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R. Karim

H. How

C. Vittoria
Northeastern University

A. Widom Northeastern University

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# Measurement of kappa in high $T_c$ superconductors

R. Karim, H. How, and C. Vittoria

Department of Electrical Engineering, Northeastern University, Boston, Massachusetts 02115

A. Widom

Department of Physics, Northeastern University, Boston, Massachusetts 02115

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The experimental magnetic-field derivative of the microwave absorption signal, obtained using electron paramagnetic resonance techniques, has a line shape that depends on the Ginzburg-Landau model parameter  $\kappa$  of the superconducting sample at a given temperature. The type-II superconducting equation of state can be utilized to describe the drop in the output microwave power derivative, from its maximum at  $H \simeq H_{c1}$  to its much lower values when  $H \gg H_{c1}$ , in order to estimate the values of  $\kappa$ . The technique also allows for the experimental determination of hysteretic behavior in B as a function of H.

Since the work of Blazey et al. and Karim et al. there have been many physical models employed to explain the differential microwave absorption (with respect to H) of high-T<sub>c</sub> superconductors in low magnetic fields [experimentally obtained using the electron paramagnetic resonance (EPR) technique]. Initially, Blazey et al. 1 ascribed the low-magnetic-field effects as a feature of a superconducting spin glass consisting of weakly coupled superconducting grains. From this viewpoint, they argued for a new type of critical field  $H_{c1}^* \simeq (\Phi_0/2S)$ , where  $\Phi_0$  is the superconducting flux quantum and S is the effective projected area of superconducting "current loops" in the glassy state. They estimated  $S \sim 5 \times 10^{-8}$  cm<sup>2</sup>. Portis et al.<sup>3</sup> suggested that the microwave absorption was related to vortex (fluxoid) interactions with the vortices (fluxoids) being driven by the rf modulating field of the EPR measurement technique. Other models include arrays of superconducting grains coupled by Josephson weak links.4

The above discussion is representative of the many very different kinds of models previously employed. All of the above models explain parts of the experimental data, but none of the above models gives a very adequate overall description of the systematic features of the experimental data.

The purpose of this work is to present experimental data in the context of the most simple and widely used model in type-II superconductivity (including high- $T_c$  materials); i.e., the Ginzburg-Landau model. With the single assumption (originally due to Bardeen and Stephen)<sup>5</sup> that the dissipation is due to the normal regions around to the vortex lines, we find that the overall features of the experiments are reasonably well described. Given the present uncertainties regarding a truly microscopic theory of high-T<sub>c</sub> superconductors, the Ginzburg-Landau model serves presently (in our view) as the best (and perhaps the only) phenomenological model for defining material parameters such as the London penetration depth  $\Lambda$  and the electron-pair coherence length  $\xi$ , or equivalently  $\kappa = (\Lambda / (\Lambda / (\Lambda + \Lambda)))^{-1}$  $\xi$ ). To the extent that these parameters have a well-defined physical meaning, the EPR microwave absorption technique provides a useful probe with which to measure  $\kappa$ .

The experimental technique consisted of measuring the differential microwave absorption in a magnetic field H using a standard EPR method (with some modifications) that has been described elsewhere.<sup>2</sup> The resonant frequency of the cavity was  $f_0 = 9.35$  GHz, and the modulating field was less than 1 Oe. An Oxford ESR 900 cryostat was employed so that the temperature could be varied in the interval (3 K $\leq T \leq$  300 K) with a stability of  $\delta T \simeq$  0.2 K. Data were collected on a PC (AT 6300) for analysis and fitting. A polycrystalline YBCO sample (volume = 5  $\times$  10<sup>-3</sup> cm<sup>3</sup>) was characterized using a standard dc fourprobe measurement in conjunction with the microwave absorption technique. The onset of superconductivity was measured to be at  $T_c \simeq 92$  K. The sample resistivity exhibited typical metallic behavior before dropping to zero;  $T_c$ (complete)  $\approx 87 \text{ K}$ .

An experimental hysteresis loop in the differential (with respect to the modulation field) microwave absorption is shown in Fig. 1, at  $T=76~\rm K$ . The units shown are arbitrary, but the resulting data are proportional to the derivative of the real part of the surface impedance (at the resonant frequency  $f_0$ ) with respect to H; i.e.,  ${\rm Re}[\partial Z(H,T)/\partial H]$ . The sample (polycrystalline YBCO) was cooled in virtually zero field ( $H_{\rm cooling} < 0.1~\rm Oe$ ). As H is swept back and forth, the heights of the absorption peaks are somewhat different being dependent on the direction of the sweep and (with little doubt) the number of trapped vortices of magnetic flux.

The ratio of the maximum signal level at  $H = H_{c1} \sim 10$  Oe to the signal level at  $H \sim 1000$  Oe (which is relatively constant with respect to changes in H) is  $\sim 70$  at T = 76 K and  $\sim 20$  at T = 35 K. For T < 35 K this ratio is constant with respect to temperature changes. It will now be argued that this ratio is of use in estimating the Ginzburg-Landau parameter  $\kappa$ .

