Residual magnetization and rf absorption in $Y_1Ba_2Cu_3O_{7-\delta}$ superconductors due to the trapping of magnetic flux in weak magnetic fields

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The results of an experimental study of the trapping of a magnetic flux in fields ranging from 0.005 to 240 Oe in a single-crystal sample, a thin-film sample, and a ceramic sample of $Y_1Ba_2Cu_3O_{7-\delta}$ are presented. The spatial distribution of a trapped flux can be used to explain the dependence of the residual magnetic moment M_{res} on the field and on the cooling conditions. The correlated behavior of M_{res} and the residual rf magnetic susceptibility χ_{res} is demonstrated in the particular case of a ceramic sample.

One of the characteristic features of high-T_c superconductors that sets them apart from classical type-II superconductors is the ability of the magnetic flux to penetrate them and to be trapped in weak fields, much weaker than the first critical field H_{c1}, which is determined by the London penetration depth λ_L and the coherence length. In $Y_1Ba_2Cu_3O_{7-\delta}$, for example, H_{c1} is on the order of 100 Oe (Ref. 1). After a cooling in zero field (ZFC) the diamagnetic screening signal reaches 100% and upon cooling in the presence of a field (FC) the Meissner effect is found to be small.[2] The detection of the flux creep[3] and the rf absorption,[4] along with the difference in the magnetic susceptibilities at ZFC and FC (Ref. 5), can be explained on the basis of a model for superconducting glass which can also be used for single crystals. In the last case the twinning planes can be viewed as interfaces between regions with different phases of the wave function.[6]

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In the present letter we report the results of an experimental study of the residual magnetic moment M_{res} and the residual rf absorption in high-T_c superconducting samples of $YBa_2Cu_3O_{7-\delta}$ as a function of the magnetizing field. We will show that these functional dependences can be described by taking into account only the spatial distribution of the magnetic field.

The value of M_{res}, which remained constant in the sample after a magnetizing field H was applied to it, was measured using a quantum magnetosensitive probe with optically oriented atoms, which was inserted into a shielded solenoid.[7] The level of residual variations of the field in the shield was no greater than 10^{-6} Oe. The values of χ'_{res} and χ''_{res} ($\chi_{res} = \chi'_{res} + i\chi''_{res}$) were measured at a frequency of 41 MHz by means of an autodyne oscillator, whose tank circuit contained the sample. The measurements were carried out at 77 K. The x-ray photographs of the test samples corresponded to a single-phase composition. The control experiments with the initial compositions, carried out at $T > T_c$, have enabled us to rule out the contribution of magnetic impurities to the observed effects.

The procedure used to measure M_{res} can be summarized as follows. In the case of zero-field cooling, the sample which was precooled to 77 K in zero field was magnetized in the field H. After removing the field, the sample was transferred to the measuring solenoid with the magnetosensitive probe, where it was placed in the far zone with respect to the probe. In the case of cooling in the presence of a field, the sample was cooled in the magnetizing coils in a field $H \geqslant 1$ Oe. The sample was then inserted into the measuring solenoid. At lower fields H, the sample was cooled directly in the solenoid field. The measuring field, usually amounting to 0.08 Oe, was then applied. To separate the signal associated with the residual flux from the signal of the diamagnetic screening in the solenoid field, we carried out the measurements at two orientations of the sample differing by 180°. When the thin-film and single-crystal samples were magnetized, the field H was oriented along the normal to the surface of the crystal or the film.

In the case of cooling in the presence of a field, the value of M_{res} of all the test samples increases linearly with the field in low fields $H_1 < H < H_2$ and remains constant in $H > H_3$. The magnitude of the minimal field H_1, in which the trapping occurs, is determined by the sensitivity of the detector and by the parameters of the samples. For the single crystal $H_1 \lesssim 0.5$ Oe. In ceramic samples, which produce a much stronger signal in comparison with that of the single crystal, we have $H_1 \lesssim 0.005$ Oe. The diamagnetic screening of the samples in the solenoid field $H \leqslant 1$ Oe amounted to $\sim 100\%$ and the Meissner effect was no greater than 10%. In the case of zero-field cooling, the field begins to penetrate the sample at a certain threshold value of the field H^*_{c1}, measured in oersteds. This field penetration is detected from the flux trapping.

