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ac inductance measurements of thin superconductors and ferromagnets: Demagnetization effects

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Measurements of magnetic properties of thin-film superconductors at 77 K using dc magnetic fields and ac inductance techniques are discussed. The effects of demagnetizing fields on these measurements are analyzed and compared with results for thin ferromagnets. It is shown that for perpendicular magnetic fields opposite effects are predicted and observed for ferromagnets as compared to superconductors.

INTRODUCTION

ac inductance methods are commonly used to measure the magnetic properties of superconductors.[1] Weak ac magnetic fields in these materials generate screening currents that exclude magnetic flux from the sample interior, leading to an easily measured change in inductance of a coil surrounding the sample. Thin films of superconductors can be measured with this technique if the ac field is applied perpendicular to the plane of the sample, generating screening currents in the plane of the film (with the field directed in the plane of the film, the change in inductance produced is usually too weak to measure). An additional dc magnetic field can be applied to study the effects of a stronger field on the magnetization of the sample. We have used this technique to study anisotropy effects produced by rotating a dc magnetic field about the plane of superconducting films. Interpretation of these experiments is complicated by the fact that with the measuring field perpendicular to the plane of the film the sample now has a large demagnetizing factor, resulting in a demagnetizing field which affects the magnetic field inside of the sample. In this report we will examine how this demagnetizing effect enters into these experiments, and we will show how this effect produces an interesting difference between superconductors and ferromagnets.

THEORY

The voltage v induced in the secondary of a mutual induction coil by an alternating current in the coil primary is given by[2]

$$v = KfH\chi \ , \qquad (1)$$

where K is a geometrical constant, f the current frequency, H the magnetic field produced in the primary, and $\chi = dM/dH$ the complex magnetic susceptibility of a sample in the secondary, where M is the sample magnetization. $\chi = \chi' - i\chi''$, where χ' is the real or in phase with the primary current component of the susceptibility, and χ'' is the imaginary or absorptive component. χ' and χ'' can be separately measured using phase-sensitive detection techniques. This measurement determines an external susceptibility χ_{ex} given by dM/dH_{ex}, where H_{ex} is the applied or external magnetic field. χ_{ex} may or may not be the same as χ_{in}, the internal susceptibility, as seen below. In a typical superconductor measurement, a very low (<1 Oe) ac field is used which usually cannot penetrate into the sample (H_{ex} is lower than H_{c1}). χ_{ex} is then proportional to the sample magnetization, or excluded magnetic flux. A typical plot of both χ' (often simply called the flux exclusion) and χ'' for a 1-μm-thick sample of $YBa_2Cu_3O_{7-x}$ is shown in Fig. 1.

If a dc magnetic field is now added to the ac field, the internal field in the sample $H(\text{in})$ is related to the external field H_{ex} by

$$H_{in} = H_{ex} - DM \ , \qquad (2)$$

where DM is the demagnetizing field and D the demagnetizing factor.[3] D is a function of the shape of the sample and the direction of the magnetic field, ranging from zero for a long thin rod or plate with the field along the rod or in the plane of the plate, to 0.5 for the field perpendicular to the rod length to 1.0 for the field perpendicular to the plane of the plate. These values are exact for infinite geometries only, and for other shapes D can only be calculated exactly for uniformly magnetized ellipsoids of revolution. Tables of estimated or experimentally determined values for some geometrical shapes are avail-

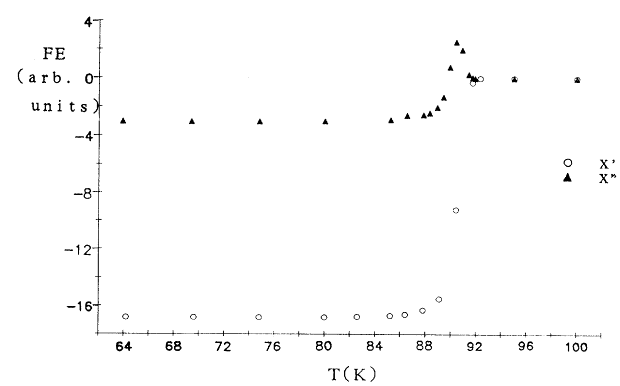

FIG. 1. Flux exclusion vs temperature for a $YBa_2Cu_3O_{7-x}$ film.

able, but D is generally not accurately known for a given sample. The difference between H_{in} and H_{ex} is unimportant for weakly magnetic materials like paramagnets and diamagnets, whatever the value of D, because M is small for these cases. However, for ferromagnets and superconductors where M can be large, H_{in} can be quite different from H_{ex}. For superconductors M represents a negative magnetization compared to that for ferromagnets; as will be seen, this difference can produce quite different results.

