Restoration of Superconductivity in High Parallel Magnetic Fields in Layered Superconductors

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We derive an equation determining the upper critical field $H^{\parallel}_{c2}(T)$ parallel to conducting planes of a layered superconductor from the BCS theory. It extends the descriptions of $H^{\parallel}_{c2}(T)$ within the Ginzburg-Landau-Abrikosov-Gor'kov theory and the Lawrence-Doniach model to the case of strong magnetic fields. From this equation, it follows that orbital effects of an electron motion along an open Fermi surface in a magnetic field start to restore superconductivity at magnetic fields higher than the quasiclassical upper critical field and result in the appearance of a reentrant phase with $T_c(H) \simeq T_c(0)$. A stability of the reentrant phase against fluctuations is discussed. [S0031-9007(98)05633-6]

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Quasiclassical approach of the Ginzburg-Landau-Abrikosov-Gor'kov (GLAG) theory to the upper critical field $H_{c2}(T)$ [1,2], developed by Werthamer *et al.* [3] and Maki [4], describes well most of the traditional type II superconductors with large Fermi surfaces (FS's) (see Gor'kov [2]). Small oscillatory corrections to the results [1,2] due to Landau quantization of energy levels were investigated by Rajagopal *et al.* [5] and by Gruenberg *et al.* [6] at low temperatures, $T \ll T_c(0)$, and moderate magnetic fields, $H \simeq H_{c2}(0)$, where $H_{c2}(0)$ is the quasiclassical upper critical field at $T = 0$ [2,3]. The case of strong magnetic fields when only one Landau level is filled (i.e., "quantum limit") was considered by Abrikosov [7], Brazovskii [8], and Yakovenko [9]. It was found that, in a 3D isotropic case, superconductivity is unstable in the quantum limit due to formation of excitonic phases [7–9] or non-Fermi-liquid metal [9]. Recent statements about the stability of superconductivity in the quantum limit in a 3D case (see Ref. [10] and references therein for a review) seem to be controversial in view of the results [7–9] (see discussion in Ref. [9]).

On the other hand, most of the new type II superconductors are highly anisotropic quasi-two-dimensional (Q2D) [quasi-one-dimensional (Q1D)] conductors with narrow electron bands in the direction perpendicular to the planes (chains). In such compounds, quantum effects resulting from Bragg reflections of electrons moving along open FS's in a magnetic field can be large (as shown in the case of a spin-density-wave formation in Q1D conductors [11]). One of us [12] showed that the same effects lead to the survival of superconductivity at $H > H_{c2}(0)$ and to the appearance of a reentrant superconducting phase with $dT_c/dH > 0$ and $T_c(H) \simeq T_c(0)$ in high magnetic fields perpendicular to the chains of a Q1D conductor (see also Burlachkov *et al.* [13], Dupuis, Montambaux, and Sa de Melo [14], Hasegawa and Miyazaki [15]). Different physical mechanisms of the survival of a superconductivity in high magnetic fields were proposed by Klemm *et al.* [16] and by Baranov *et al.* [17]. Recent remarkable experiments by Lee *et al.* and Naughton *et al.* [18] provide strong support of the existence of superconductivity at $H > H_{c2}(0)$ in Q1D conductors $(TMTSF)_2X$ ($X = PF_6,\ ClO_4$) and seem to be in accordance with the prediction [12] (see discussion in Ref. [19]).

