Anisotropy of ESR absorption of single crystals of R–Ba–Cu–O superconductors (region of weak magnetic fields)

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In R–Ba–Cu–O single crystals at $T = 77$–92 K, a low-field ESR absorption is possible only for certain orientations of the plane of the crystal with respect to the directions of the static magnetic field $H_{=}$ and the alternating magnetic field. This absorption reaches a maximum when the C axis of the crystal makes a 45° angle with $H_{=}$.

It has been shown in a series of studies that an anomalously high absorption of microwave energy occurs in ceramic samples of R–Ba–Cu–O superconductors when the method of ESR spectroscopy is used in weak magnetic fields.[1–9] The mechanism for this effect has not yet been clearly explained. In particular, it has been suggested that the effect is of a nonresonant nature, stemming from a set of Josephson junctions[1–4] and an energy loss at grain boundaries.[5–7] Alternatively, this effect has been linked with a resonant absorption of energy by free charge carriers in a process accompanied by changes in the populations of magnetic levels.[8,9]

A study of this effect in single crystals may provide additional information of assistance in establishing its nature.

Our purpose in the present study was to learn about the general behavior characteristic of this part of the ESR spectrum in $YBa_2Cu_3O_{7-y}$ and $ErBa_2Cu_3O_{7-y}$ single crystals. The crystals were synthesized by spontaneous crystallization from a molten solution[1)] (Ref. 10). The dimensions of the crystals were $(4–6) \times (3–4) \times (0.07-0.2)$ mm; the C axis was oriented normal to the plane of the sample; and the superconducting transition temperature was $T_c = 90$–92 K.

The ESR spectra were measured with an rf spectrometer with a klystron frequency $\omega = 9.3 \times 10^9$ Hz and a modulation frequency of 9.75×10^5 Hz during the excitation of the H_{011} wave in a cylindrical resonator. The sample was positioned at an antinode of the magnetic field; the sample was reproducibly rotated around orthogonal axes within an error of 2–3°.

In the results we see the following:

1. Single crystals differ from ceramic control samples having the same geometric dimensions, the same chemical composition, and the same values of T_c in that the amplitude of the ESR signal, dP/dH, and the shape of the absorption line are clearly sensitive to the orientation of the planes of the sample with respect to the direction of the static magnetic field $H_{=}$. Essentially no signal is focused in the following orientations of the crystal: a) The C axis of the crystal is parallel to $H_{=}$. In this case a rotation of the crystal around either the C axis or an axis parallel to the magnetic

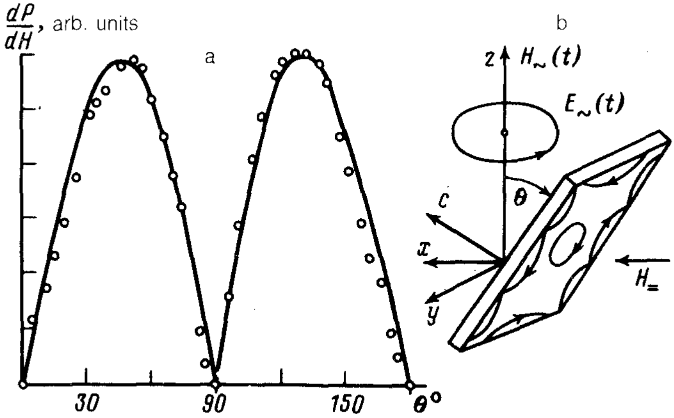

FIG. 1. a—The angular dependence $dP/dH(\theta)$ at $H_= = 2\times10^{-3}$ T and $T = 77$ K; b—orientation of the crystal with respect to $H_=$ and $H_\sim$.

component of the microwave field, $H_\sim$, does not give rise to a signal (this is true even when the plane of the wafer makes an angle of 45° with $H_=$). b) The C axis is parallel to $H_\sim$. A rotation of the crystal around either the C axis or an axis $\|H_=$ does not alter the amplitude dP/dH.

The results of greatest interest concern the behavior of $dP/dH(\theta)$ when the crystal is rotated in such a way that the C axis lies in the $(H_=, H_\sim)$ plane. Figure 1a

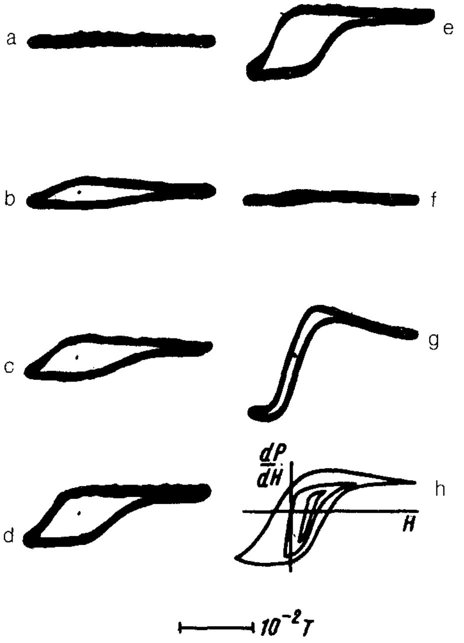

FIG. 2. Hysteresis in dP/dH. a,b,c,d,e—$\theta = 0, 5, 10, 25, 45$, and 90°, respectively; g—ceramic, for arbitrary θ; f—variation in the amplitude of the modulation of $H_=$ at a constant bias field $H^0_= = 4.9\times10^{-3}$ $T(\theta = 45°$, $T = 77$ K).