In the present experiments, a sample is held at constant temperature in a perpendicular orientation with respect to the ac magnetic field. A variable dc magnetic field is rotated from parallel to perpendicular to the direction of the ac field. Since the magnetization state of the sample in the direction of the ac field is sampled by this measurement, the component of the dc field in the direction of the ac field, $H_{ex}\cos\vartheta$, where ϑ is the angle between the ac and dc field direction, is the relevant variable field. With a thin sample mounted perpendicular to the ac field, D will be close to 1. H_{in} will be increased over that of H_{ex} by the value of M at the measuring conditions, so that flux penetration can take place for H_{ex} much less than the nominal H_{c1} value. In the ideal case of $D=1$, flux penetration occurs for any value $H_{ex}>0$.[4] For superconductors M represents flux exclusion and is thus negative by convention. For these materials the demagnetizing field in Eq. (2) will always add to the external field, so that the measured susceptibility will remain constant or decrease with applied field, depending upon how and at what field strength magnetic flux penetrates into the sample. For ferromagnets, however, the demagnetizing field will initially subtract from the external field, which can lead to a zero internal field. This effect causes a kink behavior in susceptibility measurements reported for a number of materials.[5] Thus in the present experiments the measured susceptibility of a thin plate ferromagnetic material with the measuring field perpendicular to the plane of the sample (D large) should show an initial increase as H_{ex} increases but an eventual decrease as the applied field becomes larger than the demagnetizing field. With the applied field in the plane of the sample, however, the demagnetizing field is negligible (D small), so that the susceptibility should remain constant or decrease as H_{ex} increases.

EXPERIMENTAL

Measurements were made with apparatus described earlier,[6] except in the present case the sample and compensation coils were mounted adjacent to each other instead of collinearly to fit inside of a 1-cm i.d. Dewar placed in the gap of a 4-in. electromagnet. Thin-film superconductors deposited on various substrates were cut to fit inside 1-mm i.d. glass capillary tubes. These samples were mounted on small wooden dowels so that the plane of the sample was perpendicular to the axis of the detector coil system, remaining so throughout the experiment. Thin-sheet samples of ferromagnetic materials were similarly mounted. Additional samples of the latter in the form of rectangular strips were mounted so that the long axis of the strip was parallel to the coil axis. The detector coils were held at the end of a 6-mm-diam stainless-steel tube which positioned the coils inside the Dewar in the magnet gap. The tube could be accurately rotated such that the sample and coils were turned from having the external dc field perpendicular to the sample plane (ac and dc fields parallel) to having the dc field in the plane of the sample (ac and dc fields perpendicular). The rotational positioning accuracy was estimated to be 1°, the sample positioning with respect to the coil axis somewhat less. The temperature was held at 77 K for the superconductor measurements and at room temperature for the ferromagnetic samples. The residual field of the electromagnet was reduced to the order of 5 Oe before beginning every measurement series, and empty coil mea-

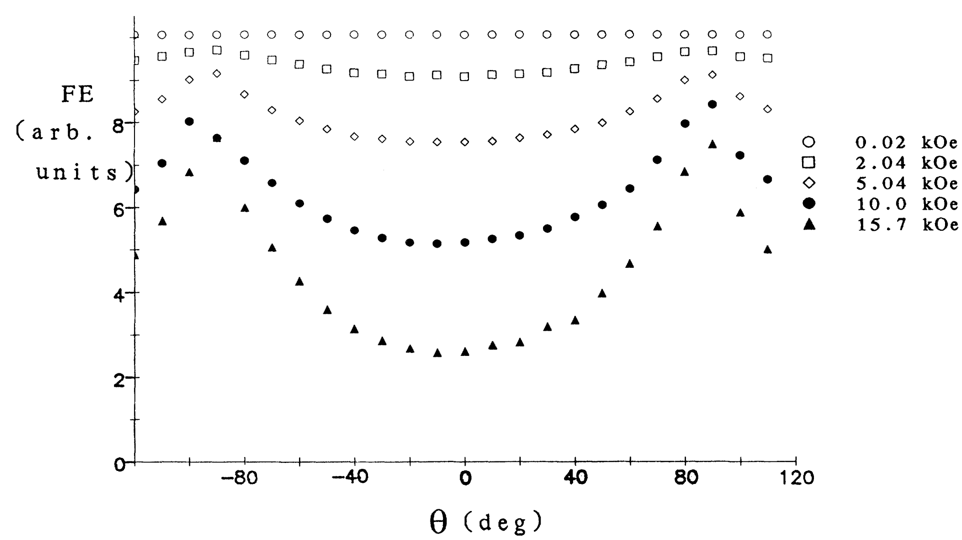

FIG. 2. Flux exclusion vs the angle between dc and ac magnetic fields for a $YBa_2Cu_3O_{7-x}$ film at 77 K for various dc fields.

