum criticality

1. Introduction

A lot of attention has been devoted recently to quasi-two-dimensional condensed matter systems presenting a band structure such that the dispersion relation of the active electrons corresponds to the one of a relativistic massless particle. The kinematics of such electrons is described

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by a Dirac instead of a Schrödinger term in the Hamiltonian [1,2]. This fact has a profound impact on the physical properties of the system. The Fermi surface reduces to a point, the Fermi point, where the density of states vanishes. This will drastically affect the physical properties of such materials. In a previous work [3], we investigated the superconducting properties of a quasi-two-dimensional system of Dirac electrons and showed that they are completely different from the ones presented by usual Schrödinger electrons. There is, in particular, a quantum phase transition connecting the normal and superconducting phases, which is controlled by the magnitude of the effective superconducting interaction coupling parameter. The Cooper theorem, therefore, is no longer valid, as one should expect in the absence of a Fermi surface.

Among the materials presenting Dirac electrons as their elementary excitations, there are a few, which have been intensely focused lately. These are high-T_c cuprates [4–7], graphene [8–10], carbon nanotubes [11] and transition metal dichalcogenides [12,13].

The interplay between superconductivity and magnetism is a subject of central interest in any research involving superconducting materials. In particular, a key issue, both from the basic and applied physics points of view is the analysis of the effects of an external magnetic field on the superconducting properties of a system. In the present work, we study the effects of an applied constant magnetic field, perpendicular to a quasi-two-dimensional superconducting system containing Dirac electrons. As investigation method, we use the effective potential for the superconducting order parameter, which we evaluate both at $T = 0$ and $T \neq 0$, as a function of the applied field (B).

We firstly consider the zero temperature case and explicitly obtain the superconducting gap as a function of the magnetic field and of the renormalized effective physical coupling parameter (λ_R) that controls the superconducting interaction. This allows us to obtain the ($T = 0$) ($B \times \lambda_R$) phase diagram, which presents a quantum critical line separating the normal and superconducting phases. A renormalization group analysis is then performed, demonstrating that the physical results do not depend on the renormalization point.

We then study the nonzero temperature regime and explicitly obtain the superconducting gap as a function of the temperature and of the applied field. From this, we extract an implicit equation relating the critical temperature with the critical magnetic field, $T_c(T_c, B_c)$. This allows us to obtain the $T \times \lambda_R$ phase diagram, which shows the critical temperature line as a function of the coupling, for different values of the magnetic field. This line resembles the one observed in the underdoped regime of high-T_c cuprates and also in transition metal dichalcogenides [14].

Also from $T_c(T_c, B_c)$, we can derive the $B \times T$ phase diagram, for different values of the coupling parameter λ_R. The critical line separating the normal and superconducting phases, in this case, shows a linear decay of the critical field, for small values of this field. This type of behavior has been reported recently in the experimental study of the copper doped transition metal dichalcogenide Cu_xTiSe_2 [14] and also in intercalated graphite compounds [15]. Since both systems potentially possess Dirac electrons as elementary excitations, it is conceivable that the peculiar properties of such electrons would be responsible for this common behavior of the critical field. In connection to this point, it would be extremely interesting to measure the critical magnetic field as a function of doping in Cu_xTiSe_2, in order to compare with the result derived from our $B \times \lambda_R$ phase diagram.

2. Model

We investigate here the effect of applying a constant magnetic field $B\hat{z}$ along the c-axis of a quasi-two-dimensional superconducting electronic system containing two Dirac points. Assum-