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«PARAMAGNETIC» MEISSNER EFFECT IN SUPERCONDUCTORS

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Introduction

In 1989 E.G.Valulin et al. [1] reported the appearance of an anomalous paramagnetic signal in monocrystalline and ceramic YBaCuO samples at $T < T_c$. This effect arose when the sample was kept at 4.2K for 15-280 min. Later Moshchalkov et al. [2] reported the observation of a paramagnetic signal in superconducting thin films. In 1992 Braunish et al. [3] observed a paramagnetic Meissner effect in bismuth-oxide superconducting ceramic samples. Because of the difficulty of explaining the paramagnetic Meissner effect (PME), the authors suggested that spontaneous currents appeared during the cooling procedure in the absence of a magnetic field. Later Sigrist and Rice [4] connected this phenomenon with spontaneous currents produced by a π-type Josephson junction, probably arising when two grains of different crystalline orientation are in contact. Nevertheless this explanation is not suitable, because the averaging of π-junctions in different superconducting clusters makes this effect negligible. So, the question is: whether it is possible to obtain a paramagnetic state during the field cooling (FC) procedure for a multiple connected superconductor, such as a ceramic one, without any special assumptions about the order parameter? In this work it is shown that such a possibility exists in the case of the capture of a magnetic field in a superconductor during FC.

Results and disscussion

Let us consider a simple example which illustrates the basic idea. Let a superconducting sample be a hollow cylinder having an external radius R and internal radius r_0 (see Fig.1). During cooling in a magnetic field H, it captures the whole magnetic flux and forces the field out from the walls, not 'outside' but 'inside' the cylinder. This is possible

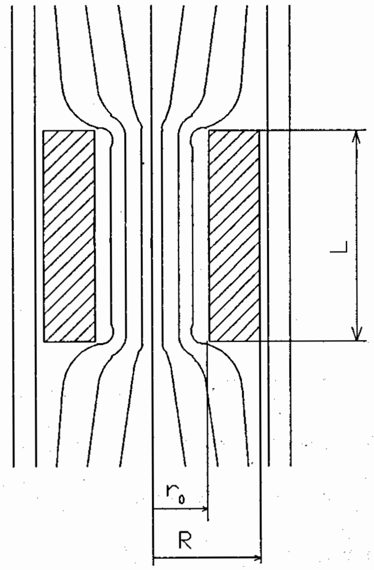

Figure 1. Illustration of magnetic flux capture in a hollow superconducting cylinder.

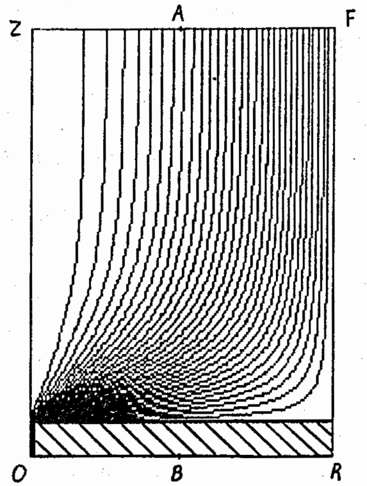

Figure 2. Distribution of constant magnetic flux lines near a superconducting sample in the case of magnetic field capture in a single flux spot.

in the case when the superconducting phase arises on the surface of the cylinder and spreads deeply into the walls of the cylinder. Thus, at the superconducting transition we obtain a superconducting cylinder which captures the $H\pi R^2$ flux . Disregarding the end effects, the magnetic moment of this cylinder is:

$$M = \int i(r)\pi r^2 dr = M_- + M_+ = -\pi HLR^2 + \pi H(R^2/r_0^2)Lr_0^2 = 0,$$

where M_- is the magnetic moment due to currents on the external surface of the cylinder, M_+ is the magnetic moment due to currents on the internal surface of the cylinder, and L is the length of the cylinder. Thus, in this case, a zero signal of magnetic moment or a "zero" Meissner effect is obtained during the FC procedure.