The magnetic properties of a superconducting sample (regardless which explicit statistical thermodynamic model is being considered) obey the thermodynamic free-energy variational law

$$\delta F = \left(\frac{1}{4\pi}\right) \int d^3r \ \mathbf{H} \cdot \delta \mathbf{B},\tag{1}$$

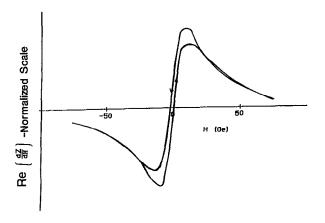


FIG. 1. A hysteresis loop of the derivative microwave absorption is shown as a function of the externally applied magnetic field H, in a polycrystal-line YBCO sample at T = 76 K.

determining the equation of state H(B,T). The Ginzburg-Landau theory calculates F using the model

$$F = \left(\frac{1}{8\pi}\right) \int d^3r |\mathbf{B}|^2 + \int d^3r \left\{ \left(\frac{1}{2M}\right) \right| \left[ -i\hbar\nabla - \left(\frac{q}{c}\right)\mathbf{A}\right] \psi \right|^2 + f(|\psi|^2, T) \right\}, \tag{2}$$

where q=2e is the electron-pair charge, and M=2m is the electron-pair mass. The London penetration depth  $\Lambda(T)$ , and the electron-pair coherence length  $\xi(T)$  appear as parameters in the free-energy per unit volume in the superconducting state  $f(|\psi|^2, T < T_c)$ ; i.e.,

$$f = -(\hbar^2/4M\xi^2)|\psi|^2 + (\pi/2)(\hbar q \Lambda/Mc\xi)^2|\psi|^4.$$
 (3)

In the Ginzburg-Landau model Eqs. (2) and (3), the value of  $\kappa$  is defined as

$$\kappa = (\Lambda/\xi). \tag{4}$$

Other phenomenological models may at first glance appear very different than the Ginzburg-Landau model, but often these differences amount merely to a redefinition of Ginzburg-Landau free-energy parameters. For example, if one writes,

$$\psi = n_s^{1/2} e^{i\theta},\tag{5}$$

then Eq. (2) has the form

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$$F = \left(\frac{1}{8\pi}\right) \int d^3r |\mathbf{B}|^2 + \left(\frac{\hbar^2}{2M}\right) \int d^3r \, n_s \left| \nabla \theta - \left(\frac{q}{\hbar c}\right) \mathbf{A} \right|^2 + F^*(n_s, \nabla n_s).$$
 (6)

 $F^*$  determines the free energy required to have a given superconducting density  $n_s$  of electron pairs, and describes (for example) the dimensions of the normal core of a vortex line when the magnetic field penetrates into the superconductor. The first two terms on the right-hand side of Eq. (6) describe the magnetic energy as well as the superconducting flow kinetic energy. If we had started with a

lattice of superconducting grains connected by Josephson weak links, then we could obtain Eq. (6) as the continuous limit of such a granular model. The qualitative features of the model would remain unchanged except that the values of  $\Lambda$  and  $\xi$  would be determined by the parameters of the granular weak link model.

A consequence of the Ginzburg-Landau approach (to be discussed in what follows) is the equation of state, valid in the given regime

$$H_{c1} < H \blacktriangleleft H_{c2}, \tag{7a}$$

$$\left(\frac{1}{\mu}\right) = \left(\frac{\partial H}{\partial B}\right) \approx 1 - \left(\frac{1}{2}\right) \left[ \left[ \left(\frac{B}{H_{c1}}\right) + 1 \right] \ln(\kappa) \right]^{-1}.$$
(7b)

While the parameters  $H_{c1}$  and  $\kappa = (\Lambda/\xi)$  may differ, depending on impurity content and fine-grained structures, the coarse-grained structure as described by the Ginzburg-Landau model is adequately determined by Eq. (7b).

The magnetic intensity  $\mathbf{H}$  of the applied field produces the physical magnetic field  $\mathbf{B}$  in the superconducting sample. The surface impedance  $\mathbf{Z}$  of the sample will change with magnetic intensity according to

$$\left(\frac{\partial Z}{\partial H}\right) = \left(\frac{\partial B}{\partial H}\right) \left(\frac{\partial Z}{\partial B}\right) = \mu \left(\frac{\partial Z}{\partial B}\right).$$
(8)

Thus Eqs. (7) provide a direct means of measuring  $(\partial B/\partial H)$  from the experimental  $\text{Re}(\partial Z/\partial H)$  if one has a model for how the surface impedance varies with B, i.e.,  $\text{Re}[(\partial Z/\partial B)]$ .

Following Kim and Stephen,<sup>6</sup> we assume that the normal regions of dissipation are proportional to the number of vortices containing magnetic flux; i.e., the effective volume of normal material is proportional to the magnetic field B. The normal volume to total volume ratio is

$$(V_n/V) = (B/H_{c2}).$$
 (9)

The decrease in the derivative EPR signal is then related to the increase in the slope of the  $(V_n/V)$  vs H curve in accordance with Eqs. (8) and (9). This leads to a maximum when  $H \simeq H_{c1}$  and roughly constant value when  $H_{c1} \ll H \ll H_{c2}$ .

