# Intermediate state in magnetic superconductors

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The usual classification of superconductors on the basis of the Ginsburg-Landau parameter is violated in ferromagnetic superconductors. Near the magnetic transition point, the mixed state gives way in a field to an intermediate state. The temperature dependence of the critical field is nonmonotonic and anomalous.

Cooper pairing occurs in magnetic superconductors despite the presence of a regular lattice of magnetic rare-earth atoms, with the result that there are many unique features in the behavior of such systems (for a review of this topic, see, for example, Ref. 1). Of particular interest are ferromagnetic superconductors, in which in the absence of a superconductivity there would be a transition to a ferromagnetic phase (while the Cooper pairing gives rise to an inhomogeneous magnetic structure). Among the ferromagnetic superconductors are the ternary compounds $ErRh_4B_4$, $HoMo_6S_8$, and $HoMo_6Se_8$ and many alloys.[1] Ferromagnetic superconductors exhibit some unusual superconducting properties even above the magnetic transition temperature (which essentially coincides with the Curie point $\Theta$). All ferromagnetic superconductors are type II superconductors; the Ginzburg-Landau parameter $\kappa = \lambda_L/\xi$ ($\lambda_L$ is the London penetration depth, and $\xi$ is the superconducting correlation length) in them is much greater than unity. Nevertheless, near the Curie temperature $\Theta$, because of the strong magnetic polarizability of the normal phase, the superconducting transition is a first-order transition in an external magnetic field,[2] and an intermediate state of a new type should arise.

Magnetic-anisotropy effects play an important role in ferromagnetic superconductors, and an anomalous behavior is seen when the field is directed along an easy-magnetization axis; this is the case which we will be discussing below. When the field is instead oriented along a hard-magnetization axis, the behavior of the ferromagnetic superconductor above $\Theta$ is ordinary, determined by the parameter $\kappa$.

If the sample is cylindrical, and if the axis of the cylinder (the $z$ axis) is an easy axis (the demagnetizing factor is $N_z = 0$), near the point $\Theta$, the field of a first-order transition will exceed that of a second-order transition. At a certain temperature $T^*$ ($\Theta < T^* < T_c$, where $T_c$ is the critical superconducting temperature), the nature of the transition will change.[3,4] Near the Curie point, the critical field is determined by the thermodynamic condition $\chi_m(T)H^2/2 = -H_{c0}^2/8\pi$, where $H_{c0}^2/8\pi$ is the energy of superconducting condensation, which at $T \ll T_c$ is essentially independent of the temperature, and $\chi_m = \mu^2 n/(T-\Theta)$ is the magnetic susceptibility of the rare-earth atoms. Their effective moment is $\mu$, and their density is $n$. Here the critical field is

$$H_c = H_{c0}/\sqrt{4\pi\chi_m(T)} \sim \sqrt{T-\Theta}$$

and it vanishes in a square-root fashion in the limit $T \to \Theta$. The field of the second-order transition, on the other hand, near $\Theta$ is determined by the exchange effect $h = I\chi_m H_{c2}/\mu n \sim T_c$, where $I$ is the exchange integral, and $H_{c2} \sim (T-\Theta)$, i.e., we have $H_{c2} \ll H_c$ near the Curie point.

In the case of a plate oriented perpendicular to the magnetic field ($N_z = 1$), an intermediate state should arise near the point $\Theta$ in a ferromagnetic superconductor. In contrast with an ordinary intermediate state, which would appear in a plate in the form of widely spaced superconducting bands as the field is reduced, in a ferromagnetic superconductor the thermodynamics favors the immediate appearance of a small-scale structure of alternating normal and superconducting regions with a period $d \ll L$, where $L$ is the plate thickness. The thickness of the superconducting layers may be less than $\lambda_L$, in which case there would be an essentially complete penetration of the field into the superconducting region.

The thermodynamic characteristics of the intermediate state can be found without reference to its detailed structure (which will be taken up in a more detailed paper). Let us assume that the thickness of the superconducting layers is $d_s$, so that the fraction of the total thickness which they represent is $\epsilon = d_s/d$. Under the condition $d \ll L$, we can conveniently determine the average magnetic susceptibility $\bar{\chi} = \chi_m(T)(1-\epsilon)$ (the magnetic susceptibility in a superconducting phase is much smaller than $\chi_m$ and can be ignored). The free energy of the intermediate state is

$$F = -\frac{\bar{\chi} H^2}{2(1+4\pi\bar{\chi})} - \epsilon\frac{H_{c0}^2}{8\pi}, \tag{1}$$

