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Reentrant orbital effect against superconductivity in the quasi-two-dimensional superconductor NbS_2

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It is well known that superconductivity at zero temperature is usually destroyed in any superconductor by either the upper orbital critical magnetic field, $H_{c2}(0)$, or the so-called Clogston paramagnetic limiting field, H_p [1]. These are due to the fact that, in the traditional singlet Cooper pair, the electrons possess opposite momenta and opposite spins. By present moment, there are also known several superconducting phases, which can exist above $H_{c2}(0)$ and H_p. Indeed, the paramagnetic limit, H_p, can be absent for some triplet superconductors (see, for example, UTe_2 [2–5]). Alternatively, for singlet superconductivity, the superconducting phase can exceed the Clogston limit by creating the non-homogeneous Fulde–Ferrell–Larkin–Ovchinnikov (FFLO or LOFF phase) [6, 7]. On the other hand, if $H_{c2}(0)$ tries to destroy superconductivity, then quantum effects of electron motion in a magnetic field can, in principle, restore it as the Reentrant Superconducting (RS) phase [8–17]. Although there are numerous experimental results, confirming the existence of the FFLO phase in several Q2D superconductors, there exist only a few experimental works [2–5], where the presumably RS phase revives in ultrahigh magnetic fields due to quantum effects of electron motion in a magnetic field in one compound – UTe_2. On the other hand, the above mentioned unique RS phenomenon has been theoretically predicted for a variety of Fermi surfaces: for Q1D [8–10], for isotropic 3D [11], and for Q2D superconductors [12–17].

Recently, the FFLO phase has been found by Lortz and collaborators in the Q2D compound NbS_2 in a parallel magnetic filed [18]. The peculiarity of this work is that at relatively low magnetic fields (i.e., in the Ginzburg–Landau (GL) area [1]) the orbital effect of the field partially destroys superconductivity but, at high magnetic fields, everything looks like there is no any orbital effect against superconductivity. The aim of our paper is to show that these happen due to the reentrant nature of the quantum effects of electron motion in a parallel magnetic field, theoretically predicted and considered in [12–17]. To this end, we derive the so-called gap equation, determining the upper critical field in slightly inclined magnetic field, which directly takes into account quantum effects of electron motion in a parallel magnetic field. The physical origin of the above mentioned quantum effects [8, 12] is related to the Bragg reflections from the Brillouin zone boundaries during electron motion in a parallel magnetic field. To compare the obtained results with the existing experimental data, we derive the gap equation both for a strictly parallel magnetic field and for a magnetic field with some perpendicular component. The latter is derived, for the best of our knowledge, for the first time. We use comparison of these equations with experimental data [18] to extract the so-called GL coherence lengths and in-plane Fermi velocity. These allow us to show that, indeed, in the magnetic fields range, $H \simeq 15\ T$, quantum effects are very strong and completely suppress the orbital effect against superconductivity. As a result, the FFLO phase appears with the transition temperature value like for a pure 2D superconductor, which satisfies the experimental situation in NbS_2 [18]. In our opinion, this is the first firm demonstration of a reentrant nature of the orbital effect against superconductivity [8–17].

Below, we consider a Q2D conductor with the following electron spectrum, which is an isotropic one within the conducting plane:

$$\epsilon(\mathbf{p}) = \frac{(p_x^2 + p_y^2)}{2m} - 2t_\perp \cos(p_z d), \quad t_\perp \ll \epsilon_F = \frac{p_F^2}{2m}, \tag{1}$$

where m is the in-plane electron mass, $t_\perp$ is the integral of the overlapping of electron wave functions in a perpendicular to the conducting planes direction; ϵ_F and p_F are the Fermi energy and Fermi momentum, respec-

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tively; $\hbar \equiv 1$. Let us consider slightly inclined with respect to the conducting planes magnetic field,

$$\mathbf{H} = (0, H_{\|}, H_{\perp}), \tag{2}$$

since the experiments in [18] are done both for the parallel and the slightly inclined fields. For our calculations, it is convenient to choose the following gauge, where the vector-potential of the magnetic field (2) depends only on coordinate x:

$$\mathbf{A} = (0, H_{\perp} x, -H_{\|} x). \tag{3}$$

We apply the Gor'kov's formulation [19] of the BCS theory of superconductivity and find the following gap equation, determining the upper critical magnetic field:

$$\Delta(x) = \\ = U \int_{-\pi}^{\pi} \frac{d\phi}{2\pi} \int_{|x-x_1|>\tilde{d}|\cos\phi|} \frac{2\pi T dx_1}{v_F |\cos\phi| \sinh\left[\frac{2\pi T|x-x_1|}{v_F|\cos\phi|}\right]} \\ \times J_0 \left\{ \frac{8t_{\perp}}{\omega_{\|}|\cos\phi|} \sin\left[\frac{\omega_{\|}(x-x_1)}{2v_F}\right] \sin\left[\frac{\omega_{\|}(x+x_1)}{2v_F}\right] \right\} \\ \times \cos\left[\frac{\omega_{\perp} p_F \sin\phi (x^2-x_1^2)}{v_F \cos(\phi)}\right] \cos\left[\frac{2\mu_B H(x-x_1)}{v_F \cos(\phi)}\right] \Delta(x_1), \tag{4}$$

where μ_B is the Bohr magneton, $\tilde{d}$ is a cut-off distance, U is electron-electron interactions constant; $\omega_{\perp} = eH_{\perp}/mc$, $\omega_{\|} = eH_{\|}/mc$, $H = \sqrt{H_{\|}^2 + H_{\perp}^2}$.

In low magnetic fields, Eq. (4) gives the GL behavior of the upper critical magnetic field, whereas at high magnetic fields, it results in the following correction, H^*_{FFLO}, to the FFLO critical magnetic field:

$$\frac{H_{\mathrm{FFLO}} - H^*_{\mathrm{FFLO}}}{H_{\mathrm{FFLO}}} = 2\frac{l_{\perp}^2}{d^2} \int_{-\pi}^{\pi} \frac{d\phi}{2\pi} \int_0^{\infty} \frac{dz}{z} \\ \times \frac{\sin^2\left[\frac{\omega_{\|} z \cos\phi}{4v_F}\right]}{\cos^2(\phi)} \cos\left(\frac{2\mu_B H z}{v_F}\right) \cos\left(\frac{2\mu_B H z \cos\phi}{v_F}\right), \tag{5}$$

where $l_{\perp} = 2t_{\perp}/\omega_{\|}(H)$, $H_{\mathrm{FFLO}} = \pi T_c / 2\gamma\mu_B$. Numerical integration of Eq. (5) for $\omega_{\|}(H = 1\,T) = 2\ K$ and $2\mu_B H(H = 1\,T) = 1.35\ K$ gives the following result:

$$\frac{H^*_{\mathrm{FFLO}} - H_{\mathrm{FFLO}}}{H_{\mathrm{FFLO}}} = -0.2\,\frac{l_{\perp}^2}{d^2}. \tag{6}$$

Finally, taking into account that, at $H \simeq 15\,T$, $l_{\perp}/d \simeq$ $\simeq 0.27$, we find that the relative change of the critical field of the appearance of the FFLO phase is very small:

$$\frac{H^*_{\mathrm{FFLO}} - H_{\mathrm{FFLO}}}{H_{\mathrm{FFLO}}} = -0.015. \tag{7}$$

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