All of the models that have been proposed, as discussed above, assume that the dissipation in the superconductor increases as the magnetic field B penetrates into the superconductor, creating normal regions. Since a magnetic field parallel to the easy planes of pair flow penetrates more easily than a magnetic field normal to the easy planes of pair flow, it might be expected that in a polycrystalline material the flux lines would follow a tortuous "random pinned path" always staying inside the interfaces between the grains. But a random pinned path for the magnetic flux lines is a very long path, and the magnetic energy stored in such a long vortex path is quite large. So, from the freeenergy viewpoint of the Ginzburg-Landau model, the flux lines of B are fairly straight, i.e., not so very random. The most simple way to see why this is true is to examine the free energy per unit length of a single vortex line. The free energy per unit length is the tension of a magnetic-flux

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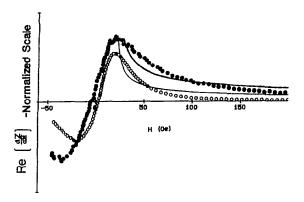


FIG. 2. The experimental curves circles are compared to the theoretical curves at T=76 K (empty circles) and T=35 K (solid circles). The values of  $\kappa$  are 7 and 20 at T=76 and 35 K, respectively.

bundle of quantized strength  $\Phi_0$ . The Ginzburg-Landau tension of a vortex is  $\tau = (\Phi_0/4\pi\Lambda)^2 \ln \kappa$ . Crudely, the free energy of "string under tension" is lowered when the string becomes straight and similarly for a vortex line.

If the normal area  $A \sim \pi \xi^2$  across a single vortex line is given, then Bardeen and Stephen<sup>5</sup> estimate the normal resistivity induced by normal core regions to be

$$\rho_n = (AB/\Phi_0 \sigma),\tag{10}$$

where  $\sigma$  is the normal-state conductivity. If the normal resistivity due to the penetration of vortices is added to the London law term then the electric field in a superconductor obeys

$$E = \left(\frac{4\pi\Lambda^2}{c^2}\right) \left(\frac{\partial \mathbf{J}}{\partial t}\right) + \rho_n \mathbf{J},\tag{11}$$

which is equivalent to a surface impedance of

$$Z(B,T) = (-4\pi i\omega/c^2)[\Lambda^2 + i(c^2\rho_n/4\pi\omega)]^{1/2},$$
 (12a)

$$\left(\frac{\partial Z(B,T)}{\partial B}\right) = \left(\frac{1}{2}\right) \left[\Lambda^2 + i(c^2 \rho_n / 4\pi\omega)\right]^{-1/2} \left(\frac{\partial \rho_n}{\partial B}\right). \tag{12b}$$

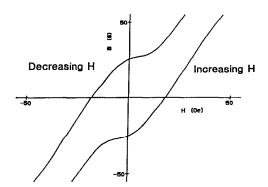


FIG. 3. B-H curve as calculated from the simple model presented in the paper, using  $\kappa = 7$  at T = 76 K, for the absorption curve presented in Fig. 1.

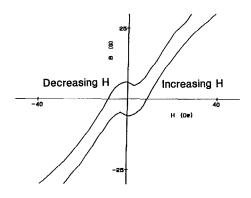


FIG. 4. B-H curve for polycrystalline YBCO sample using a deduced value of  $\kappa = 20$  at T = 35 K, for the absorption curve presented in Fig. 2.

From Eqs. (7b), (8), (10), and (12b) one may deduce hysteretic behavior in *B-H* curves, and thus  $\kappa$ , from experimental data for  $\text{Re}(\partial Z/\partial H)$ .

For polycrystalline YBCO the values of  $\kappa = (\Lambda/\xi)$  are  $\kappa \simeq 20$  at T = 35 K and  $\kappa \simeq 7$  at T = 76 K, as in Fig. 2. In Figs. 3 and 4 are shown the *B-H* curves of the polycrystalline sample at T = 35 and 76 K, respectively. The curves also yield the remnant field in the sample (yielding hysteretic effects) which for polycrystalline YBCO turns out to be about 20 G at T = 35 K and 4 G at T = 76 K. The *B-H* curves obtained by EPR techniques turn out to be in good agreement with those obtained by vibrating sample magnetometer techniques used by us and by many other workers.

In summary, we have analyzed the low-field EPR data of our own and others in a simple model assuming (i) a Ginzburg-Landau free-energy model, and (ii) a Bardeen-Stephen model for vortex induced resistivity. By such assumptions we can obtain hysteretic *B-H* curves for samples.

From the hysteretic curves we can measure  $H_{c1}$ ,  $\kappa$ , and remnant magnetic fields in the sample, all of which increase with decreasing temperature. Although the data here presented were taken using polycrystalline YBCO samples, the techniques are equally valid for single crystals, and well-ordered films of high- $T_c$  materials.

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