It is possible to achieve a "paramagnetic" Meissner effect, regarding the end effects, with a special profile of the inside hole. The magnetic moments of superconductors of different configurations were obtained by numerical simulation of the Poisson equation for cylindrical coordinates with OZ axes (see Fig.2) and a mirror symmetry with OR axes. Niman boundary conditions were used for the OR and ZF bounds, and Dirichle ones for OZ and FR. A zero vector-potential A was chosen for OZ and A_0 for FR. These boundary conditions describe a typical configuration of the magnetic field in a SQUID-susceptometer, where the field is stabilized by using a hollow superconducting cylinder [5]. For cylindrical symmetry it is more convinuent to use the value $r \cdot A$ (r is the radius in cylindrical coordinates) instead the vector-potential A. So the force lines represented in Figs.2-4 are the lines of constant $r \cdot A$, or the lines of constant flux. The vector-potential of the sample corresponds to the complete capture of the flux to obtain M_{FC}, and $A = 0$ for calculating M_{ZFC} (see Fig.3a,b) . For the sample in Fig.3 the ratio $M_{FC}/(-M_{ZFC})$ is 0.555. In Fig.4a,b,c,d the results for samples of different configurations are presented and the $M_{FC}/(-M_{ZFC})$ ratio is given for each case. It is clearly seen that M_{FC} may be as large as M_{ZFC} in absolute value.

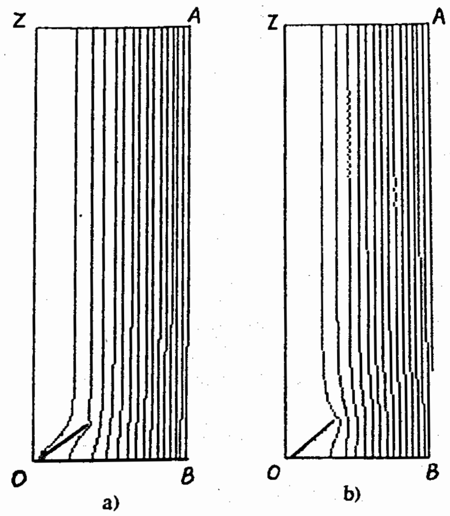

Figure 3. Distribution of constant magnetic flux lines for a specially shaped superconducting sample positioned in a uniform magnetic field for: a) FC procedure, b) ZFC procedure. Part $OBAZ$ of the entire $ORFZ$ calculation is represented in the figure.

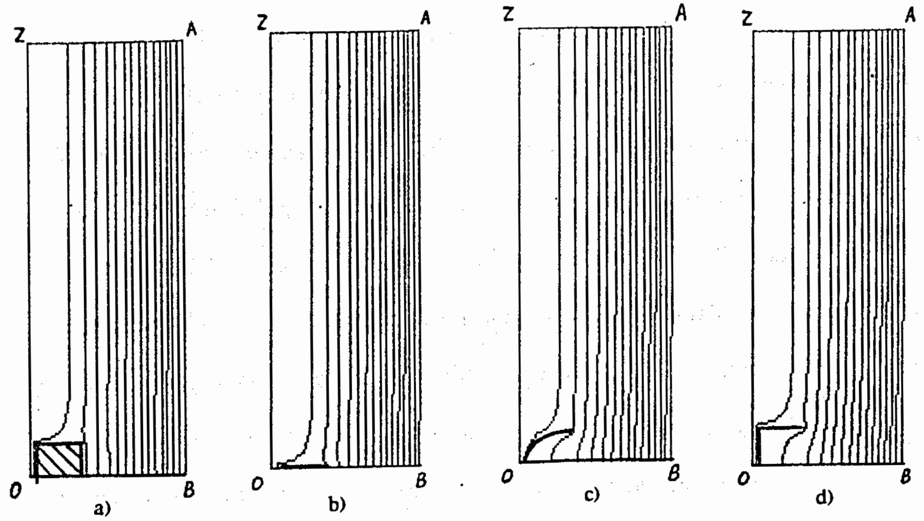

Figure 4. Distribution of constant magnetic flux lines after FC procedure for superconducting samples of different forms positioned in a uniform magnetic field: a) $M_{FC}/(-M_{ZFC}) = 0.069$; b) $M_{FC}/(-M_{ZFC}) = 0.329$; c) $M_{FC}/(-M_{ZFC}) = 0.672$; d) $M_{FC}/(-M_{ZFC}) = 0.877$. Part $OBAZ$ of the entire $ORFZ$ calculation is represented in the figure.

