Frequency dependence of magnetic-field response of granular superconductors

S. A. Vitkalov, M. M. Rzaev, and D. N. Tokarchuk
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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Experiments of granular $Y_1Ba_2Cu_3O_7$ superconducting films at $T = 77$ K have revealed that the magnetic-field dependence of the microwave absorption (9 GHz) P_Ω and that of the rf screening (100 kHz) P_ω can be brought into coincidence by doubling the magnetic-field (H) scale for the microwave response. The frequency of the magnetic-field oscillations in dP_Ω/dH is twice that of the oscillations in dP_ω/dH. A model is proposed to explain this doubling and the magnetic-field dependence.

There are several characteristic features in the microwave absorption by ceramic $Y_1Ba_2Cu_3O_{7-\delta}$ high-T_c superconductors in a magnetic field. In addition to the smooth dependence of the microwave absorption on the magnetic field there is a noisy oscillatory dependence, which has been attributed to the presence of "effective" loops in the sample.[1] On the other hand, a study of the superconducting transition temperature of random aluminum networks[2] reveals oscillations in T_c as a function of the magnetic field, which correspond to the penetration of a flux quantum $\Phi_0 = \hbar c/2e$ through several cells. We would like to know how the screening properties of granular superconductors at low frequencies are related to the microwave absorption in these superconductors.

The test samples in the present experiments were polycrystalline films produced by laser evaporation. To create some irregularities, we etched the films with an ion beam through a metal grid with a square cross section of $50 \times 50\ \mu m^2$. This procedure made it possible to amplify the deviation of the diamagnetic response from a monotonic behavior as a function of the external magnetic field.

To study the diamagnetic screening, we placed a sample between a receiving coil and a transmitting coil, each with dimensions of $2 \times 2 \times 2$ mm, operating at a frequency of 100–150 kHz. The sample with the coils was placed in a solenoid, and the screening was studied as a function of the magnetic field H. The derivative of this dependence with respect to H was also studied. To study the microwave absorption, we placed the sample at the bottom of a rectangular resonator (TE_{102} mode) operating at a frequency of 9.0 GHz. These experiments were carried out in an atmosphere of gaseous helium. The temperature was measured with a carbon resistance. The amplitude of the modulation of the field H was on the order of 10 mOe, and the modulation frequency was on the order of 15 Hz.

Figure 1 shows curves of the microwave absorption and the diamagnetic screening versus the magnetic field. If the scale of the field H is doubled for the microwave

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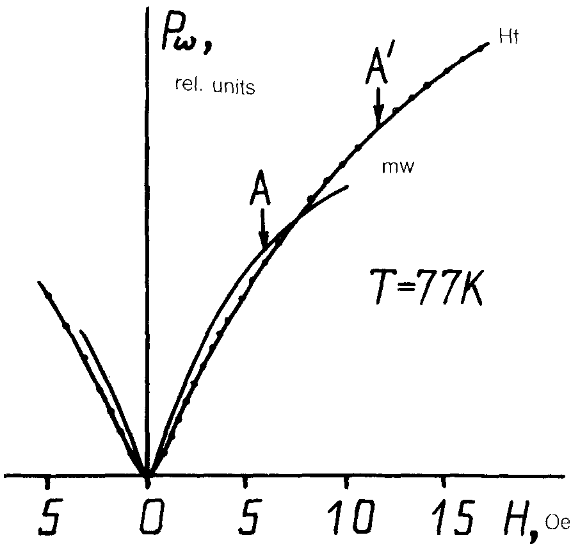

FIG. 1. Solid lines—Experimental results on the microwave absorption (mw) and the rf screening (rf) as functions of the magnetic field; points—results of a conversion of the microwave curve (the scale along the abscissa was doubled, and the scale along the ordinate was adjusted for the best fit with the rf curve; point A went into point A′ in the process).

response, and if the scale along the y axis is adjusted for the best fit of the microwave and rf curves, the microwave curve becomes the curve shown by the dotted line, which agrees much better with the rf curve. Figure 2 shows Fourier transforms of the oscillations in the magnetic field of the derivatives of the microwave absorption and of the rf screening. The characteristic frequency of the oscillations in the microwave response is seen to be larger by a factor of two. If we find the characteristic oscillation period for the microwave response from Fig. 2, and if we determine the diamagnetic demagnetization factor from low-frequency experiments (≈ 5), we find the value $S \sim 1400\ \mu\text{m}^2$ for the typical area of the loops which contribute to the magnetic-field response. This figure is much larger than both the average area of the grains in the polycrystalline samples (~ 10–$50\ \mu\text{m}^2$) and the average area of an individual Josephson junction between grains ($\sim 4\ \mu\text{m}^3$). This result means that both the rf and microwave magnetic-field responses are determined by a set of loops with a characteristic size $L_\varphi \sim \sqrt{S} - 40\ \mu\text{m}$. Let us consider an individual Josephson junction between grains i and j which is shunted by a set of superconducting loops $\tilde{x}_l$. Denoting the phase difference between the grains by φ_{ij}, and assuming that the loop $\tilde{x}_l$, is penetrated by a magnetic flux Φ_l, we find that the total superconducting current from grain i to grain j is equal to the sum of the currents I_l over the loops $\tilde{x}_l$:

