Ginzburg-Landau Expansion and the Slope of the Upper Critical Field in Disordered Superconductors with Anisotropic Pairing

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It is demonstrated that the slope of the upper critical field $|dH_{c2}/dT|_{T_c}$ in superconductors with d-wave pairing drops rather fast with concentration of normal impurities, while in superconductors with anisotropic s-wave pairing $|dH_{c2}/dT|_{T_c}$ grows, and in the limit of strong disorder is described by the known dependences of the theory of "dirty" superconductors. This allows to use the measurements of H_{c2} in disordered superconductors to discriminate between these different types of pairing in high-temperature superconductors.

The main problem of the present day physics of high-temperature superconductors is the determination the nature and type of the Cooper pairing. A number of experiments and theoretical models [1] suggest the realization in these systems of anisotropic pairing with $d_{x^2-y^2}$-symmetry with appropriate zeroes of the gap function at the Fermi surface. At the same time most of these experiments also agree with the so called anisotropic s-wave pairing, which follows from some theoretical models [2].

Recently it was shown [3, 4] that controlled disordering (introduction of normal impurities) can be an effective method of experimental discrimination between different types of anisotropic pairing. Disordering leads to different behavior of the density of states in superconducting state: d-wave pairing superconductor remains gapless, while in an anisotropic s-wave superconductor with zeroes of the gap function, small disordering leads to the opening of the finite gap on the Fermi surface.

Gap measurements, especially for the different directions in the Brillouin zone, are difficult enough to perform. The aim of the present paper is to demonstrate that much simpler, in principle, measurements of the upper critical field H_{c2} at different degrees of disorder can also provide an effective method to discern d-wave pairing from anisotropic s-wave.

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Following Refs.[3, 4], we shall analyze two-dimensional electronic system with isotropic Fermi surface and separable pairing potential of the form:

$$V(\phi, \phi') = -V\eta(\phi)\eta(\phi') \qquad (1)$$

where ϕ-is a polar angle, determining the electronic momentum direction in the plane, and $\eta(\phi)$ is given by the following model dependence:

$$\eta(\phi) = \begin{cases} cos\,(2\phi) & (\text{d}-\text{ wave }) \\ |cos\,(2\phi)\,| & (\text{ anisotropic s}-\text{ wave }) \end{cases} \qquad (2)$$

In this case the superconducting gap (order parameter) takes the form: $\Delta(\phi) = \Delta\eta(\phi)$, and positions of its zeroes for s and d cases just coincide.

BCS equations for the impure superconductor are derived in a standard way. After the traditional analysis T_c-equation reduces to [3, 4]:

$$ln\left(\frac{T_{c0}}{T_c}\right) = \alpha\left[\Psi\left(\frac{1}{2}+\frac{\gamma}{2\pi T_c}\right) - \Psi\left(\frac{1}{2}\right)\right] \qquad (3)$$

where γ - is the usual electron damping due to impurity scattering. $\alpha = 1$ for d-wave case and $\alpha = (1-8/\pi^2)$ for anisotropic s-wave pairing, T_{c0}-is the transition temperature in the absence of impurities, $\Psi(x)$- is the usual digamma function. In case of d-pairing T_c is completely suppressed for $\gamma = \gamma_c \approx 0.88T_{c0}$. In anisotropic s-case the dependence of T_c on γ is much weaker, for $\gamma \gg T_{c0}$ we obtain $T_c \sim T_{c0}[1-\alpha ln(\gamma/\pi T_{c0})]$.

Ginzburg-Landau expansion for the free-energy density of a superconducting state up to terms quadratic over Δ_q can be written as:

$$F_s - F_n = A|\Delta_q|^2 + q^2C|\Delta_q|^2 \qquad (4)$$

and is determined by the usual loop-expansion for the free-energy of an electron in the field of random fluctuations of the order-parameter with some small wave vector $\mathbf{q}$. The only unusual thing is the complete disappearance of the contribution of "diffusion ladder" in d-wave case due to symmetry factors of Eq.(2) appearing in the vertices of the loops [5] . Finally, the coefficients of Ginzburg-Landau expansion can be written in the following form:

$$A = A_0 K_A ; \qquad C = C_0 K_C \tag{5}$$

where A_0 and C_0 are the usual expressions for the case of isotropic s-wave pairing [6]:

$$A_0 = N(0)\frac{T - T_c}{T_c}; \qquad C_0 = N(0)\frac{7\zeta(3)}{48\pi^2}\frac{v_F^2}{T_c^2} \tag{6}$$

where $N(0)$ - is normal density of states at the Fermi level, v_F-is electron velocity at the Fermi surface, and all peculiarities of models under consideration are actually contained in dimensionless coefficients K_A and K_C. For the impure system we get rather complicated expression for these coefficients, but the appropriate disorder dependecies can be analyzed in some detail [5].

Close to T_c the upper critical field H_{c2} is determined by:

$$H_{c2} = -\frac{\phi_0}{2\pi}\frac{A}{C} \tag{7}$$

where $\phi_0 = c\pi/e$ — is magnetic flux quantum. Then the slope of the upper critical field close to T_c is:

$$\left|\frac{dH_{c2}}{dT}\right|_{T_c} = \frac{24\pi\phi_0}{7\zeta(3)v_F^2} T_c \frac{K_A}{K_C} \tag{8}$$

Dependence of $|dH_{c2}/dT|_{T_c}$ on γ/T_{c0} for both models is shown in Fig.1. We can see that for the case of d-wave pairing the slope of H_{c2} drops to zero on the scale of $\gamma \sim T_{c0}$. For the case of anisotropic s-wave pairing, on the contrary, the slope grows with disorder and after some transition region of $\gamma \sim T_{c0}$ it crosses over to the usual linear dependence $|dH_{c2}/dT|_{T_c} \sim \gamma$, which is characteristic of the theory of "dirty" superconductors with isotropic s-wave pairing [6]. In our opinion this sharp difference can be used a simple enough criterion of experimental discrimination of d-wave superconductors from anisotropic s-wave case. Unfortunately, in case of high-T_c oxides the situation is complicated by the known nonlinearity of temperature dependence of H_{c2}, which is observed in rather wide region close to T_c.

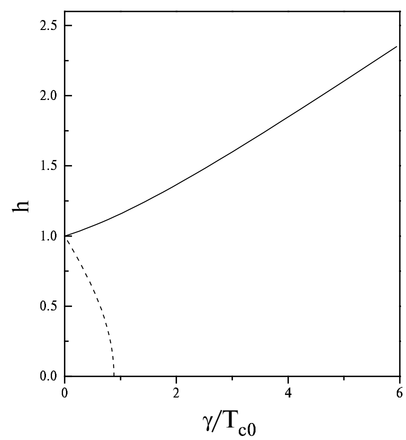

Figure 1. Dependence of normalized slope of the upper critical field $h = \left|\frac{dH_{c2}}{dT}\right|_{T_c} / \left|\frac{dH_{c2}}{dT}\right|_{T_{c0}}$ on disorder parameter γ/T_{c0}. Dashed line - the case of d-wave pairing, full line - the case of anisotropic s-wave pairing.

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