Manifestation of superconductivity of the twinning planes of high-temperature superconductors

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The effect of local enhancement of superconducting twinning near the twinning planes on the properties of high-temperature superconductors is studied.

High-temperature superconductors such as $YBa_2Cu_3O_{7-\delta}$ reveal a well-developed twinning structure with a (110) twinning plane. The twinning boundaries in these superconductors form a regular sequence with a spacing between the boundaries[1-3] $L \sim 500$ Å–1500 Å. The appearance of a twinning structure in these compounds is the result of a transition from the tetragonal phase to the orthorhombic phase at a high temperature (~ 700 °C).

Khaĭkin and Khlyustikov[4] found (see the review by Khlyustikov and Buzdin[5]) that in a number of metals the presence of the twinning plane leads to the appearance of a twinning plane superconductivity, whose critical temperature T_c is higher than the bulk critical temperature T_{c0}. Fang *et al.*[6] recently reported that in oriented $YBa_2Cu_3O_{7-\delta}$ crystallites the critical field directed parallel to the twinning plane was found to depend on the temperature in a square-root manner, which is characteristic of twinning plane superconductivity. Fang *et al.*[6] attributed this behavior, like Khaĭkin and Khlyustikov in their experiments, to the twinning plane superconductivity. Furthermore, the specific heat of a $YBa_2Cu_3O_{7-\delta}$ single crystal has recently been measured precisely.[7] These measurements showed that the specific heat has two anomalies, a small one at 93 K and one that is considerably more pronounced at 89 K. The results obtained by Inderhees *et al.*[7] can be explained logically in terms of the twinning plane superconductivity.

The twinning plane causes a relatively small increase in the superconducting critical temperature ΔT_c: $\Delta T_c = T_c - T_{c0} \sim 4$–5 K (we assume that $T_c \approx 93$ K and $T_{c0} \approx 89$ K) and $\Delta T_c / T_{c0} \ll 1$. This circumstance allows us to use the following modified Ginzburg-Landau functional to describe the twinning plane superconductivity[5]:

$$F = a|\psi|^2 + \frac{b}{2}|\psi|^4 + \frac{1}{4m}\left|\left(\vec{\nabla} - \frac{2ie}{c}\mathrm{A}\right)\psi\right|^2 - \gamma\delta(x)|\psi|^2 , \tag{1}$$

where $a = (T - T_{c0})/\eta T_{c0}$. Here we will specially call attention only to the last delta-function term which describes the enhancement of superconductivity near the twinning plane (the $x = 0$ plane). The coefficient γ is directly related to the increase in the critical temperature,

$$\frac{\Delta T_c}{T_{c0}} \equiv \tau_0 = m\eta\gamma^2 .$$

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In the presence of a system of parallel twinning planes, an increase in the critical temperature due to the mutual effect of the twinning planes becomes a factor when the distance L between the twinning planes approaches the length characteristic of the twinning plane superconductivity $\xi(T_c) = (\eta/4m\tau_0)^{1/2} \sim \xi_0\sqrt{T_{c0}/(T_c - T_{c0})} \sim 10^2$ Å for $YBa_2Cu_3O_{7-\delta}$. Ordinarily, a twinning structure with a period considerably larger than $\xi(T_c)$ apparently forms, and the critical temperature must be nearly the same as the critical temperature of a single twinning plane.

Turning now to the question of the behavior of the specific heat of the system of parallel twinning planes, we note that it is easy to find a solution for the order parameter $\psi(x)$ in quadratures and to find a general expression for the specific heat $C(T)$. As a result, we find a system of equations

$$\frac{L}{2\xi(T_c)} = \int_{\varphi_1}^{\varphi_0} \frac{\sqrt{2}\,d\varphi}{\sqrt{(\varphi^2-\varphi_1^2)(2t+\varphi^2+\varphi_1^2)}},$$

$$\varphi_1^4 + 2t\varphi_1^2 = \varphi_0^4 + 2(t-1)\varphi_0^2, \tag{2}$$

$$\frac{C}{\Delta C_0} = -\frac{T}{T_{c0}}\frac{2\xi(T_c)}{L}\frac{d}{dt}\int_{\varphi_1}^{\varphi_0}\frac{\sqrt{2}\,\varphi^2 d\varphi}{\sqrt{(\varphi^2-\varphi_1^2)(2t+\varphi^2+\varphi_1^2)}},$$

where $\varphi = \psi/\psi_0$ is a dimensionless order parameter $[\psi_0 = (\tau_0/\eta b)^{1/2}]$, φ_0 and φ_1 are the maximum and minimum values of this order parameter, $t = (T - T_{c0})/T_c - T_{c0})$, and $\Delta C_0 = (T_{c0}\eta^2 b)^{-1}$ is a jump in the specific heat produced as a result of a bulk superconducting phase transition in the absence of a twinning plane.