Figure 1 shows the experimental points on the curve of $M_{res}(H)$ (curve 1 for FC and curve 2 for ZFC) for a single-crystal sample measuring $2 \times 1 \times 0.02$ mm ($T_c \approx 92$ K, $\rho_{ab}|_{T=100\,K} \approx 60 \mu\Omega\cdot$cm). In high fields $M_{res}(H) = M_{max\,res} \approx 10^{-6}$ A·m^2 and does not depend on the manner in which it is cooled. The solid curves in Fig. 1 represent the result of the calculation of $M_{res}(H)$ for FC and ZFC based on semiempirical equations which take into account the spatial distribution of the magnetic field in the sample. A model describing the magnetization of type II superconductors on the basis

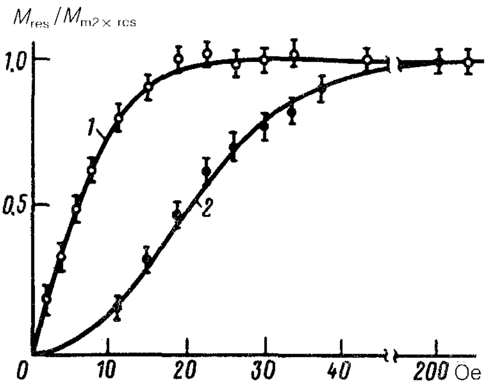

FIG. 1. Residual magnetic moment of a single crystal vs the magnetizing field (*1*) in the case of cooling in the presence of a field and (*2*) in the case of colling in a zero field. Points—Experimental results; solid lines—calculation.

of such representations was proposed by Bean,[8] who studied the magnetization of an infinite cylinder, whose axis is parallel to the magnetic field. In this case $|dB_z/d\rho| \approx J_c$, where J_c is the critical current density.

In another limiting case it can be shown that $|dB_z/d\rho| \approx d/RJ_c \ll J_c$ for a thin disk of thickness d and radius $R \gg d$, whose plane is perpendicular to the direction of the magnetic field. The dependence of the residual magnetic moment on the magnetizing field H in this case can be described by the following equations in which we use the notation $\alpha = H/J_{cd}$. For FC:

$$M_{res}(H)/M_{max\ res} = 3\alpha - 3\alpha^2 + \alpha^3 \qquad 0 \leqslant \alpha \leqslant 1$$
$$M_{res}(H) = M_{max\ res} \qquad \alpha \geqslant 1 \,. \tag{1}$$

For ZFC we have

$$M_{res}(H)/M_{max\ res} = \frac{3}{4}(2\alpha^2 - \alpha^3) \qquad 0 \leqslant \alpha \leqslant 1$$
$$M_{res}(H)/M_{max\ res} = 1 - 2\left(1 - \frac{\alpha}{2}\right)^3 \qquad 1 \leqslant \alpha \leqslant 2 \tag{2}$$
$$M_{res}(H) = M_{max\ res} \qquad \alpha > 2 \,.$$

Here $M_{max\ res} = 1/3\,VJ_cR$, where V is the volume of the sample. The theoretical curves in Fig. 1 were calculated from these equations for $d = 20\ \mu$m, $R = 0.75$ mm, and $J_c = 1.1 \times 10^8$ A/m^2.

Figure 2 shows the results of the measurement of M_{res} for an 80-nm-thick film having the shape of a semicircle of radius 5.5 mm with $T_c \approx 90$ K. Curves 1 and 2, which correspond to FC and ZFC, are described well, as in the case of a single crystal, by Eqs. (1) and (2) for $d = 80$ nm, $R = 3.4$ mm, and $J_c = 9.2 \times 10^9$ A/m^2.