The aim of our Letter is to extend the results on the reentrant superconductivity in a Q1D case [12] to a Q2D case important for applications. We point out that, in Sr_2RuO_4, high-T_c, and organic Q2D compounds, feasibly high parallel magnetic fields of 10–200 T lead to the quantum limit of superconductivity in a magnetic field due to Q2D → 2D crossover of an electron motion. As shown below, in superconductors with moderate coupling of the layers, the quantum limit corresponds to the case when "effective thickness" $l_\perp(H)$ of electron wave functions in the direction perpendicular to the planes is of the order of the interlayer distance *d*. In superconductors with Josephson coupling of the layers, the quantum limit occurs when $l_\perp(H) \simeq \xi_\perp(0)$, where $\xi_\perp(0)$ is the coherence length perpendicular to the layers. The critical field $H^{\parallel}_{c5}$ corresponding to the quantum limit is shown in Fig. 1 and Table I. In the quantum limit, electron wave functions are localized on the layers. Therefore, diamagnetic currents cannot destroy "two-dimensionalized" BCS pairs, and superconductivity with $T_c(H) \simeq T_c(0)$ is restored at $H \simeq H^{\parallel}_{c5}$ within mean field theory in the case of *p*-wave pairing. In fact, mean field critical temperature $T_c(H)$ begins to increase with an increasing magnetic field at lower magnetic fields $H > H^{\parallel}_{c4}$, where $H^{\parallel}_{c4} \leq H^{\parallel}_{c5}$ (see Fig. 1). This provides a method to determine superconductivity type in Sr_2RuO_4, which is known to be a candidate for *p*-wave pairing (see Ref. [20] by Rice *et al.*). In *s*(*d*)-wave superconductors, the orbital effects start to increase $T_c(H)$ at $H > H^{\parallel}_{c4}$ if $H^{\parallel}_{c4} \leq H_p$, and the reentrant phase with $T_c(H) \simeq T_c(0)$ occurs if $H^{\parallel}_{c5} \leq H_p$, where H_p is the Pauli limiting field. We also find that superconductivity survives in *s*(*d*)-wave superconductors at low temperatures when the magnetic field is in the

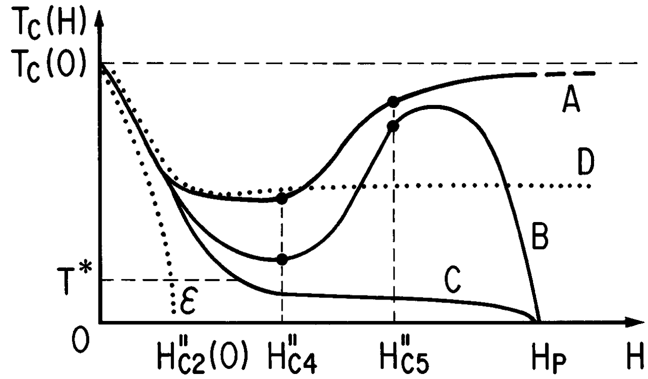

FIG. 1. Solid curves: sketches of possible magnetic field dependences of $T_c(H)$ based on qualitative analysis of Eq. (6). Curve A stands for the case of p-wave pairing. Curves B and C correspond to $s(d)$-wave pairing in the case where $H_{c2}^{\parallel}(0)$, $H_{c5}^{\parallel} \leq H_p$ and in the case where $H_{c2}^{\parallel}(0) \leq H_p \leq H_{c5}^{\parallel}$, respectively. Dotted curve D stands for the results of the Lawrence-Doniach model, whereas dotted curve E stands for the GLAG theory results.

range $H_{c2}^{\parallel}(0) < H \leq H_p$ (see Fig. 1). We stress that the above-mentioned phenomena are beyond the descriptions of $H_{c2}^{\parallel}(T)$ within both the GLAG theory [1–4] and Lawrence-Doniach (LD) model [21] which are the limiting cases [22] of the suggested gap equation. At the end of the Letter, we argue that the reentrant phase is expected to survive in the presence of fluctuations in superconductors with moderate coupling of the layers [i.e., when $\xi_\perp(0) \geq d$]. Possible applications of the obtained results to real layered compounds are discussed (see also Table I).

