First-order phase transition to a rotational phase in anisotropic superconductors

A. I. Buzdin and A. Yu. Simonov
M. V. Lomonosov State University, Moscow

(Submitted 6 September 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **50**, No. 7, 325–327 (10 October 1989)

Layered superconductors in which a second-order phase transition occurs in a field parallel to the layers and a first-order phase transition occurs in a field perpendicular to the layers are studied. It is shown that a first-order phase transition to a rotational phase occurs in a tilted field and that regions of normal phase alternate with regions of rotational phase in the intermediate state.

In anisotropic layered superconductors the ratio of the fields H_{c2}/H_{c1} depends strongly on the field orientation: This ratio is at a maximum when the field is parallel to the layers and it is at a minimum when the field is perpendicular to the layers[1,2] (Fig. 1). There can therefore be a situation in which a second-order superconducting

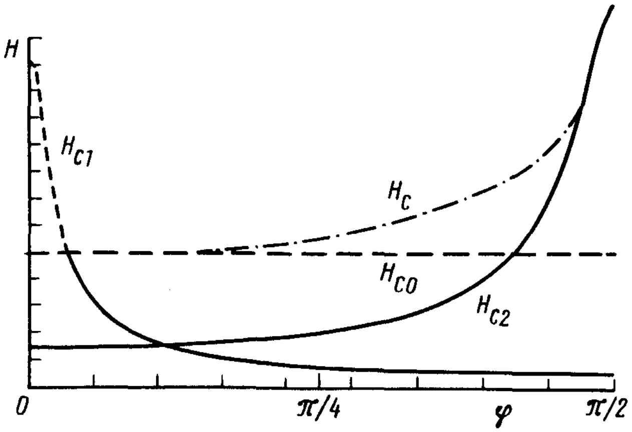

FIG. 1. The critical fields of a layered superconductor versus the angle φ between the field and the anisotropy axis.

transition occurs in a parallel field ($H_{c2} > H_{c1}$) and a first-order transition occurs in a perpendicular field ($H_{c2} < H_{c0}$, where H_{c0} is a thermodynamic critical field). Such a situation occurs, for example, in an intercalated graphite C_8K with $T_c \approx 0.15$–0.20 K (Ref. 3). We will analyze below the peculiar behavior of such superconductors. In the analysis we will use the Ginzburg–Landau functional with an anisotropic "effective" mass (see e.g., Ref. 1)

$$F = a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \frac{1}{4m_i} - |(\nabla_i - \frac{2ie}{c}A_i)\Psi|^2 + \frac{B^2}{8\pi}, \tag{1}$$

where $m_i = (m_x, m_y, m_z)$ are the principal values of the tensor of the "inverse effective masses"; here $m_x = m_y = m_\parallel \ll m_z = m_\perp$, and a strong anisotropy limit applies

$$k^2 = m_\parallel / m_\perp = (\xi_\parallel / \xi_\perp)^2 = (\lambda_\perp / \lambda_\parallel)^2 \gg 1. \tag{2}$$

Here $\xi_\parallel$ ($\xi_\perp$) is the correlation wavelength at right angles to the layers, and $\lambda_\parallel$ ($\lambda_\perp$) is the screening depth of the field for the case in which the screening currents flow parallel (perpendicular) to the layers. The case which we analyzed corresponds to the case in which the conditions $\xi_\perp \ll \lambda_\parallel \ll \xi_\parallel \ll \lambda_\perp$ hold.

As we know,[2] the angular dependence of the field $H_{c1}(\varphi)$ is (φ is the angle between the field direction and the anisotropy axis ν)

$$H_{c1}(\varphi) = H^0_{c1}(\sin^2\varphi + \cos^2\varphi / K^2)^{-1/2}, \qquad H^0_{c1} = H_{c1}(\pi/2), \tag{3}$$

and the angle θ between the vortex axis and ν is related to φ by the relation $\tan\theta = k^2 \tan\varphi$. It is important to note that in a tilted field the vortices (aside from the small neighborhood of the angles near zero) are nearly parallel to the layers (since $k^2 \gg 1$), and the condition $H_{c1}(\varphi) < H_{c0}$ holds. This situation means that the vortices penetrate the superconductor in a field H_{c0} and that this field is no longer the true (intrinsic) field of the first-order phase transition. Accordingly, in a tilted field a first-order phase transition occurs to the rotational state and the transition field H_c is higher than H_{c0} and depends on the angle φ.

To calculate the field $H_c(\varphi)$, we will use the Gibbs potential $\Phi = F - BH/4\pi$ of the vortex lattice which is oriented at an angle θ to the anisotropy axis[2,4].

$$\Phi_s = -\frac{1}{8\pi}H_{c0}^2 + \frac{1}{8\pi}B^2 + \frac{1}{4\pi}BB_0(\sin^2\theta + k^2\cos^2\theta)^{1/2} - \frac{1}{4\pi}HB\cos(\theta - \varphi). \quad (4)$$

Here B_0 coincides, as usual (see, e.g., Ref. 5), within logarithmic error, with H_{c1}^0 ($B_0 = H_{c1}^0 \ln(d/\xi)/\ln(\lambda/\xi)$, where $d(B)$ is the period of the vortex lattice, and the slight logarithmic dependence of B_0 on B and θ may be disregarded. Expression (4) holds for the fields $H \gg H_{c1}^0$.

