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Peculiar vortex structures in Fulde-Ferrell-Larkin-Ovchinnikov phase

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Abstract. A long time ago, it was predicted by Larkin and Ovchinnikov and Fulde and Ferrell that the non-uniform superconducting state (FFLO state) must appear in the magnetic field acting on the electron spins. Up to now, there have been no unambiguous experimental proofs in the favour of this state observation. We discuss the unusual properties of such a state, which can permit its identification. It is demonstrated that in 2D (or quasi 2D) superconductors the FFLO state leads to an appearance of a very special oscillatory – like dependence of the upper critical field versus the angle with the respect to the layers. The new solutions, corresponding to the higher Landau level functions are realized, and the vortex lattice structures are quite exotic. Corresponding vortex states reveal the zeros of superconducting order parameter with high winding numbers. The predicted quasi-oscillatory angular and temperature dependence of B_{c2}, as well as a cascade of first order transitions must permit the unambiguous identification of mysterious FFLO state. Very recently the magnetic-field-induced superconductivity has been observed in the quasi two-dimensional (2d) organic conductor $(BETS)_2FeCl_4$ which is an excellent candidate for the observation of the discussed effects.

1. INTRODUCTION

Usually the behaviour of a superconductor under magnetic field is determined by the orbital effect (the interaction of superconducting order parameter with a vector-potential). However, the magnetic field also acts on the spins of the electrons and this gives an additional mechanism of Cooper pairs' destruction - the paramagnetic effect. When the orbital effect is suppressed, which is the case when there is a thin superconducting film in a parallel field, heavy fermion, or magnetic superconductors, the paramagnetic effect becomes important. In these cases, as it was predicted a long time ago by Larkin and Ovchinnikov [1] and also by Fulde and Ferrell [2], a non-uniform superconducting state (so-called **FFLO** state) appears. We discuss on the simple qualitative level the physical reasons of the FFLO state appearance and demonstrate that a generalised Ginzburg-Landau theory for FFLO superconductors may be proposed - it provides an adequate description of non-uniform states near the tricritical point on the (H, T) phase diagram. Note that for quasi-2D superconductors, the situation is very peculiar: in the presence of the orbital effect, the non-uniform state formation leads to the appearance of a new type of solutions for the superconducting order parameter **[3,** 4]. This gives rise to an unusual oscillatory temperature dependence of the upper critical field.

It is straightforward to analyse the non-uniform phase in the framework of generalized Ginzburg-Landau expansion. The standard Ginzburg-Landau functional is (see for example [5]):

$$F = a|\Psi|^2 + \gamma|\nabla\Psi|^2 + \frac{b}{2}|\Psi|^4, \qquad (1)$$

where Ψ is the superconducting order parameter and the coefficient a becomes zero at the transition temperature T_c. At $T< T_c$ the coefficient a is negative and the minimum of (1) is achieved for uniform superconducting state with $|\Psi|^2=-a/b$. If we take into account the paramagnetic effect of the magnetic field, all the coefficients in (1) will depend on field H (note that we neglect the orbital effect at the moment, that is why there is no vector-potential **A** in (1)). What is most important is that the coefficient γ changes sign at the point (H^*, T^*) of the phase diagram ($H^*=1.07\,T^*/\mu_B$). The negative sign of γ means that the minimum of the functional does not correspond to a uniform state anymore. To describe such a situation it is necessary to add a higher order derivative in the expansion (1) and the generalized Ginzburg-Landau expansion will be:

$$F_0 = a(H,T)|\Psi|^2 + \gamma(H,T)\left|\vec{\nabla}\Psi\right|^2 + \frac{\lambda(H,T)}{2}\left|\vec{\nabla}^2\Psi\right|^2 + \frac{b(H,T)}{2}|\Psi|^4. \quad (2)$$

Near tricritical point (H^*, T^*) the wave vector of modulation is small in comparison with the inverse superconducting coherence length ξ_0^{-1} and it is justified to use Ginzburg-Landau expansion. For negative γ the most favourable is to have a non-uniform solution $\Delta \sim \exp(i\mathbf{q}_0\mathbf{r})$ with the wave vector $\mathbf{q}_0$ corresponding to the minimum of q dependent part of (2): $-|\gamma|q^2+(\lambda/2)q^4$, i.e. $q_0^2=|\gamma|/\lambda$. Then we see that to describe the FFLO state it is necessary to include the higher derivatives terms in Ginzburg-Landau expansion. We will demonstrate that this leads to the profound modification of the whole picture emerging from the general phenomenological approach. Note that such phenomenological description on the basis of modified Ginzburg-Landau functional is adequate only the tricritical point. At low temperatures the modulation period of FFLO state becomes of the order of superconducting coherence length and the microscopic analysis is needed.