Let us consider a Q2D conductor with electron spectrum

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

in a parallel magnetic field $\mathbf{H} = (0, H, 0)$. In the gauge $\mathbf{A} = (0, 0, -Hx)$, electron wave functions have a form

$$\Psi_\epsilon(x, y, z) = \exp(ip_y y)\exp(ip_\perp z)\psi_\epsilon(x, p_y, p_\perp), \tag{2}$$

and the Schrödinger equation for $\psi_\epsilon(x, p_y, p_\perp)$ can be obtained by means of the Peierls substitution $p_\perp \to p_\perp - (e/c)Hx$:

$$\left[\frac{1}{2m}\left(-\frac{d^2}{dx^2} + p_y^2\right) - 2t_\perp \cos\left(p_\perp d - \frac{\omega_c x}{v_F}\right)\right] \times \psi_\epsilon(x, p_y, p_\perp) = \epsilon\psi(x, p_y, p_\perp), \tag{3}$$

where $\omega_c = ev_F dH/c$, v_F is the Fermi velocity, $\epsilon_F = mv_F^2/2$, and $\hbar = 1$.

Taking account of $t_\perp \ll \epsilon_F$, we can ignore the existence of small closed orbits and can represent the solutions of Eq. (3) in a simple form:

$$\psi_\epsilon^\pm(x, p_y, p_\perp) = \frac{\exp\{\pm ip_x^0 x \pm im\delta\epsilon x/p_x^0 \mp i(\lambda p_F/2p_x^0)[\sin(p_\perp d - \omega_c x/v_F) - \sin(p_\perp d)]\}}{\sqrt{p_x^0}}, \tag{4}$$

where $\delta\epsilon = \epsilon - \epsilon_F$, $p_F = mv_F$, $p_x^0 = \sqrt{p_F^2 - p_y^2}$, and $\lambda = 4t_\perp/\omega_c$; sign $+(-)$ stands for $p_x > 0$ $(p_x < 0)$. [Note that Bloch-like wave functions (4) correspond to continuous energy spectrum $\delta\epsilon^\pm(\mathbf{p}) = \pm p_x^0(p_x \mp p_x^0)/m + N\omega_c(p_x^0/p_F)$, where p_x is a quasimomentum limited to the "magnetic Brillouin zone," $|p_x| < \omega_c/2v_F$, and N is an integer].

Green's functions for wave functions (4) can be constructed by means of a standard procedure [23]:

$$G_{i\omega_n}^{\pm\pm}(p_y, p_\perp; x, x_1) = \frac{-i\,\mathrm{sgn}(\omega_n)m}{p_x^0}\exp[\mp\omega_n(x - x_1)m/p_x^0]\exp[\pm ip_x^0(x - x_1)] \times \exp\left\{\pm i\lambda\left(\frac{p_F}{p_x^0}\right)\sin\left[\frac{\omega_c(x - x_1)}{2v_F}\right]\cos\left[p_\perp d - \frac{\omega_c(x + x_1)}{2v_F}\right]\right\}, \quad \pm\omega_n(x - x_1) > 0, \tag{5}$$

where $\omega_n = 2\pi T(n + \frac{1}{2})$.

A linearized gap equation determining the mean field transition temperature $T_c(H)$ can be derived using Gor'kov equations for nonuniform superconductivity [24]. As a result, we have

$$\Delta(\phi, x) = \int_0^{2\pi}\frac{d\phi_1}{2\pi}U(\phi, \phi_1)\int_{|x - x_1| > a^*|\sin\phi_1|}^{\infty} dx_1 \frac{2\pi T}{v_F \sin\phi_1 \sinh[(2\pi T|x - x_1|/v_F \sin\phi_1)]} \times J_0\left\{\frac{2\lambda}{\sin\phi_1}\sin\left[\frac{\omega_c(x - x_1)}{2v_F}\right]\sin\left[\frac{\omega_c(x + x_1)}{2v_F}\right]\right\}\cos\left[\frac{2k\mu_B H(x - x_1)}{v_F \sin\phi_1}\right]\Delta(\phi_1, x_1). \tag{6}$$

