Upper critical magnetic field of high-temperature superconductors in the region of strongly interacting fluctuations

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The temperature dependence of the upper critical magnetic field, $H_{c2}(\tau)$, has been determined at temperatures near the critical temperature, $T \to T_c$, where strongly interacting fluctuations play an important role. It is shown that this quantity depends on the index of the similarity theory and has a positive curvature.

The temperature region near the critical temperature ($T \to T_c$), in which strongly interacting fluctuations play an important role, is known to be exceedingly narrow. The reason is that the width of this region, ΔT, satisfies the relation $\Delta T \approx T_c \text{Gi}$, where $\text{Gi} \sim 10^2 (a/\xi_0)^4$, and a is the interatomic distance[1]; the critical temperature which appears here is quite low for ordinary superconductors ($T_c \sim 10$ K), and the coherence length ξ_0 is quite large in typical superconductors ($\sim 10^3$–10^4 Å). We thus see that this temperature region would be too narrow to be seen experimentally.

The situation has been changed radically by the discovery of high-temperature metal oxides. These systems have an extremely short coherence length,[2,3] $\xi_0 \approx 20$ Å, and a critical temperature $T_c \approx 100$ K, so the estimate of ΔT would be ≈ 1 K. The phenomena which occur in this temperature region are thus completely amenable to experimental study.

To determine the upper critical magnetic field as a function of the temperature, $H_{c2}(\tau)$, $\tau = 1 - T/T_c$, taking the strong interaction of fluctuations into account, we need to use a similarity theory, in whose equations we should include (in a gauge-invariant way) the magnetic vector potential **A**.

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To solve this problem, we use a simplified method to incorporate the interacting fluctuations, making use of the fact that the critical indices are numerically small[1]: $\alpha \approx 0.08$, $\eta = 0.04$. Assuming that these numerical indices are zero, we find the equations of the so-called Ψ theory, in which the gradient term is the same as in the theory of a self-consistent field.[4,5]

The free-energy functional in this model (the complex nature of the order parameter in superconductors is also taken into account) is of the form

$$\Phi = \int \left\{ C_0 \left| \left(-i\partial - \frac{2e}{c} \mathbf{A} \right) \psi \right|^2 + \alpha_0 \tau |\tau|^{1/3} |\psi|^2 + b_0 |\tau|^{2/3} |\psi|^4 + D_0 |\psi|^6 + \ldots \right\} d^3\mathbf{r} \tag{1}$$

$$C_0 \approx \hbar^2 / 2m\xi_0^2 ; \qquad \alpha_0 \approx (\hbar^2/2m\xi_0^2)^2 f ,$$

where C_0, α_0, b_0, and D_0 are expansion coefficients; e and m are the charge and mass of the electron; c is the velocity of light; ψ is the order parameter; and $\mathbf{r}$ is the spatial coordinate.

The coefficient of the gradient term is chosen in such a way that is coincides with the corresponding coefficient in the self-consistent Ginzburg-Landau functional.

In functional (1), in contrast with the self-consistent expansion, all the expansion terms are, at equilibrium, of the same order in τ. In order to use (1) we thus need an additional small factor in ψ, which is unrelated to τ. A typical example of a system of this sort (in addition to the thin films of liquid helium, studied in Ref. 5) is a superconductor which undergoes a second-order phase transition in a static magnetic field. At a constant value of τ, the order parameter vanishes ($\psi \to 0$) as $H \to H_{c2}$.

To determine the critical magnetic field, as in the case of a self-consistent field, we need to find that magnetic field in which the sign of the term in (1) changes. This term is quadratic in the order parameter. The equation for determining the critical magnetic field is

$$C_0 \left(-i\partial - \frac{2e}{c} \mathbf{A} \right)^2 \psi + \alpha_0 \tau |\tau|^{1/3} \psi = 0 \tag{2}$$

$$A_y = -Hx .$$

Determining the lower energy level of this equation, we find, working in the standard way,

$$H_{c2}(\tau) \approx \frac{\varphi_0}{\xi_0^2} f \tau^{4/3} , \tag{3}$$

where φ_0 is the flux quantum, and f is a temperature-independent coefficient.

Functional dependence (3) is plotted in Fig. 1 (curve 1).

In view of the pronounced anisotropy of the electrical properties of high-temperature metal-ceramics, we should replace the gradient term in (1) and (3) by

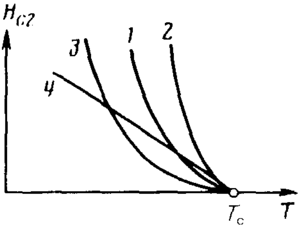

FIG. 1. Temperature dependence of the upper critical field. a—For a polycrystalline sample; 2—for a single crystal, in the case in which the field is parallel to the layers; 3—for a single crystal, for the case in which the field is perpendicular to the layers; 4—the case of a self-consistent field.

$$C_{\parallel}\left(-i\partial-\frac{2e}{c}\mathbf{A}\right)_{\parallel}^{2}+C_{\perp}\left(-i\partial-\frac{2e}{c}\mathbf{A}\right)_{\perp}^{2} \tag{4}$$

$$C_{\parallel}\approx\hbar^2/2m\xi_{\parallel}^2\ ;\quad C_{\perp}\approx\hbar^2/2m\xi_{\perp}^2\ ,$$

where $\xi_{\parallel}$ and $\xi_{\perp}$ are the coherence lengths of the parallel and perpendicular layers.

Determining the critical fields of the parallel and perpendicular layers, we find

$$H_{c2}^{\parallel}\approx\frac{\varphi_0}{\xi_{\parallel}\xi_{\perp}}f_1\tau^{4/3}\ ;\quad H_{c2}^{\perp}\approx\frac{\varphi_0}{\xi_{\parallel}^2}f_2\tau^{4/3}\ , \tag{5}$$

[curves 2 and 3 in Fig. 1; curve 4 shows $H_{c2}(\tau)$ in the approximation of a self-consistent field].

Interestingly, the positive curvature of the $H_{c2}(\tau)$ curve is observed in a narrow temperature interval in essentially all of the experiments on high-temperature ceramics which have been reported to date. A precise determination of the index in the functional dependence $H_{c2}(\tau)$ would be important for testing the existing theory.

This approach might also be taken into order to incorporate the strong interaction of fluctuations in the calculation of other quantities, such as the paraconductivity and diamagnetic susceptibility above T_c.

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