Minimizing (4) with respect to B and θ and equating Φ_s to the normal-phase Gibbs potential $\Phi_N = -H^2/8\pi$, we find the first-order transition field

$$H_c(\varphi) = \frac{(B_0^2 + H_{c0}^2\cos^2\varphi)^{1/2} - B_0\sin\varphi}{\cos^2\varphi} \approx \frac{H_{c0}}{\cos\varphi}, \quad (5)$$

which can be used at the angles $\cos\varphi > \xi_\perp/\lambda_\parallel$ ($\xi_\perp/\lambda_\parallel \ll 1$), and the condition $\tan 0 \approx k^2B_0/H_{c0} \approx k\xi_\parallel/\lambda_\parallel \gg k$, holds in the transition field; i.e., $\theta \approx \pi/2$—the vortex structure is oriented along the layers. As can be seen from (5), the transition field $H_c(\varphi)$ is, in fact, higher than H_{c0} (see Fig. 1).

The magnetic induction in the transition field H_c is $B_c \approx H_c\sin\varphi \approx H_{c0}\tan\varphi$, and an abrupt change in the momentum during the transition is

$$\Delta M = |B - H|/4\pi = H_c\cos\varphi/4 = H_{c0}/4\pi, \quad (6)$$

The momentum M is directed along the anisotropy axis. Curiously, its abrupt change due to the transition does not depend on the angle φ. Physically, the characteristic features of the magnetic properties which are being considered are attributable to the absence of screening of the field component which is parallel to the layers.

If the angle φ between the field and the anisotropy axis decreases ($\varphi \to \pi/2$), the first-order phase transition is replaced by a second-order transition at a certain $\varphi = \varphi_0$; the characteristic value of the angle φ_0 is $(\pi/2 - \varphi_0) \sim \xi_\perp/\lambda_\parallel = \xi_\parallel/\lambda_\perp \ll 1$.

Because M and H are noncollinear, a transition to the superconducting state gives rise to a mechanical torque $K = [MH]$, where $K = K_y = -H_c^2\sin 2\varphi/8\pi = -H_{c0}^2\tan\varphi/4\pi$, which can be measured experimentally.

The following point is worth noting. It seems paradoxical that the condition $H_c(\varphi) \gg H_{c2}(\varphi)$ is satisfied in the case of penetration of the field into the superconducting sample. The point here is that the magnetic induction B in the sample is directed along the layers, while the corresponding upper critical field for $\varphi = \pi/2$ is $H_{c2}(\varphi) > H_c(\varphi)$.

It was assumed above that the internal Maxwellian field H in the sample coincides with the external magnetic field H_0. In other words, it was assumed that the demagnetization factor n is zero. This case corresponds to the physical case in which the sample has the shape of a needle whose axis is directed along M, i.e., along the v axis. In the case of the ellipsoid of revolution, on the other hand, whose axis corresponds to the v axis ($n = n_\parallel$), the relationship between B and H is given by[6]

$$(1-n)H_{\parallel}+nB_{\parallel}=H_{0\parallel}\,, \qquad \frac{1+n}{2}H_{\perp}+\frac{1-n}{2}B_{\perp}=H_{0\perp}\,.$$

In the field interval $(1-n)H_c(\varphi)\leqslant H_0\leqslant H_c(\varphi)$ the intermediate state must exist. We wish to emphasize that in contrast with the ordinary intermediate state, in our case we have a domain structure in which the normal domains alternate with the mixed-state (vortex-state) domains. The domain walls are oriented nearly parallel to the anisotropy axis and the field dependence of the magnetic moment in the intermediate state is typically given by

$$M=M_{\parallel}=\frac{\cos\varphi}{4\pi n}(H_c(\varphi)-H_0)\,.$$

The uncharacteristic vortex-type intermediate state in the tilted field can, in our view, be detected in the C_8K compound either by measuring the $M(H_0)$ dependence or by using magnetooptical methods.

We wish to thank A. A. Abrikosov for a useful discussion.

[1]L. N. Bulaevskiĭ, Usp. Fiz. Nauk **116**, 449 (1975) [Sov. Phys. Usp. **18**, 514 (1975)].
[2]A. V. Balatskiĭ *et al.*, Zh. Eksp. Teor. Fiz. **90**, 1478 (1986) [Sov. Phys. JETP **63**, 866 (1986)].
[3]Y. Koike *et al.*, Physica B **99**, 503 (1980).
[4]R. G. Mints, Fiz. Tverd. Tela **30**, 2512 (1988) [Sov. Phys. Solid State **30**, 1445 (1988)].
[5]P. G. de Gennes, Superconductivity of Metals and Alloys, Benjamin, New York, 1966.
[6]L. D. Landau and E. M. Lifshitz, Electrodynamics of Continuous Media, Pergamon Press, Oxford, 1982.

Translated by S. J. Amoretty