The superconducting gap $\Delta(\phi, x)$ in Eq. (6) depends on the coordinate of the center of mass of BCS pair x as well as on the position on the Fermi surface, where ϕ is the polar angle between $\mathbf{H}$ and two-component vector $\mathbf{p} = (p_x^0, p_y)$. Here, $k = 1$ for $s(d)$ pairing and $k = 0$ for p pairing, respectively; a^* is a cutoff distance; the matrix element of the interaction of two BCS pairs, $U(\phi, \phi_1)$, depends only on in-plane momenta (e.g., $U(\phi, \phi_1) = U$ for s pairing, $U(\phi, \phi_1) = U\cos(\phi)\cos(\phi_1)$ for equal spin p pairing, and $U(\phi, \phi_1) = U\cos(2\phi)\cos(2\phi_1)$ for $d_{x^2-y^2}$ pairing).

TABLE I. Estimated values of the parameters $H_{c4}^{\parallel}$, $H_{c5}^{\parallel}$, $H_{c2}^{\parallel}(0)$, H_p, and T^*.

Q2D compound	$H_{c4}^{\parallel}$ (T)	$H_{c5}^{\parallel}$ (T)	$H_{c2}^{\parallel}(0)$ (T)	H_p (T)	T^* (K)
Sr_2RuO_4	5–10	35–55	0.8	?	0.05
$TlBa_2CaCu_2O_x$	100–150	120–170	100–150	205	...
$Tl_2Sr_2Ca_3Cu_4O_x$	50–100	50–100	50–100	170	...
β-$(ET)_2AuI_2$	40–50	40–50	6.5	7.5	0.3
κ-$(ET)_2I_3$	10–15	10–15	7	6.5	0.5

Quantum effects coming from a periodic electron motion along open orbits in a magnetic field are seen in a periodicity of the Bessel function $J_0(\ldots)$ in Eq. (6) in variables x and x_1. The choice of the periodic solution $\Delta_0(\phi, x + \pi v_F/\omega_c) = \Delta_0(\phi, x)$ in the case of p pairing leads to a logarithmic divergence in Eq. (6) as $T \to 0$. Therefore, a superconducting phase is stable in an arbitrary magnetic field. Note that $J_0(\ldots) \to 1$ in high fields and, thus, superconductivity is restored with $T_c(H) \simeq T_c(0)$. Possible temperature dependences of $H_{c2}^{\parallel}(T)$ are sketched in Fig. 1. Detailed analysis of the solutions of Eq. (6) will be published elsewhere [22]. Below, we summarize some main analytical results which are derived in the limiting cases of strong $[\xi_\perp(0) \gg d]$ and Josephson $[\xi_\perp(0) \ll d]$ couplings of the layers.

The "fourth critical field" corresponding to the appearance of the reentrant phase with $dT_c/dH > 0$ can be expressed as

$$H_{c4}^{\parallel} \simeq \begin{cases} 7.7 H_{c2}^{\parallel}(0), & \xi_\perp(0) \gg d\,, \\ 2.5 \frac{\xi_\perp^{3/2}(0)}{d^{3/2}} H_{c2}^{\parallel}(0), & \xi_\perp(0) \ll d\,. \end{cases} \quad (7)$$

The "fifth critical field," above which the destructive influence of orbital effects on superconductivity is completely suppressed, is given by

$$H_{c5}^{\parallel} \simeq \begin{cases} 8.0 \frac{\xi_\perp^2(0)}{d^2} H_{c2}^{\parallel}(0), & \xi_\perp(0) \gg d\,, \\ 3.2 \frac{\xi_\perp(0)}{d} H_{c2}^{\parallel}(0), & \xi_\perp(0) \ll d\,, \end{cases} \quad (8)$$