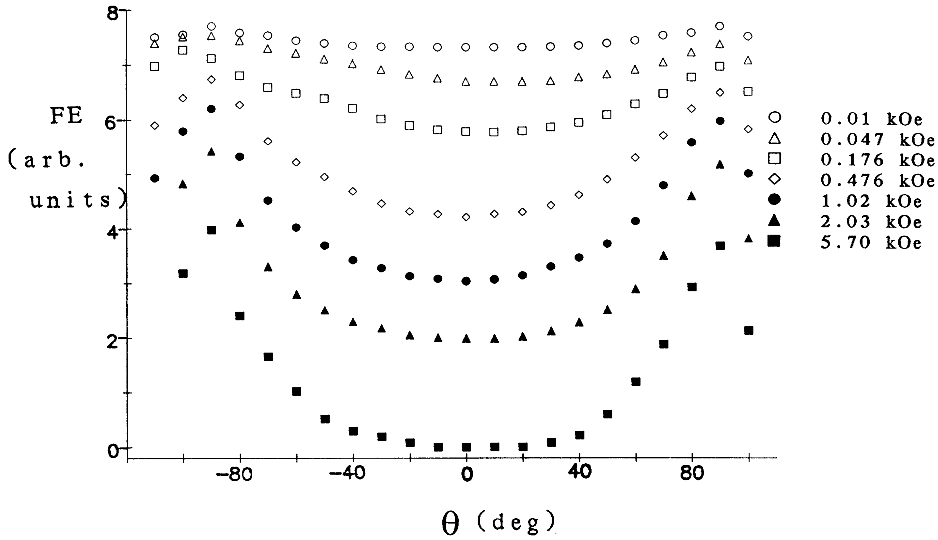

FIG. 3. Flux exclusion vs the angle between dc and ac magnetic fields for a $Tl_2Ba_2CaCu_2O_x$ film at 77 K for various dc fields.

surements were made at various dc field strengths to determine the (small) background pickup which was subtracted from the sample runs. In the case of the superconductor measurements, each sample was heated to above T_c after each field rotation measurement to avoid complications of pinned flux in the samples.

RESULTS

Data for a typical 1-μm-thick sample of $YBa_2Cu_3O_{7-x}$ prepared by coevaporation upon a $LaAlO_3$ substrate is shown in Fig. 2, where relative flux exclusion at 77 K is plotted versus the angle between the ac and dc magnetic field directions for various fixed dc field strengths. It is seen that for relatively weak magnetic fields (less than a few hundred oersteds) flux exclusion is reduced for the dc field in the direction perpendicular to the sample plane, and the amount of reduction increases as the magnitude of the field increases. Figure 3 shows data for a 1-μm-thick sample of $Tl_2Ba_2Ca_1Cu_2O_x$. This material is much more strongly affected by magnetic fields, with fields greater than 5 kOe effectively reducing the flux exclusion to values too weak to measure.

In contrast to the results found above for thin-film superconductors, Fig. 4 shows susceptibility versus the angular dependence upon the direction of an external dc field at room temperature for a thin (100 μm) plate of nickel mounted with the plane of the sample perpendicular to the measuring ac field. It is found that for this ferromagnetic material the measured susceptibility initially increases with increasing dc field up to about 5 kOe, above which value it rapidly decreases as the field continues to increase. Figure 5 shows susceptibility versus the