The temperature evolution of the specific heat for $L/\xi(T_c) = 12$ [the result of a numerical calculation based on Eqs. (2)] is shown in Fig. 1 along with the experimental data of Ref. 7. If the period is large $L \gg \xi(T_c)$, the jump in the specific heat at $T = T_c$ is $\Delta C/\Delta C_0 = 2\xi(T_c)/L$ and at $T = T_{c0}$ the value of the specific heat $C/\Delta C_0 \to 0.61$.

A comparison with the results of the experimental study of Inderhees *et al.*[7] (Fig. 1) shows that $\Delta C/\Delta C_0 \sim 1/6$, so that the period is $L \sim 12\xi(T_c) \sim 10^3$ Å. These results correspond to the typically observed twinning structure of $YBa_2Cu_3O_7$. As can be seen from the experimental data[7] (Fig. 1), a small specific-heat peak, which is evidently connected with the fluctuation effects ignored in (2), appears near T_{c0}.

Let us briefly consider the behavior of $H_{c2}(T)$ near $T = T_c$ (H is perpendicular to the x axis). According to the analysis[5,8] based on the use of functional (1),

$$H_{c2}(T) = \sqrt{2}(dH^0_{c2}/dT)\sqrt{(T_c - T)(T_c - T_{c0})},$$

where H_{c2} is the bulk critical field. The functional dependence $H_c 2(T)$ observed by Fang *et al.*[6] corresponds to this expression. If the quantity[9] $dH^0_{c2}/dT \sim 1$ T/K is used

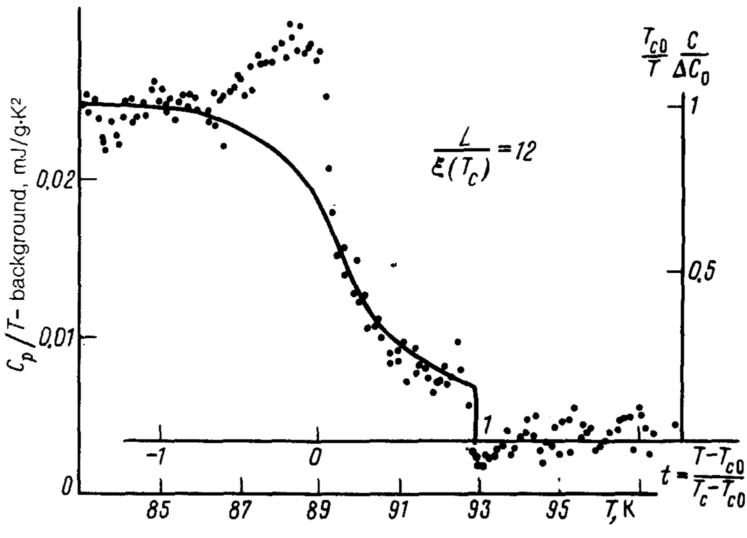

FIG. 1.

for the field which is parallel to the c axis,[9] it follows from the data of Ref. 6 that $T_c - T_{c0} \sim 5–6$ K.

In the presence of a twinning plane system, the superconductivity which arises is nonuniform in nature: the order parameter has a maximum value near the twinning planes and a minimum value between them. This situation may stem from the fact that the superconducting gap has two different values which were measured in experiments on nuclear-magnetic-resonance relaxation and nuclear-quadrupole-resonance relaxation,[10] since the hyperfine interaction is of a contact nature.

The strong nonuniformity of the superconducting order parameter due to the twinning planes accounts for the characteristic features of the vortex pinning in $YBa_2Cu_3O_{7-\delta}$ single cyrstals, which were observed by Avdeev *et al.*[11]

In the case of a dense twinning system, in which the distance between the twins is $L<\xi(T_c)$, the critical temperature may increase appreciably because of the relaxation of the proximity effect. In particular, T_c of tin[12] was found to increase by a factor of three under multiple twinning conditions. It is conceivable that the reports indicating the presence of superconductivity at temperatures above 100 K stem from the appearance of small-scaled twinning structure at those temperatures. A systematic study of the effect of the twinning structure period on the critical temperature and on the other properties of high-temperature superconductors would clearly be of considerable interest.

We know that the critical temperature of high-temperature superconducting films, which are fabricated using different techniques, does not exceed 89 K (see, e.g., Refs. 13 and 14). This temperature may be the result of the absence of twinning boundaries.

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