FIRST-ORDER PHASE TRANSITION INTO VORTEX STATE IN LAYERED SUPERCONDUCTORS

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The layered superconductors with second-order phase transition in parallel field and first-order phase transition in perpendicular field are considered. In the case of inclined field the first-order phase transition into vortex state is predicted. New type of intermediate state with the coexistence of normal and vortex regions must appear.

In the anisotropic layered superconductors the ratio H_{c1}/H_{c2} depends drastically on the field orientation - it is minimal for magnetic field parallel to the layers and maximal for the case of perpendicular field orientation [1,2]. Then the interesting situation is possible: in the parallel field the superconductivity transition is of the second-order ($H_{c2}>H_{c1}$), but in the perpendicular field first-order transition takes place (i.e. $H_{c2}<H_{co}$, where H_{co} is thermodynamic critical field, see Fig.). This case is realized in the intercalated graphite compound C_8K with $T_c \approx 0.15-0.20$ K [3].

We consider the peculiar properties for layered superconductors of this type in the framework of Ginzburg-Landau functional F with anisotropic "effective mass" [1]:

$$F = a|\psi|^2 + (b/2)|\psi|^4 + (4m_i)^{-1}|(\hbar\nabla_i - (2ie/c)A_i)\psi|^2 + B^2/8\pi \qquad (1)$$

where $m_i=(m_x, m_y, m_z)$ are the principal values of the "effective mass" tensor and $m_x=m_y=m_{||}$, $m_z=m_\perp$. We consider strong anisotropic limit

$$k^2 = m_\perp/m_{||} = (\xi_{||}/\xi_\perp)^2 = (\lambda_\perp/\lambda_{||})^2 \gg 1 \qquad (2)$$

Here $\xi_{||}(\xi_\perp)$ is the coherence length along(perpendicular) the layers and $\lambda_{||}(\lambda_\perp)$ is London penetration depth when the screening current flows parallel(perpendicular) to the layers. Further on we shall concentrate on the situation $\xi_\perp \ll \lambda_{||} \ll \xi_{||} \ll \lambda_\perp$ which precisely corresponds to the change of an order of phase transition with field orientation.

The angular dependence $H_{c1}(\varphi)$ (φ is the angle between field and anisotropy axes $\vec{\nu}$-the normal to the layers) is given by the following expression (see e.g. [2])

$$H_{c1}(\varphi) = H^o_{c1}(\sin^2\varphi + \cos^2\varphi/k^2)^{-1/2}, \quad H^o_{c1} = H_{c1}(\pi/2) \qquad (3)$$

and the angle θ between $\vec{\nu}$ and the axis of vortex is determined by the relation $\mathrm{tg}\theta = k^2\mathrm{tg}\varphi$. It should be emphasized that for the case of an

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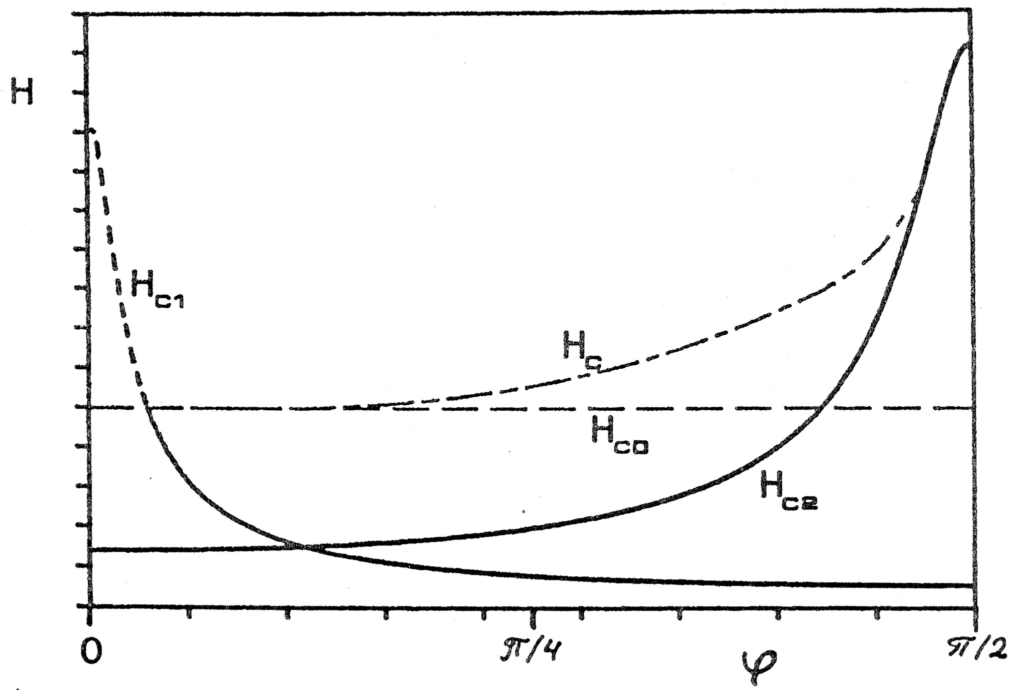

inclined field the vortices are practically parallel to the layers (as $k^2 \gg 1$), and the condition $H_{c1}(\varphi)<H_{co}$ is fulfilled. This means that vortices must penetrate into superconductor at $H=H_{co}$, and this field will not be the true critical field of the first-order transition. Therefore, in the case of an inclined field the first-order phase transition into vortex state must occur, and the corresponding critical field H_c will be greater than H_{co} and angular dependent.