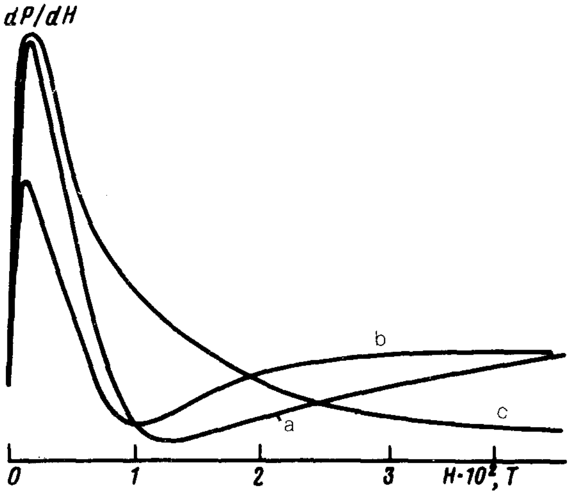

FIG. 3. ESR spectra typical of single crystals. a—$\theta = 45°$; b—$\theta = 5°$, sample 4; c—$\theta = 45°$, sample 7.

shows the angular dependence $dP/dH(\theta)$ as the sample is rotated around the y axis (Fig. 1b); this dependence can be approximated by$^{2)}$ $dP/dH \sim \sin 2\theta$. Figure 2 shows several oscilloscope traces which demonstrate the angular dependence of the shape of the absorption line$^{3)}$ and the nature of the hysteresis in dP/dH as the direction in which $H_{=}$ is scanned is changed at a frequency of 50 Hz.

2. The hysteresis loop is considerably broader in the single crystals than in the ceramic samples: $(4\text{–}6) \times 10^{-3}$ T in comparison with $(1\text{–}2) \times 10^{-3}$ T (for a scanning time $H_{=} \approx 2 \times 10^{-2}$ s; Fig. 2g).

3. The absorption in the single crystals, like that in the ceramic samples, has the shape characteristic of conduction electrons in a metal; see Fig. 3, which shows typical curves of $dP/dH(H)$ for various single crystals.

The dependence of the amplitude and shape of the ESR signal on the orientation of the plane of the crystal with respect to the directions of both the static and alternating magnetic fields, along with the positive sign of dP/dH at small values of $H_{=}$ (the sign here is the same as the sign of dP/dH at the front of the absorption line of DPPH), casts doubt on an interpretation of this behavior on the basis of a Josephson or some other nonresonant mechanism.

The angular dependence $dP/dH \sim \sin 2\theta$ can be interpreted in a simple way on the basis of the Bohr model for the diamagnetism of electrons under conditions such that some of the charge carriers which have been reflected from the surface of the sample create from "jumping orbits" a closed current loop in the plane of the sample.[12] The direction of the current in the loop is opposite the current of the closed orbits of charge carriers, and the overall magnetic moment $M = M^{\max} \cos\theta$ is directed along the normal to the surface (i.e., along the C axis). The carriers on the jumping orbits spend a large part of the time in a skin layer, setting the stage for a resonant absorption of the microwave field.[13] The absorption averaged over a period is, as we know,[14] $\bar{p} = \mathbf{M}\mathbf{H}_{\sim}(t) \sim \sin\theta\cos\theta$.

In ceramic samples the ESR signal does not depend on the orientation of the entire sample with respect to $H_=$, since it is the sum of signals from each of a large number of grains, in various orientations, near the surface.

In order to explain all of the experimental data at the elementary level it will probably be necessary to incorporate the following: a) the pronounced nonuniformity of the total magnetic field in the surface region which is characteristic of superconductors; b) the presence in these materials of atoms of heavy metals, which are capable of manifesting a spin-orbit coupling of band charge carriers.[15] Accordingly, the carriers may be thought of as quasiparticles with an effective magnetic moment which contains spin and orbital components. The interlevel transitions are of such a nature that orbital transitions due to the magnetic component of the microwave field become possible.[16] Judging from the large value of the g-factor—more than 200 (the effective mass is correspondingly small: less than 10^{-2} of the mass of a free carrier)—the orbital component is predominant in this case.

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[1)] The samples had twins in the (001) plane.

[2)] An ESR signal—poorly expressed—was observed in Ref. 7 in the configurations $\|H_=$ and $C\perp H_=$, probably (in view of the pronounced sensitivity of dp/dH to θ at small values of θ) due to an inexact positioning of the surface of the sample with respect to $H_=$ because of the small dimensions of the sample.

[3)] To determine the contribution of the electric component of the microwave field to the nature of the absorption, we moved a sample with dimensions of 1.5×1.5 mm over a distance of 4–5 mm in the resonator (for various orientations of the crystal). No significant changes occurred in the signal as a result. It can thus be suggested that in this case the magnetic component is the component which determines the absorption of energy from the microwave field.

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