2. LAYERED SUPERCONDUCTORS IN TILTED FIELD

We consider the properties of strongly anisotropic layered superconductors in tilted magnetic field. The orbital effect is related with the perpendicular to the layers component of the magnetic field only. The corresponding vector-potential **A** must be incorporated in the free energy following the usual gauge-invariant scheme $\vec{\nabla} \rightarrow \vec{D} = \vec{\nabla} - \frac{2ie}{c}\vec{A}$. However, the peculiar property of the BCS model is that the coefficient b becomes equal to zero at the same point (H^*, T^*), where the gradient term vanishes. Then it is needed to take into account the terms $\sim|\Psi|^6$, $|\Psi|^2|\mathrm{grad}\Psi|^2$ and the corresponding free energy functional for two dimensional superconductor is written as [6, 7]:

$$\frac{F_0}{N(0)T_c^2} = 0.86\frac{H-H_0(T)}{H^*}|\Psi|^2 + 3\frac{T-T^*}{T^*}\xi_0^2\left|\vec{D}\Psi\right|^2 + 0.15\frac{T-T^*}{T^*}|\Psi|^4 + 3.1\xi_0^4\left|\vec{D}^2\Psi\right|^2 +$$
$$+0.85\xi_0^2\left\{|\Psi|^2\left|\vec{D}\Psi\right|^2 + \frac{1}{8}\left[(\Psi^*)^2\left(\vec{D}\Psi\right)^2 + (\Psi)^2\left(\vec{D}\Psi^*\right)^2\right]\right\} + 0.11|\Psi|^6, \quad (3)$$

where N(0) is the density of states at the Fermi level, $H_0(T)$ is the effective field of the second-order transition from normal to uniform superconducting state (the critical field of the transition into **FFLO** state in the absence of the orbital effect is somewhat higher then $H_0(T)$). The phenomenological theory of FFLO superconductivity must be developed on the basis of (3) and the properties of FFLO superconductors occur to be quite unusual. For example, here we demonstrate that the new vortex phases exist in FFLO state and the criteria of their stability are different from the standard Abikosov parameter β_A [5].

Note also that in the absence of the orbital effect the FFLO ground state corresponds to the modulation of the superconducting order parameter along one direction. The appearance of this modulated state occurs via second order transition and near the transition line it is a sinusoidal modulated phase. In principle, the distribution of the electrons polarization is also modulated in FFLO state – it is maximal in the region where the superconducting order parameter vanishes. This effect is however too small to be detected by the neutron scattering experiments. It is more promising to study the manifestation of FFLO state via the orbital effect.

In order to calculate H_{c2}, we need to solve the linear eigenvalue problem. Near tricritical point, it is given by

$$0.86\frac{H_{c2}-H_0(T)}{H^*}\Psi - 3\frac{T-T^*}{T^*}\xi_0^2\vec{D}^2\Psi + 3.1\xi_0^4\vec{D}^4\,\Psi = 0. \quad (4)$$

The eigenvalues of the operator **D' are** well known, they are Landau levels $-4\frac{|e|H}{\hbar c}(n+1/2)$ **. It** immediately follows from **(4)** that there are higher Landau levels, that give solutions for H_{c2} in FFLO phase (for more details see [3, 4, 7]). Schematically the phase diagram near the tricritical point is presented in Fig.1. The critical field is given by a sequence of curves corresponding to solutions for the superconducting order parameter with different orbital momenta. Experimentally, the resulting unusual temperature dependence of the critical field can provide **a** decisive evidence for the formation of the non-uniform state.

