Quasi-one-dimensional superconductors: from weak to strong magnetic field

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We discuss the possible existence of a superconducting phase at high magnetic field in organic quasi-one-dimensional superconductors. We consider in particular (i) the formation of a Larkin-Ovchinnikov-Fulde-Ferrell state, (ii) the role of a temperature-induced dimensional crossover occurring when the transverse coherence length \( \xi(T) \) becomes of the order of the lattice spacing, and (iii) the effect of a magnetic-field-induced dimensional crossover resulting from the localization of the wave functions at high magnetic field. In the case of singlet spin pairing, only the combination of (i) and (iii) yields a picture consistent with recent experiments in the Bedeigh salts showing the existence of a high-field superconducting phase. We point out that the vortex lattice is expected to exhibit unusual characteristics at high magnetic field.

I. INTRODUCTION

According to conventional wisdom, superconductivity and high magnetic field are incompatible. A magnetic field acting on the orbital electronic motion breaks down the reversibility and ultimately restores the metallic phase. In the case of singlet pairing, the coupling of the field to the electron spins also suppresses the superconducting order (Pauli or Clogston-Chandrasekhar limit \( T^* \)).

Recently, this conventional point of view has been challenged, both theoretically \([2-5]\) and experimentally \([7]\), in particular in quasi-1D organic materials. Because of their open Fermi surface, these superconductors exhibit unusual properties in the presence of a magnetic field. A first recognized by Lebed' \([2]\), the possible existence of a superconducting phase at high magnetic field results from a magnetic-field-induced dimensional crossover that freezes the orbital mechanism of destruction of superconductivity. Moreover, the Pauli pair breaking (PPB) effect can be largely compensated by the formation of a Larkin-Ovchinnikov-Fulde-Ferrell (LOFF) state \([2,5,8]\).

The aim of this paper is to discuss three aspects of high-field superconductivity in quasi-1D conductors: the formation of a LOFF state (i), and the respective roles of temperature-induced (ii) and magnetic-field-induced (iii) dimensional crossovers.

We consider a quasi-1D superconductor with an open Fermi surface corresponding to the dispersion law \( E_k = \sqrt{v_F (k_x^2 + k_y^2 + k_z^2)} + \phi_k \cos(k_x a) + \phi_k \cos(k_z a) + \cdots \) (I)

is the Fermi energy, and \( v_F \) the Fermi velocity for the motion along the chains. \( t_y \) and \( t_z \) are the transfer integrals between chains. The magnetic field \( H \) is applied along the \( y \) direction and we denote by \( T_{c0} \) the zero-field transition temperature. \( (\text{In Bedeigh salts, } T_{c0} = 1 \text{ K, and } t = t_z/2 \text{ is in the range } 2-10 \text{ K} \; [3,4,7]) \)

II. LOFF STATE IN QUASI-1D SUPERCONDUCTORS

We first discuss the effect of a magnetic field acting on the electron spins. Larkin and Ovchinnikov, and Fulde and Ferrell, have shown that the destructive influence of Pauli paramagnetism on superconductivity can be partially compensated by pairing up and down spins in the presence of a non-zero total momentum \( \mathbf{Q} \). At low temperature (i.e., high magnetic field), when \( T < T_0' \), the non-uniform state becomes more stable than the uniform state corresponding to a vanishing total momentum of Cooper pairs.

Quasi-1D superconductors appear very particular with respect to the existence of a LOFF state \([4]\). The fundamental reason is that, because of the quasi-1D structure of the Fermi surface, the partial compensation of the Pauli pair breaking effect by a spatial modulation of the order parameter is much more efficient than in isotropic systems. Indeed, a proper choice of the Cooper pair momentum allows one to keep one half of the phase space available for pairing whatever the value of the magnetic field. Thus, the critical field \( H_{c2} (T) / 1-T \) diverges at low temperature \([4]\).

III. TEMPERATURE-INDUCED DIMENSIONAL CROSSOVER

At low temperature, strongly anisotropic superconductors may exhibit a dimensional crossover that allows the superconducting phase to persist at arbitrary strong field (in the mean-field approximation) in the absence of PPB effect.

Within the Ginzburg-Landau theory, at high temperature \((T > T_0)\) the mixed state is an (anisotropic) vortex lattice. The critical field \( H_{c2} (T) \) is determined by

\[ H_{c2} (T) = \frac{\Phi_0}{2\pi R^2} \left( \frac{T}{T_0} \right)^{\alpha} \]

where \( \alpha \) is the critical exponent and \( R \) is the radius of the vortex core.
\[ H_{\zeta} \left( \Gamma \right) = \varphi \cdot 2 \left( \tau \left( \Gamma \right) \right) \] where \( \varphi \) and \( \tau \) are the superconducting coherence lengths and \( \varphi \) the \( \tau \) quan-

...and the lattice spacing \( d \). Vortex cores, which have an extension \( \tau \left( \Gamma \right) \) in the \( z \) direction, can then be between planes without destroying the superconducting order in the planes. The superconducting state is a Josephson vortex lattice and is always stable at low temperature for arbitrary magnetic \( \text{eld} \) (see Fig. 3 in Ref. 4). A proper description of this situation, which takes into account the discreteness of the lattice in the \( z \) direction, is given by the Lawrence-Donihue model [4, 9].

It is tempting to conclude that this temperature-induced dimensional crossover, together with the formation of a LOFF state, could lead to a diverging critical magnetic \( \text{eld} \) \( H_{c2} \left( \Gamma \right) \) at low temperature. It has been shown in Ref. 4 that this is not the case: the PPB effect strongly suppresses the high-magnetic \( \text{eld} \) superconducting phase (this point is further discussed in sect. 4.1 (see Fig. 1b)). Therefore the temperature-induced dimensional crossover cannot explain the critical magnetic \( H_{c2} \left( \Gamma \right) \) measured in Bichgauk salts [7] in the case of spin singlet pairing.