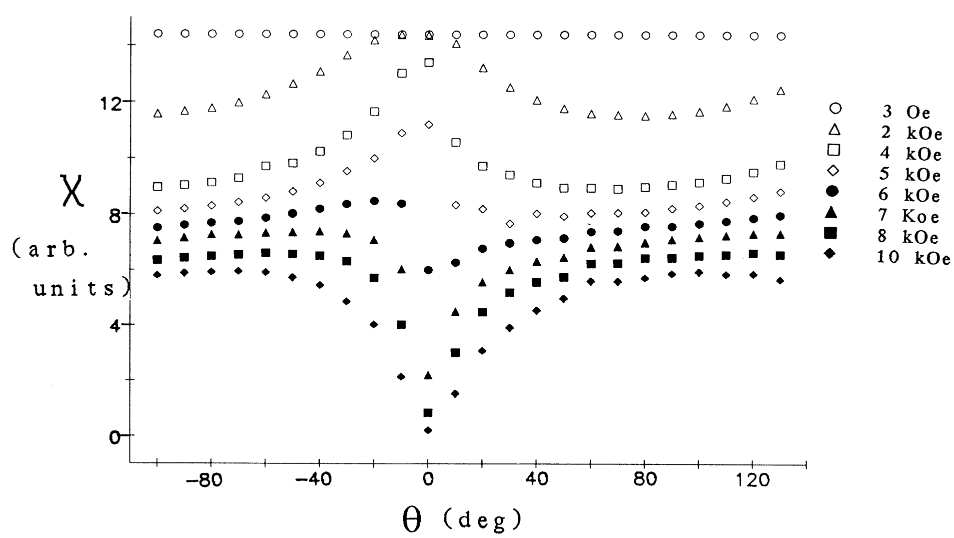

FIG. 4. Susceptibility vs the angle between dc and ac magnetic fields for a perpendicular Ni sheet at 300 K for various dc fields.

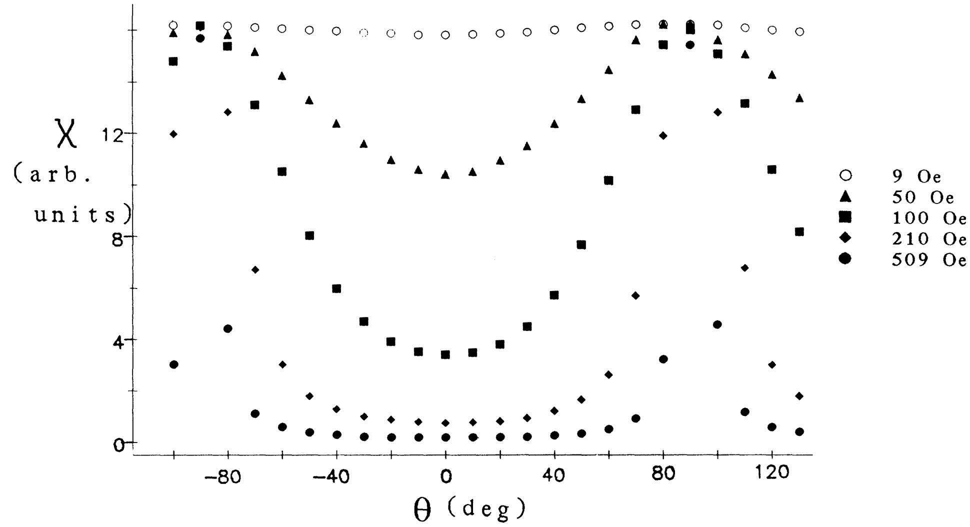

FIG. 5. Susceptibility vs the angle between dc and ac magnetic fields for a parallel Ni sheet at 300 K for various dc fields.

angular dependence on the direction of an external dc field at room temperature for the same Ni material mounted with the plane of the plate parallel to the direction of the measuring ac field. In contrast to Fig. 4, the results now show a continual decrease of susceptibility with increasing dc magnetic field, similar to results for the superconducting samples. Similar results as for the nickel samples were obtained for thin samples of iron and Co-Netic shielding material.

DISCUSSION

As shown by Eq. (2), for superconductors with a large demagnetizing factor the external magnetic field is added to by the relatively large-sample demagnetizing field so that magnetic field penetration into these materials can take place for even low fields. Figures 2 and 3 illustrate this process and show that particular material characteristics determine the size of fields necessary for the penetration process. In contrast to superconductors, ferromagnets with a large demagnetizing field show a different behavior, again controlled by Eq. (2), where for low applied fields the demagnetizing field initially decreases the initial field, leading to an initial increase of the sample susceptibility with applied field, as shown in Fig. 4. Eventually the applied field becomes large enough to overcome the internal field and a reduction in the susceptibility takes place. The situation is different if the material does not have an appreciable demagnetizing field, as in the case of the thin nickel sample with the field in the plane of the sample. Here, as shown in Fig. 5, the applied field causes a continual decrease in susceptibility similar to the case of the superconductors discussed earlier.

The results presented above show how experiments of the kind discussed can provide information on the effect of external magnetic fields on the internal magnetic field state of superconductors and ferromagnets. For simple classical superconductors with well-defined critical fields these measurements provide information on magnetic field magnitudes and demagnetizing factors which perhaps are not of great interest. However, for the recently discovered high-temperature superconductors (HTSC) whose magnetic and other properties have yet to be fundamentally explained, the above experiments can provide new information on magnetic properties which can be related to, for example, surface or bulk structure. Examples of this type of new information obtained from the above experiments for a number of HTSC films are planned to be discussed in a separate report.

ACKNOWLEDGMENTS

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