Now we will consider one more important case. The flux is captured and suppressed not in the center of the sample but is distributed uniformly throughout the sample as flux spots. The most typical example is the vortex lattice (see Fig.5). The surface may be divided into areas S_i , which contain only one flux spot. If we calculate the positive contribution to the magnetic moment, because of surface screening currents induced by the captured flux, we obtain for the configuration presented in Fig.2,

$$M = aHR^3$$

$[M] = A \cdot cm^2$, $[H] = Oe$, $[R] = cm$, $a = 1.38$.

In this formula the constant a is given for the case $r_0 \to 0$. Nevertheless, if $r_0 < 0.2R$, the error in M is less than 10%. Thus, for the magnetic moment of a sample with a surface square S, and N number of flux spots, we obtain:

$$M = a\sum_{i=1}^{N} HR_i^3 = aH(S/(\pi \mathrm{N}))^{0.5}.$$

M has a maximum value for $N = 1$. If N is large, the paramagnetic contribution has the asymptotical approximation $1/\sqrt{N}$. This paramagnetic moment will increase with any aberration in the uniformity of flux spot distribution.

The large PME ($M_{FC}/(-M_{ZFC}) = 0.4$) observed in article [3] may be induced by the effect described above if the sample consists of separate superconducting clusters which contain one or only a few flux spots after the FC procedure. In such an explanation of the experiment, the susceptibility after the FC procedure should reach a constant if the magnetic field goes to zero. It is easy to understand the transition from a diamagnetic Meissner effect to PME with a decrease in the magnetic field. During magnetic field compression, the flux will not be captured until the maximum compressed field is less than the critical field of the intergranular links. Observance of the long-time relaxation of the magnetic moment in ceramic and monocrystalline samples after FC [1], the authors found not only a positive change in the magnetic moment in time, but also that the magnetic moment changed from negative to positive. This behavior may be also understood by taking into account the suggestion that the structure of frozen flux spots (or vortices) in the sample tends to a more inhomogeneous state, for example, because of the attraction of vortices to pinning centers.

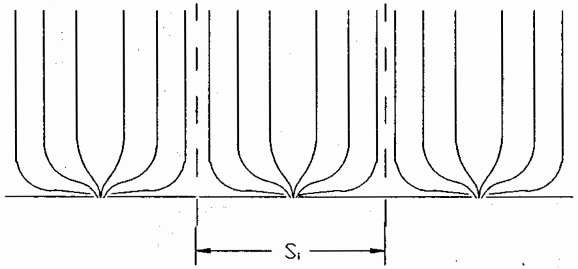

Figure 5. Illustration of the distribution of flux lines in the case of magnetic flux capture in a number of flux spots on the surface of a superconducting film.

Conclusions

The numerical simulation shows that:

1. A superconducting sample may achieve the paramagnetic moment during the FC procedure if it captures the main part of the magnetic flux permeating the sample in its normal state.

2. In some cases the paramagnetic moment may be as large as the diamagnetic one ($M_{FC}/(-M_{ZFC}) \approx 1$). The $M_{FC}/(-M_{ZFC})$ ratio reaches a maximum value in samples whose topology leads to the capture of the magnetic flux and its compression into a single flux spot.

3. The capture of the magnetic flux in a number of flux spots gives rise to a small paramagnetic signal M_{FC} in comparison with $-M_{ZFC}$.

4. The long-time relaxation of the magnetic moment after the FC procedure may show not only an increase in the magnetic moment over the time but also a change in sign from negative to positive.

Acknowledgments

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