The calculations based on the functional (3) permit to find out the energy of different vortex configurations and determine the true ground state [7]. In the usual case the analysis on the basis of Ginzburg-Landau functional predicts the formation of the triangular Abrikosov vortex lattice. For FFLO state the situation becomes much more rich and many different vortex structures can exists. The sequence of vortex structures near the tricritical point is presented in Fig.1. It turns out that the normal-to-superconducting transition becomes of the first order in some temperature and angle intervals. In addition the lines of the first-order transition must separate the states with different orbital momenta and vortex lattice symmetry. It is clear that such transitions will be accompanied by a jump of the magnetic moment and the critical current. These transitions may be provoked by a magnetic field and/or a temperature change and by **a** variation of the angle between the field and the superconducting layers. In tilted magnetic field the variety of vortex structures is a consequence of competition between two length scales, the average distance between quantized vortices (determined by the perpendicular component of the magnetic field), and the LOFF period determined by the total field acting on the electrons spins.

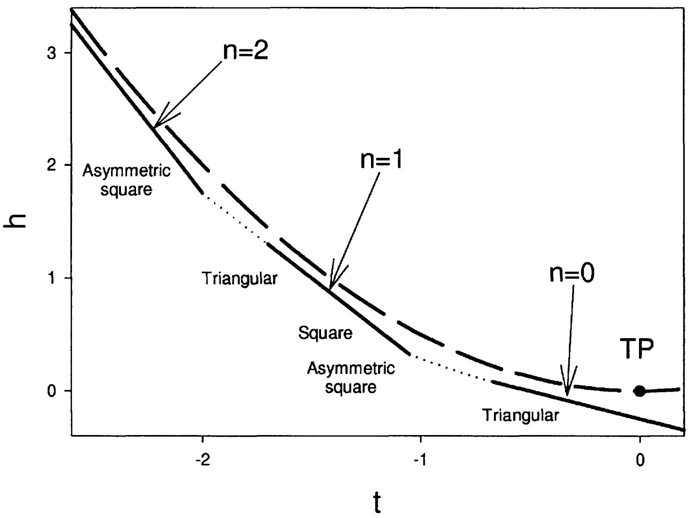

Figure 1. Schematic diagram [7] showing the different vortex states and configurations in FFLO state in two-dimensional superconductors in tilted field. h and t are the dimensionless magnetic field and temperature measured from $H^*$and T^*. The first order critical lines are represented as dotted line.

The analysis of the lattice structures exhibits zeros of the superconducting order parameter with positive and negative winding numbers w, |w|>1, as well as strongly anisotropic structures. In Fig. 2 we present as an example several vortex lattice configurations obtained numerically [7] by use of the functional (3). They correspond to the Landau level function n=1 and have several zeros in the unit cell. Note that zeros are positioned inequivalently and those different types of symmetry in their positions as well as different indices n lead to a variety of vortex lattices and first order phase transitions between them.

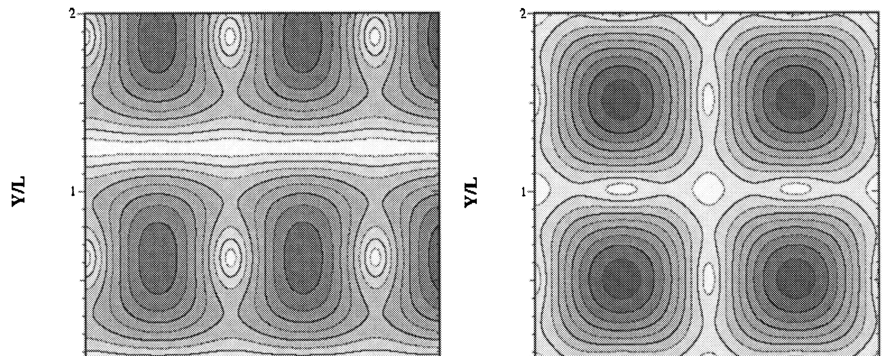

Figure 2. The distribution of the amplitude of the superconducting order parameter is represented for the asymmetric and square lattices with Landau level n=1. The dark zones correspond to the maximum of the order parameter and the white zones to its minimum.