The critical field $H_c(\varphi)$ could be easily calculated using Gibbs potential $G=F-\vec{B}\vec{H}/4\pi$ for the vortex lattice oriented at angle θ to anisotropy axis $\vec{\nu}$ [2,4]

$$G_s=-\frac{1}{8\pi}H_{co}^2+\frac{1}{8\pi}B^2+\frac{1}{4\pi}BB_o\sqrt{\sin^2\theta+k^2\cos^2\theta}-\frac{1}{4\pi}HB\cos(\theta-\varphi) \tag{4}$$

Here, as usual [5], $B_o=H_{c1}^o\ln(d/\xi)/\ln(\lambda/\xi)$, it is equivalent to H_{c1}^o up to the logarithmic accuracy ($d(B,\theta)$ is the period of vortex lattice, and we may neglect weak logarithmic dependence of B_o on B and θ). Note, that Eq. (4) is adequate for $H \gg H_{c1}^o$.

Minimizing (4) over B and θ we can find the equilibrium value for G_s. The condition $G_s(H_c)=G_n(H_c)$ gives us the critical field H_c

($G_n=-H^2/8\pi$ is the Gibbs potential for normal phase):

$$H_c(\varphi)=\frac{\sqrt{B_o^2+H_{co}^2\mathrm{Cos}^2\varphi}-B_o\mathrm{Sin}\varphi}{\mathrm{Cos}^2\varphi}\approx\frac{H_{co}}{\mathrm{Cos}\varphi} \qquad (5).$$

This expression is correct at angles $\mathrm{Cos}\varphi > \xi_\perp/\lambda_{||}$, and for $H=H_c$ $tg\theta\approx\approx k^2B_o/H_{co}\approx k\ \xi_{||}/\lambda_{||} \gg k$, i.e. $\theta\approx\pi/2$ and vortex lattice is oriented practically parallel to the layers. As it follows from Eq.(5) the critical field $H_c(\varphi)$ really exceeds H_{co} (see Fig.).

For $H=H_c$ magnetic induction is $B_c\approx H_c\mathrm{Sin}\varphi \approx H_{co}tg\varphi$, and the magnetic moment jump

$$\Delta M = |B-H|/4\pi = H_c\mathrm{Cos}\varphi/4\pi = H_{co}/4\pi \qquad (6)$$

$\vec{M}$ is directed along axis $\vec{\nu}$ and its jump does not depend on angle φ. The physical nature of such peculiarities of the magnetic behavior is connected with the absence of screening of parallel field.

We assumed above that the internal field H in the sample coincides with external $\mathfrak{H}$ one, i.e. demagnetization factor n=0. This corresponds to the physical situation when the sample is needle-like with axis along $\vec{M}$, i.e. along $\vec{\nu}$. In the case of ellipsoidal sample with rotation axis coinciding with $\vec{\nu}$ ($n=n_{||}$), the relationship between $\vec{B}$ and $\vec{H}$ is as follows [6]

$$(1-n)H_{||} + nB_{||} = \mathfrak{H}_{||} \quad , \qquad (1+n)H_\perp/2 + (1-n)B_\perp/2 = \mathfrak{H}_\perp$$

Within the interval of magnetic field $(1-n)H_c(\varphi)\le \mathfrak{H}\le H_c(\varphi)$ the intermediate state must exist. For this case, in contrast to the usual intermediate state in the superconductors, the sequence of normal domains and domains of the vortex state is realized. The domain walls orientation practically coincides with anisotropy axis $\vec{\nu}$, and we obtain a specific $\vec{M}(H)$ dependence for this intermediate state

$$\vec{M}=M_{||}= \mathrm{Cos}\varphi\ (H_c(\varphi)-\mathfrak{H})/4\pi n$$

In conclusion the existence of this peculiar intermediate state could be detected in C_8K compound by magnetic $\vec{M}(H)$ measurements or by magnetooptic methods.

REFERENCES:

1. L.N. Bulaevskii, Usp.Fiz.Nauk, 1975, **116**, 449 [Sov.Phys.Usp., 1975, **18**, 514 .
2. A.V. Balatskii et.al. Zh.Eksp.Teor.Fiz. ,1986, **90**, 1478. [Sov.Phys.JETP., 1986, **63**, 866].
3. Y.Koike et.al., Physica B,1980, **B99** , 503.
4. R.G. Mintz, Fiz.Tverd.Tela, 1988, **30**, 2512 .
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, London, 1960).