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A chiral triplet quasi-two-dimensional superconductor in a parallel magnetic field

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Since discovery of superconductivity in the quasi-two-dimensional (Q2D) conductor Sr_2RuO_4 [1], it has been intensively investigated for more than 25 years (for reviews, see [2, 3]). Some analogy of this Q2D superconductor with the superfluid ^{3}He was recognized from the beginning and the existence of a chiral triplet superconducting phase in the Sr_2RuO_4 was suggested [4]. This scenario of superconducting pairing was supported by the observations of no change of the Knight shift between normal and superconducting phases [5, 6] and breaking of the time reversal symmetry in the superconducting phase [7, 8]. On the other hand, there were arguments against the chiral triplet superconductivity scenario, which were almost ignored that time by scientific community. One of the first argument was the paramagnetic limitation of the parallel upper critical magnetic field in Sr_2RuO_4 [9, 10]. In addition, the predicted in the chiral triplet scenario edge currents were not found in the Sr_2RuO_4 [11,12] but were found zeros of superconducting gap on Q2D Fermi surface (FS) [13, 14], which is against the fully gaped chiral triplet scenario [4]. Recently, the strongest experimental argument against the triplet scenario of superconductivity in Sr_2RuO_4 was published [15], where strong drop of the Knight shift in superconducting state of the above mentioned material was experimentally discovered.

As seen from the above discussion, the situation with the chiral triplet scenario of superconductivity in Sr_2RuO_4 is still rather controversial. The goal of our Letter is two-fold. First, we improve and make our pioneering argument [9] in favor of singlet superconductivity in Sr_2RuO_4 to be firm. The point is that in [9] (see also recent [16]) we calculated the ratio $H_{\parallel}(0)/(|dH_{\parallel}^{GL}/dT|_{T=T_c}T_c) = 0.75$, where $|dH_{\parallel}^{GL}/dT|_{T=T_c}$ is the so-called Ginzburg–Landau (GL) slope, for s-wave Q2D superconductivity and compared it with the experimental one, 0.45–0.5 [17–19]. To make our argument against the chiral triplet scenario to be firm, below we calculate the above mentioned ratio exactly for the in-plane isotropic chiral triplet superconductor with $\mathbf{d}$ vector order parameter [4, 20],

$$\mathbf{d} = \mathbf{z}\ \Delta_0\ (k_x \pm i k_y), \tag{1}$$

and obtain even stronger inconsistency,

$$H_{\parallel}(0) = 0.815\ |dH_{\parallel}^{GL}/dT|_{T=T_c}\ T_c, \tag{2}$$

with the experimental values [17–19], where, to the best of our knowledge, Eq. (2) is the first time obtained in the Letter. The second our goal is to suggest one more test for chiral triplet superconductivity, which may already exist in the slightly in-plane anisotropic Q2D triplet superconductor UTe_2 [21] and, as we hope, will be discovered in some other Q2D compounds in the future.

Let us consider a layered superconductor with the following in-plane isotropic Q2D electron spectrum:

$$\epsilon(\mathbf{p}) = \epsilon(p_x, p_y) - 2t_{\perp} \cos(p_z c^*), \quad t_{\perp} \ll \epsilon_F, \tag{3}$$

where

$$\epsilon(p_x, p_y) = \frac{(p_x^2 + p_y^2)}{2m}, \quad \epsilon_F = \frac{p_F^2}{2m}. \tag{4}$$

[In Equations (3) and (4), $t_{\perp}$ is the integral of overlapping of electron wave functions in a perpendicular to the conducting planes direction, m is the in-plane electron mass, ϵ_F and p_F are the Fermi energy and Fermi momentum, respectively; $\hbar \equiv 1$.] In a parallel magnetic field, which is applied along $\mathbf{x}$ axis

$$\mathbf{H} = (H, 0, 0), \tag{5}$$

it is convenient to choose the vector potential of the field in the form:

$$\mathbf{A} = (0, 0, Hy). \tag{6}$$

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Using the Matsubara's Green functions technique [22], it is possible to derive the following so-called linearized Gor'kov's equation, determining the parallel upper critical magnetic field in the isotropic chiral superconductor (1):

$$\Delta(\phi, y) = \int_0^{2\pi} \frac{d\phi_1}{2\pi} g \cos(\phi - \phi_1) \int_{|y-y_1|>d|\sin\phi_1|}^{\infty} \times$$
$$\times \frac{2\pi T dy_1}{v_F |\sin\phi_1| \sinh\left(\frac{2\pi T |y-y_1|}{v_F |\sin\phi_1|}\right)} \times$$
$$\times J_0\left[\frac{2t_\perp \omega_c}{v_F^2 |\sin\phi_1|}(y^2 - y_1^2)\right] \Delta(\phi_1, y_1), \qquad (7)$$

where g is the effective electron coupling constant, d is the cut-off distance, $J_0(...)$ is the zero order Bessel function. In Equation (7) the superconducting gap $\Delta(\phi, y)$ depends on a center of mass of the BCS pair, y, and on the position on the cylindrical FS (4), where ϕ and ϕ_1 are the polar angles counted from $\mathbf{x}$ axis.

By means of the Ginzburg–Landau (GL) procedure [16] to the Gor'kov's Eq. (7) we find the so-called GL slope for parallel upper critical magnetic field:

$$H_\parallel^{GL}(T) = \left(\frac{\phi_0}{2\pi\xi_\parallel\xi_\perp}\right)\tau = \left[\frac{8\sqrt{2}\pi^2 c T_c^2}{7\zeta(3) e v_F t_\perp c^*}\right]\tau, \qquad (8)$$

where $\tau = (T_c - T)/T_c$.

More complicated problem is to solve Eq. (7) at $T = 0$ and, thus, to find the upper critical magnetic field at zero temperature, $H_\parallel(0)$. This is possible to do only by means of numerical calculations. Here, we summarize procedure of the numerical solution of Eq. (7) and obtain the following new result:

$$H_\parallel(0) = 10.78 \frac{c T_c^2}{e v_F t_\perp c^*}. \qquad (9)$$

Note that solution for the superconducting gap, $\Delta(y)$ of Eq. (7) is not of an exponential shape and changes its sign several times in space, in contrast to the 3D case. Using Eqs. (8) and (9), it is possible to obtain Eq. (2).

As we already mentioned, in the candidate for the chiral triplet in-plane isotropic superconductivity, Sr_2RuO_4, the corresponding experimental coefficients [17–19] are almost two times smaller than the calculated in this Letter (2), which is a strong argument against the chiral triplet scenario.

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