3. MAGNETIC-FIELD-INDUCED SUPERCONDUCTIVITY IN THE QUASI TWO-DIMENSIONAL ORGANIC CONDUCTOR λ -$(BETS)_2FECL_4$

Recently a very interesting phenomenon of the magnetic-field-induced superconductivity has been observed in the quasi two-dimensional (2d) organic conductor $(BETS)_2FeCl_4$ [8,9]. At zero magnetic field the antiferromagnetic ordering of Fe^{3+} moments in this compound gives rise to a metal-insulator transition at temperatures around 8 K. A magnetic field above 10 T restores the metal phase. Further increase of the magnetic field induces the superconducting transition at H~17 T. As it has been revealeddemonstrated in the very high magnetic field experiments [9], the maximum critical temperature T_c~ 4 K is obtained at H~33 T and T_c drops to 2 K at H~42 T. Such an unusual behavior was interpreted in [8,9] as a manifestation of the Jaccarino-Peter (JP) effect [10], when the exchange field of aligned Fe^{3+} spins compensates the external field in their combined effect on the electron spins. The total (effective) magnetic field acting on the electrons spins is H_{eff}=H-H_{ex}, where H_{ex} is the field created by exchange interaction between fully polarized Fe” spins and conduction electrons. If the critical transition temperature is maximal at H−33 T, we may conclude that in $(BETS)_2FeCl_4$ the field H_{ex}=33 T.

In the clean $(BETS)_2FeCl_4$ superconductor strong quasi-2D anisotropy leads to negligible orbital effect for the field applied parallel to the layers. The parallel upper critical field is responsible for the paramagnetic (spin) effect only. The temperature dependence of H_{c2} here may be well described by the two-dimensional (2D) model for electrons.

To check whether the LOFF state is indeed realized in $(BETS)_2FeCl_4$ **a** decisive experimental test may be proposed, namely the study of the dependence H_{c2} for tilted-toward-the-plane field orientation. The perpendicular component of the magnetic field suppresses pairing by the orbital mechanism and leads to the formation of the vortex state on the already non-uniform LOFF background caused by the paramagnetic effect. The interplay between orbital and the paramagnetic effects gives rise to **a** very peculiar upper-critical-field behavior [3, 4], resulting from the solutions with higher Landau level functions for the superconducting order parameter in the vortex state. The calculations made in [11], predict quite special form of phase diagrams in $(BETS)_2FeCl_4$ – see Fig. 3. In these calculations the model with isotropic 2D Fermi surface has been used and value 5 T was taken for the orbital magnetic critical field at T=O [8]. Note that the asymmetry of the curves for $\theta \neq 0$, is related with the fact that in spite of the paramagnetic effect compensation at H= H_{ex} , the orbital effect is higher for higher magnetic field.

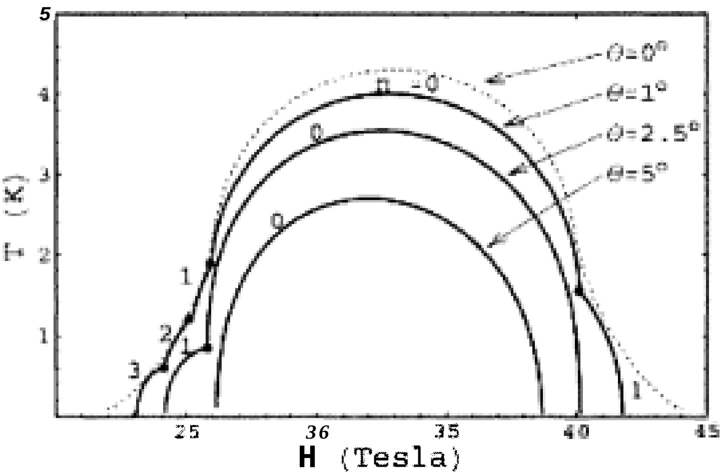

Figure 3. The dependence of the transition temperature T on the applied magnetic filed H, calculated in [11], for $(BETS)_2FeCl_4$ at different tilted (toward conducting plane) angles 8. Different parts of curves corresponds to different Landau-level states characterised by the index n.

4. CONCLUSIONS

We may anticipate the cascade of transitions into the higher Landau-level states in the tilted magnetic field in FFLO phase. Such behavior is characteristic for FFLO state and must disappear at higher temperatures (above the tricritical point). In addition to resistivity measurements, neutron scattering, μSR, and NMR experiments could provide additional information about the structure of peculiar vortex phases formed due to the interplay of spin and orbital effects. Quasi-2D organic superconductors $(BETS)_2FeCl_4$ and $(BEDT\text{-}TTF)_2X$ family may be good candidates for FFLO state observation and the discussed qualitative effects could permit unambiguous identification of this state.

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