where ϕ_0 is the flux quantum, $|T_c(0) \times [dH_{c2}^{\parallel}(T)/dT]_{T_c(0)}| = \phi_0/[2\pi\xi_\perp(0)\xi_\parallel(0)]$, and $\xi_\perp(0)$ and $\xi_\parallel(0)$ are out-of-plane and in-plane coherence lengths. [Note that we define $H_{c5}^{\parallel}$ in the cases $\xi_\perp(0) \gg d$ and $\xi_\perp(0) \ll d$ by the equations $\ln[T_c(0)/T_c(H_{c5}^{\parallel})] \simeq 1$ and $[T_c(0) - T_c(H_{c5}^{\parallel})] \simeq \frac{1}{2}[T_c(0) - T_c(H_{c4}^{\parallel})]$, respectively].

Revival of superconductivity at $H > H_{c2}^{\parallel}(0)$ and $T \leq T^*$ as well as the appearance of the reentrant phase at $H > H_{c4}^{\parallel}$ in p-wave and $s(d)$-wave [if $H_{c2}^{\parallel}(0) \leq H_p$] superconductors with $\xi_\perp(0) \gg d$ can be described as follows:

$$T_c(H) \simeq T^* \left[\frac{H_{c2}^{\parallel}(0)}{H}\right]^{A\sqrt{t_\perp/\omega_c(H)}}, \qquad T^* \simeq 0.1\left[\frac{d}{\xi_\perp(0)}\right] T_c(0), \qquad A \simeq 1\,. \quad (9)$$

In such superconductors, $T_c(H)$ in the reentrant phase can also be estimated at $H \geq H_{c5}^{\parallel}$ if $H_{c5}^{\parallel} \leq H_p$:

$$\frac{T_c(H) - T_c(0)}{T_c(0)} \simeq -2\left[\frac{t_\perp}{\omega_c(H)}\right] \ln\left[\frac{\xi_\perp(0)}{d}\right]. \quad (10)$$

In the case $\xi_\perp(0) \ll d$, $T_c(H)$ can be found at $H_{c4}^{\parallel} \ll H \ll H_{c5}^{\parallel}$:

$$\frac{T_c(H) - T_c(0)}{T_c(0)} \simeq -2\left[\frac{\xi_\perp(0)}{d}\right]^2 + 0.25\left[\frac{\xi_\perp(0)}{d}\right]^2 \times \left[\frac{\omega_c(H)}{\pi T_c(0)}\right]^2 - 2.1\left[\frac{k\mu_B H}{\pi T_c(0)}\right]^2. \quad (11)$$

Equation (11), with $k = 0$, describes the reentrant phase in p-wave superconductors. It describes the reentrant phase in $s(d)$-wave superconductors if $\omega_c(H) \geq 2.8[d/\xi_\perp(0)]\mu_B H$.

Note that the existence of Fermi liquid is expected at temperatures above $T_c(0)$ in Sr_2RuO_4 as well as in most organic superconductors and optimally doped and overdoped high-T_c ones [25]. Therefore, Eq. (6) should well describe mean field transitions in these clean Q2D superconductors. The existing studies of superconducting fluctuations (see, for example, [26,27]) ignore the quantum effects in a parallel magnetic field. Below, we limit our discussion to a qualitative analysis of a physical meaning of a mean field phase in superconductors with moderate coupling of the layers [i.e., when $\xi_\perp(0) \geq d$]. By transforming Eq. (4) into coordinate space, one can find that the effective thickness $l_\perp(H)$ of electron wave functions is bigger than the interlayer distance d, if $H_{c2}^{\parallel}(0) < H \leq H_{c5}^{\parallel}$. In this range of magnetic fields, the mean field superconducting phase described in the Letter is expected to have a direct physical meaning. At $H \gg H_{c5}^{\parallel}$, electrons are localized on the layers and fluctuations possess 2D properties. To our knowledge of 2D fluctuations, the superconducting state survives in their presence either as a 3D phase [26] or as a 2D (i.e., Berezinskii-Kosterlitz-Thouless) phase [26,27] with transition temperatures $T_{3D}, T_{2D} \simeq T_c(0)$. Therefore, it is natural to suppose that the reentrant superconducting state survives at $H \gg H_{c5}^{\parallel}$ and $T \leq T_c(0)$. Estimations of mean field parameters for several superconductors with $\xi_\perp(0) \geq d$ are presented in Table I. It is seen that Sr_2RuO_4, $TlBa_2CaCu_2O_x$, and $Tl_2Sr_2Ca_3Cu_4O_x$ are candidates for observation of the reentrant phase, whereas β-$(ET)_2AuI_2$ and κ-$(ET)_2I_3$ are expected to preserve superconductivity at $H > H_{c2}^{\parallel}(0) \simeq 5$–$10$ T and $T \leq 0.3$–0.5 K.