**IV. MAGNETIC-FIELD-INDUCED DIMENSIONAL CROSSOVER**

The microscopic justification of the Ginzburg-Landau or Lawrence-Donihue theory of the mixed state of type II superconductors is based on a semiclassical approximation (known as the semiclassical integral equation approximation) that completely neglects the quantum effects of the magnetic \( \text{eld} \). At low temperature (or high magnetic \( \text{eld} \)) and in sufficiently clean superconductors, when \( \tau \left( \Gamma \right) \), \( \lambda \) is the frequency of the semiclassical motion, and the elastic scattering time); these effects cannot be neglected and an exact description of the \( \text{eld} \) is required.

To be more specific, we write the Green's function (or electron propagator) as [10]

\[ G \left( r_1 ; r_2 \right) = \exp \left( i e \Phi \right) \delta \left( r_1 - r_2 \right); \]

where \( A \) is the vector potential. The Ginzburg-Landau or Lawrence-Donihue theory identifies \( G \) with the Green's function \( G_0 \) in the absence of magnetic \( \text{eld} \). The latter intervenes only through the phase factor \( \exp \left( i e \Phi \right) \); \( \Phi \) breaks down the semi-quantum states and tends to suppress the superconducting order.

When \( \tau \left( \Gamma \right) \), the approximation \( G = G_0 \) breaks down and a proper treatment of the \( \text{eld} \) is required. In isotropic systems, \( G \) includes all the information about the Landau level quantization. In strongly anisotropic conductors, it describes a magnetic- \( \text{eld} \)-induced dimensional crossover \[2, 3\] (i.e., a concomitant quantization of the spectrum into a Wannier-Stark ladder (i.e., a set of 1D spectra if we neglect the energy dispersion along the \( \text{eld} \)). This precise quantization that allows one to construct a LOFF state in a way similar to the 1D or (zero- \( \text{eld} \)) quasi-1D case \[5\]. Thus, when the \( \text{eld} \) is treated semiclassically, the region of stability of the LOFF state in the \( H-T \) plane becomes very narrow as in isotropic 2D or 3D systems \[5, 11\].
Fig. 1. (a) Phase diagram for \( t_e = t_{e0} \approx 1.33 \). \( Q \) is a pseudo momentum for the Cooper pairs in the \( \text{eik} \). The three dotted lines correspond to \( Q = 2 \, b = v_F \), \( G = 0 \), \( Q = 1 \, c = v_B \). (b) Phase diagram in the Lawrence-Doniach model.

B. Smaller anisotropy

For a smaller anisotropy, the coherence length \( z(\Gamma) \) is always larger than the spacing between chains: \( z(\Gamma) > d \). There is no possibility of a temperature-induced dimensional crossover.

Fig. 2a shows the phase diagram without the PPB effect for \( t_e = t_{e0} = 4 \). The low-\( \text{eik} \) Ginzburg-Landau regime (corresponding to the shaded triangle in Fig. 2) is followed by a cascade of superconducting phases separated by 1st-order transitions. These phases correspond to either \( Q = 0 \) or \( Q = G \, t_{e} = v_B \) [3]. In the quantum regime, the \( \text{eik} \)-induced localization of the wave functions plays a crucial role in the pairing mechanism. The transverse periodicity \( a_z \) of the vortex lattice is not determined by the Ginzburg-Landau coherence length \( z(\Gamma) \) but by the magnetic length \( d(t_e = 1) \). The 1st-order phase transitions are due to commensurability effects between the crystal lattice spacing \( d \) and \( a_z \); each phase corresponds to a periodicity \( a_z = N \, d \) (\( N \) integer). \( N \) decreases by one unit at each phase transition. The mixed state evolves from a triangular Abrikosov vortex lattice in weak \( \text{eik} \) to a triangular Josephson vortex lattice in very high \( \text{eik} \) (where \( N = 2 \)). It has been pointed out that \( a_z \) decreases in both the Ginzburg-Landau and quantum regimes, but increases at the crossover between the two regimes where \( !_c \approx T \) [3]. This suggests that the mixed state exhibits unusual characteristics in the quantum regime. Indeed, the amplitude of the order parameter and the current distribution show a symmetry of linear type. In particular, each chain carries a non-zero total current (except the last phase \( N = 2 \)). We expect these unusual characteristics to influence various physical measurements.

Fig. 2b shows the phase diagram when the PPB effect is taken into account. There is an interplay between the cascade of phases and the formation of a LOFF state. The latter corresponds to phases with \( Q = 2 \, b = v_B \) and \( Q = G \, t_{e} = v_B \).

V. CONCLUSION

Our discussion shows that a temperature-induced dimensional crossover could explain recent experiments in the Bechgaard salts only in the case of triplet pairing, although this would require a value of the interchain coupling \( t_e \) slightly smaller than what is commonly expected [3,4,7]. In the more likely case of singlet pairing, the existence of a high-\( \text{eik} \) superconducting phase in quasi-1D conductors may result from a magnetic-\( \text{eik} \)-induced dimensional crossover and the formation of a LOFF state. The crossover between the sem classical Ginzburg-Landau and quantum regimes, which occurs when \( !_c \approx T \), is accompanied by an increase of the transverse periodicity of the vortex lattice. This, as well as the characteristics of the vortex lattice in the quantum regime (linear symmetry of the order parameter amplitude and the current distribution), suggests that the.
high-field superconducting phase in quasi-1D conductors should exhibit unique properties.

VI. REFERENCES

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