where the first term is the magnetic component of the energy. The appearance of an intermediate state, i.e., the appearance of a value $\epsilon > 0$, is favorable under the condition

$$H < H_c = (1+4\pi\chi_m)(4\pi\chi_m)^{-1/2}$$

[the internal field at $H = H_c$ is the same as the critical field in the case $N_z = 0$: $H_{c0}[4\pi\chi_m(T)]^{-1/2}$]. The fraction of the total thickness represented by the superconducting regions in the intermediate state is given as a function of the field by

$$\epsilon = \frac{H_c - H}{H_c}\left(1 + \frac{1}{4\pi\chi_m}\right). \tag{2}$$

When the energy of the boundaries and the field nonuniformity in the intermediate state is taken into account, we find a relative correction to $H_c$ on the order of $(\xi\chi_m/L)^{1/2}$. In the general case of an arbitrary value of the demagnetizing factor $N_z$, the critical field is

$$H_c(T) = H_{c0}\left(\frac{1}{\sqrt{4\pi\chi_m(T)}} + N_z\sqrt{4\pi\chi_m(T)}\right). \tag{3}$$

It is important to note (Fig. 1) the nonmonotonic behavior of $H_c(T)$: At $\chi_m(T) = N_z/4\pi$, there is a minimum in $H_c$. In the immediate vicinity of the temperature $\Theta$ we need to allow for the nonlinearity of the dependence $M(H)$ in the expres-

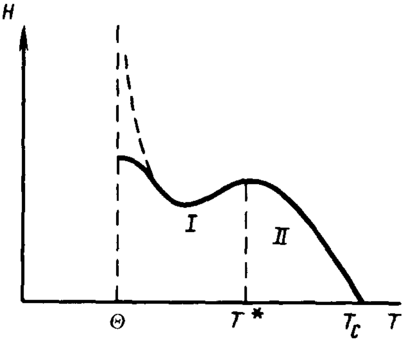


FIG. 1. Schematic temperature dependence of the critical field in a ferromagnetic superconductor ($N_z \neq 0$). The dashed part of the curve ignores nonlinear effects in the magnetization near the Curie point Θ.

sion for the free energy in (1); the result will be to limit the growth of $H_c(T)$. A minimum on the $H_c(T)$ curve has in fact been observed recently in experiments[5] on $ErRh_4B_4$ single crystals. This minimum may be taken as indirect evidence of the appearance of an intermediate state. It is difficult to make a detailed comparison with the experiments of Ref. 5, since the samples studied there were irregular in shape.

A fundamental distinguishing feature of the intermediate state in a ferromagnetic superconductor is that it appears as a small-scale structure with $d \ll L$ [an analysis of the intermediate state yields $d \sim (L\xi/\chi_m)^{1/2}$ in order of magnitude]. On the other hand, the critical field for the appearance of a single thin superconducting region is well below $H_c$ (Ref. 1). It may thus be difficult to nucleate an equilibrium intermediate state in a ferromagnetic superconductor; this circumstance would be reflected by pronounced hysteresis effects (in the field).[5]

Just below $H_c$ in the intermediate state, the moment is a linear function of the field:

$$M = [H - H_{c0}(4\pi\chi_m)^{-1/2}]/4\pi N_z.$$

In a weak magnetic field, the intermediate state may go into a mixed state.

It is important to note that the parameter $\kappa$ remains essentially constant in a ferromagnetic superconductor near the point Θ, and the relationship between $\kappa$ and the energy ($\sigma_{ns}$) of a plane $N/S$ boundary is completely different from that in an ordinary superconductor.[6] In order of magnitude we have $\sigma_{ns} \sim \xi H_{c0}^2 - \lambda_L H_c^2$, and since in the case $N_z = 0$ we have $H_c^2 \sim H_{c0}^2/\chi_m$ we find the condition for a change in the sign of $\sigma_{ns}$:$\chi_m(T) \sim \lambda_L/\xi$. This condition necessarily holds near the Curie point. On the other hand, the appearance of vortices at $\sigma_{ns} > 0$ may still be favored from the energy standpoint [the condition $\chi_m(T) < (\lambda_L/\xi)^2$ would have to hold here]. Under certain conditions, an intermediate state of a new type can arise in a ferromagnetic superconductor, with an alternation of normal domains and superconducting domains of a vortex phase.

It would be very interesting to see a direct experimental study of the intermediate state in ferromagnetic superconductors, especially in high-quality $HoMo_6S_8$ crystals.

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