In addition to curves 1 and 2, Fig. 2 shows the change in M_{res} with increasing field H (curves 3–5) and with decreasing field (curve 6) after cooling the sample in

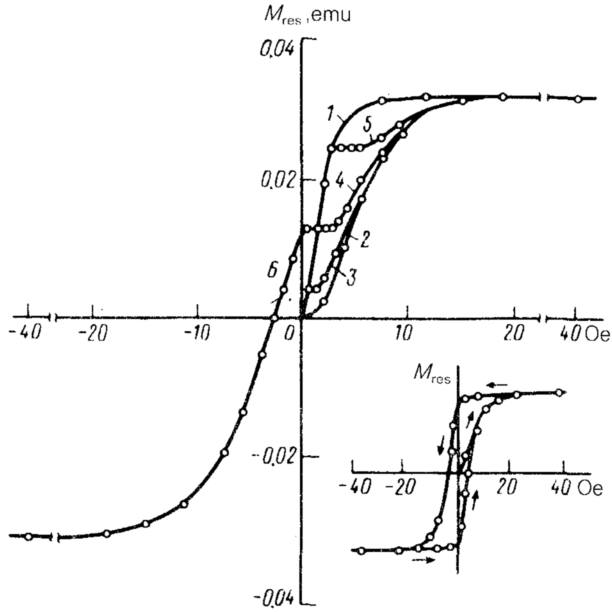

FIG. 2. Behavior of the residual magnetic moment of a thin-film sample recorded when various methods of cooling and magnetizing were used. *1*—Cooling in the presence of a field; *2*—cooling in a zero field; *3–5*—cooling in the presence of a field, with a subsequent increase of the field H without warming the sample; *6*—cooling in the presence of a field, with a subsequent reduction of the field H without warming the sample.

various initial fields. The initial points on curves 3–6 were thus obtained upon cooling the sample in a field, while all remaining points were measured upon gradual magnetization of the sample in a field H without warming it. We see that curves 3–5 have horizontal parts corresponding to a constant value of $M_{\rm res}$ as H is increased. The length of these segments increases approximately linearly with increasing field H but remains shorter than the distance between curves 1 and 2 for a given $M_{\rm res} = {\rm const}$. Curve 6 has a similar horizontal section between curve 1 and the $H=0$ line. Such a behavior of the $M_{\rm res}(H)$ curves is also characteristic for the model under consideration.

The inset in Fig. 2 shows the total hysteresis loop for the film. Such hysteretic behavior of $M_{\rm res}$ is also characteristic of other types of samples. The entire hysteresis loop of the film an single crystal in this case is described well on the basis of the suggested model for the corresponding values of the parameters R, d, and J_c.

The direct proof of the link between rf absorption and flux trapping is found from a comparison of the $M_{\rm res}(H)$ and $\chi''_{\rm res}(H)$ curves obtained from a ceramic sample (Fig. 3). The sample in the form of a cube 7 mm on a side had a density of 5.8 g/cm^3 and $T_c \approx 93$ K. Each curve (a) and (b) in Fig. 3 was obtained for ZFC. The $\chi''_{\rm res}(H)$ curve was measured with $H \| H_\sim$, where $H_\sim$ is an alternating magnetic field in the tank of the autodyne oscillator. As can be seen from the figure, the $M_{\rm res}$ and $\chi''_{\rm res}(H)$ curves behave approximately the same when H increases from 0 to 240 Oe and when H decreases from 240 to 0. The behavior of $M_{\rm res}$ differs from that of $\chi''_{\rm res}$, however, in the region of negative H. The minimum value is $\chi''_{\rm min} \approx 0.6\chi''_{\rm max}$, whereas $M_{\rm res}$ vanishes at $H = H' \approx 25$ Oe. The difference in the curves of $M_{\rm res}(H)$ and $\chi''_{\rm res}(H)$ at $H<0$ can