In Q2D superconductors, a so-called "melting line" $T_{melt}(H)$ usually separates a vortex state with a zero resistivity from a melted vortex state with a finite resistivity. In highly anisotropic compounds, $T_{\mathrm{melt}}(H)$ significantly differs from the mean field transition line $T_c(H)$ [28]. In Sr_2RuO_4, however, $T_c(H) \simeq T_{\mathrm{melt}}(H)$ [29]. This has allowed determination of $T_c(H)$ at $H < H_{c2}^{\parallel}(0)$ and seems to be a common property of superconductors with $\xi_\perp(0) \geq d$ [29]. According to Refs. [28,30], it is quite likely that thermodynamic fluctuations in a parallel magnetic field are much weaker than in a perpendicular one. Therefore, in-plane torque [31] and magnetization [28,30] measurements may prove useful to determine $T_c(H)$ in more anisotropic superconductors with $\xi_\perp(0) < d$. Very recently, it has been shown [32] that $T_c(H)$ determined by analyzing the Raman spectra in the melted vortex state of $Tl_2Ba_2CuO_{6+\delta}$ is in a good agreement with the GLAG theory [1–3]. We believe that this method will be extended to the case of high parallel magnetic fields. The most common methods to detect the reentrant superconducting state in high parallel magnetic fields seem to be studies of critical currents and nonlinear *I-V* characteristics. If the reentrant state survives as a 2D phase, it can also be detected by measuring *I-V* characteristics (see, for example, [33]).