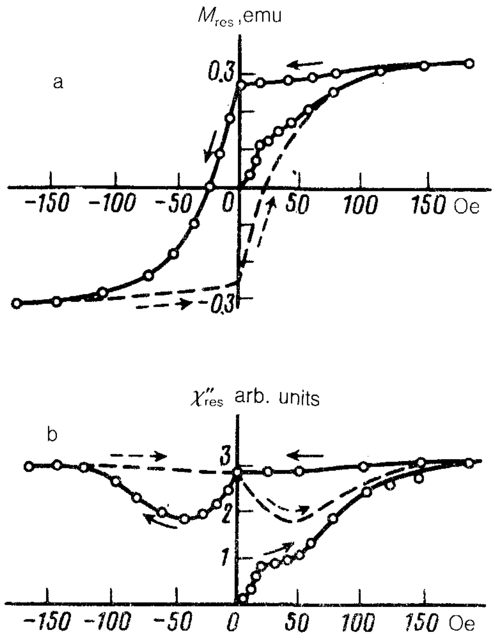

FIG. 3. Dependence of the magnetizing field of a ceramic sample on (a) the residual magnetic moment and (b) the imaginary part of the residual rf magnetic susceptibility.

also be explained by the spatial distribution of the magnetic flux in the sample. A change in sign of the magnetizing field causes the sample to form domains which account for contributions with different signs to $M_{\rm res}$. At the same time, the rf absorption which does not depend on the magnetization direction is determined by the absolute value of the trapped flux in the region of penetration of the alternating field. Since this quantity depends on the orientation of the field H with respect to $H_\sim$, the $M_{\rm res}(H)$ curves for $H \| H_\sim$ differ from those for $H \perp H_\sim$, as can be seen in Fig. 4. The field H' at which $M_{\rm res}(H') = 0$ corresponds to the cancellation of the contributions with opposite signs to $M_{\rm res}$, rather than to the "demagnetization" of the sample, which

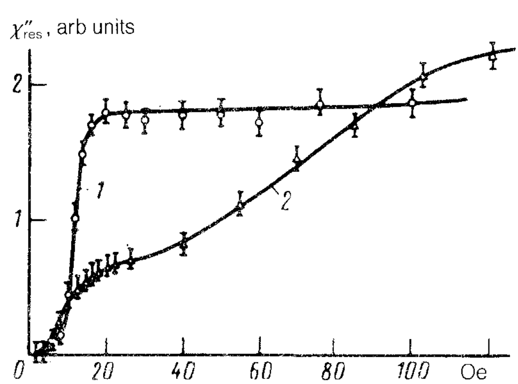

FIG. 4. Residual absorption of the rf power vs the magnetizing field. *1*—$H_\sim \perp H$; *2*—$H_\sim \| H$.

accoutns for the zero level of rf absorption. The $\chi''_{res}(H)$ and $M_{res}(H)$ curves obtained in the case of cooling in a field are also the same when $H \| H_{\sim}$ at $H > 0$. The rf absorption thus qualitatively represents the volume distribution of the trapped flux when $H \| H_{\sim}$.

The probable cause of rf absorption is the energy dissipation due to the redistribution of the magnetic flux as a result of application of the field $H_{\sim}$ between the circuits with the Josephson junctions. A similar absorption mechanism is found in rf SQUIDS. This assumption is confirmed by the dependence of χ' and χ'' on the amplitude of the alternating field $H_{\sim}$, which was observed in the region 0.3 mOe $< H_{\sim} \leqslant$ 3mOe. An increase in χ' and χ'' resulting from an increase of $H_{\sim}$ apparently corresponds to an increase in the number of circuits in which the flux is redistributed in the presence of $H_{\sim}$.

All the particular features of the heavier of the residual magnetization resulting from different methods of cooling and magnetization in weak fields, as well as the correlation between the change of this magnetization and the rf absorption can therefore be explained by taking into account the spatial distribution of the trapped flux.

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