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[1] A. A. Abrikosov, Zh. Eksp. Teor. Fiz. **32**, 1442 (1957) [Sov. Phys. JETP **5**, 1174 (1957)].
[2] L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **37**, 833 (1959) [Sov. Phys. JETP **10**, 593 (1960)].
[3] N. R. Werthamer, E. Helfand, and P. C. Hohenberg, Phys. Rev. **147**, 295 (1966).
[4] K. Maki, Physics (Long Island City, N.Y.) **1**, 21 (1964).
[5] A. K. Rajagopal and R. Vasudevan, Phys. Lett. **23**, 539 (1966).
[6] L. W. Gruenberg and L. Gunter, Phys. Rev. **176**, 606 (1968).
[7] A. A. Abrikosov, J. Low Temp. Phys. **2**, 37 (1970); **2**, 175 (1970).
[8] S. A. Brazovskii, Zh. Eksp. Teor. Fiz. **61**, 2401 (1971) [Sov. Phys. JETP **34**, 1286 (1972)]; **62**, 820 (1972) [**35**, 433 (1972)].
[9] V. M. Yakovenko, Phys. Rev. B **47**, 8851 (1993).
[10] M. Rasolt and Z. Tesanovic, Rev. Mod. Phys. **64**, 709 (1992).
[11] L. P. Gor'kov and A. G. Lebed, J. Phys. (Paris), Lett. **45**, L433 (1984); P. M. Chaikin, Phys. Rev. B **31**, 4770 (1985); M. Heritier, G. Montambaux, and P. Lederer, J. Phys. (Paris), Lett. **45**, L943 (1984); T. Ishiguro and K. Yamaji, *Organic Superconductors* (Springer-Verlag, Berlin, 1990), Chap. 9.
[12] A. G. Lebed, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 89 (1986) [JETP Lett. **44**, 114 (1986)].
[13] L. I. Burlachkov, L. P. Gor'kov, and A. G. Lebed, Europhys. Lett. **4**, 941 (1987).
[14] N. Dupuis, G. Montambaux, and C. A. R. Sa de Melo, Phys. Rev. Lett. **70**, 2613 (1993); N. Dupuis and G. Montambaux, Phys. Rev. B **49**, 8993 (1994); C. A. R. Sa de Melo, Physica (Amsterdam) **260C**, 224 (1996).
[15] Y. Hasegawa and M. Miyazaki, J. Phys. Soc. Jpn. **65**, 1028 (1996); M. Miyazaki and Y. Hasegawa, J. Phys. Soc. Jpn. **65**, 3283 (1996).
[16] R. A. Klemm and K. Scharnberg, Phys. Rev. B **24**, 6361 (1981).
[17] M. A. Baranov, D. V. Efremov, and M. Yu. Kagan, Physica (Amsterdam) **218C**, 75 (1993).
[18] I. J. Lee, M. J. Naughton, G. M. Danner, and P. M. Chaikin, Phys. Rev. Lett. **78**, 3555 (1997); M. J. Naughton, I. J. Lee, G. M. Danner, and P. M. Chaikin, Synth. Met. **85**, 1481 (1997); I. J. Lee, A. P. Hope, M. J. Leone, and M. J. Naughton, Synth. Met. **70**, 747 (1995).
[19] D. Jerome, Nature (London) **387**, 235 (1997).
[20] T. M. Rice and M. Sigrist, J. Phys. Condens. Matter **7**, L643 (1995).
[21] L. N. Bulaevskii and A. A. Guseinov, Pis'ma Zh. Eksp. Teor. Fiz. **19**, 742 (1974) [JETP Lett. **19**, 382 (1974)]; R. A. Klemm, A. Luther, and M. R. Beasley, Phys. Rev. B **12**, 877 (1975).
[22] A. G. Lebed (to be published).
[23] A. A. Abrikosov, L. P. Gor'kov, and I. E. Dzyaloshinskii, *Methods of Quantum Field Theory in Statistical Mechanics* (Dover, New York, 1963).
[24] L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **34**, 735 (1958) [Sov. Phys. JETP **34**, 735 (1958)]; M. Sigrist and K. Ueda, Rev. Mod. Phys. **63**, 239 (1991).
[25] For recent data, see *Proceedings of M^2S-HTSC-V* [Physica (Amsterdam) **282C–287C** (1997)].
[26] S. E. Korshunov and A. I. Larkin, Phys. Rev. B **46**, 6395 (1992); A. Golub and B. Horovitz, Europhys. Lett. **39**, 79 (1997).
[27] K. B. Efetov, Zh. Eksp. Teor. Fiz. **76**, 1781 (1979) [Sov. Phys. JETP **49**, 905 (1979)].
[28] For the existing methods to determine $T_c(H)$, see M. Lang, Supercond. Rev. **2**, 1 (1996), and references therein.
[29] See discussions in K. Toshida, Y. Maeno, S. Nishizaki *et al.*, J. Phys. Soc. Jpn. **65**, 2220 (1996), and Ref. [12] therein.
[30] M. Lang *et al.*, Phys. Rev. B **49**, 15 227 (1994).
[31] T. Ishida *et al.*, Czech. J. Phys. **46**, 1217 (1996), Suppl. 53.
[32] G. Blumberg, M. Kang, and M. V. Klein, Phys. Rev. Lett. **78**, 2461 (1997).
[33] H. Sato *et al.*, Synth. Met. **70**, 915 (1995).