$$I_{ij} = \sum_{\tilde{x}_l} I_l(\tilde{x}_l,\ \varphi_{ij}, \Phi_l/\Phi_0\ ) \tag{1}$$

Here I_l is proportional to the admittance $\sigma(\tilde{x}_l)$ of loop $\tilde{x}_l$: $I_l \sim |\sigma(\tilde{x}_l)| e^{i\theta(\tilde{x}_l)}$, where Φ_0 is the flux quantum. If an alternating voltage $V_\omega = V_0 e^{i\omega t}$ is applied to junction ij, the phase difference φ_{ij} will oscillate at the frequency ω:

$$\frac{d\varphi_{ij}}{dt} = \frac{2e}{\hbar} V_\omega; \quad \varphi_{ij} = \varphi_{ij}^0 + \frac{2e}{i\hbar\omega} V_0 e^{i\omega t}, \tag{2}$$

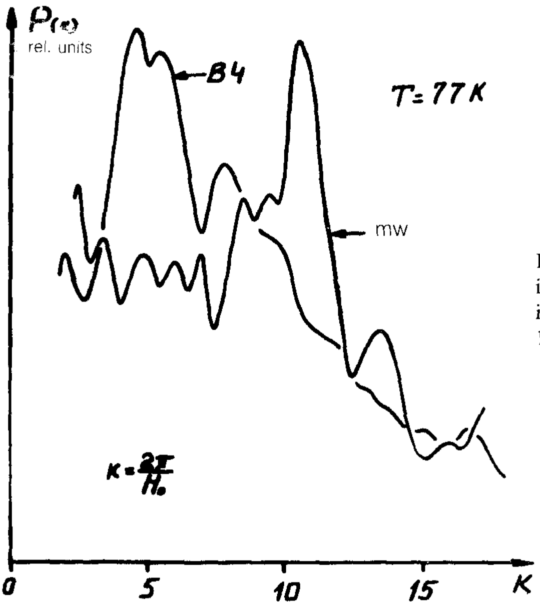

FIG. 2. Fourier spectrum of noisy oscillations in the microwave absorption and the rf screening as functions of the magnetic field. Sample 1 after ion etching ($H_0 = 0.7$ Oe).

where e is the charge of an electron, and $\hbar$ is Planck's constant. For simplicity we assume that loop $\tilde{x}_l$ contains a single Josephson junction, which determines the current through the loop $\tilde{x}_l$, and we also assume that this current is small, so that we find the expression $\Delta\varphi_l \approx -\varphi_{ij} - \Phi_l/\Phi_0$ for the phase difference at this junction. We furthermore assume that this junction is shunted by a capacitance C_l. Let us find the change in the current as a function of the magnetic field through junction ij at low frequencies: $\omega \to 0$. In this case we can ignore the effect of the capacitances C_l, and we find the following expression for the average current change:

$$\langle \Delta I_{ij}^{\omega} \rangle = \langle I_{ij}^{\omega}(H) - I_{ij}^{\omega}(0) \rangle = \langle \sum_{\tilde{x}_l} [\sigma_{\omega}(\tilde{x}_l, H) - \sigma(\tilde{x}_l, 0)] \rangle V_{\omega}$$

$$\approx \frac{2e}{i\hbar\omega} \langle I_l \rangle \langle \sum_{\tilde{x}_l} [\cos(\Phi_l/\Phi_0) - 1] \rangle V_{\omega} \approx A \int_0^{\infty} e^{-x/L_{\varphi}} [\cos(\frac{\alpha}{d} Hx) - 1]/x dx, \qquad (3)$$

where A is a constant. When we switched from a summation to an integration in (3), we noted that the number of loops $\tilde{x}_l$ with ends in i and j, consisting of N_l grains, is proportional to $1/N_l$, and such a loop is penetrated on the average by a flux $\Phi_l = HS_l \approx \alpha HN_l$ (we are assuming a random position of the grains, so the area of grain $\tilde{x}_l$ is $S_l \approx (d\sqrt{N_l})^2 = d^2 N_l$, where d is the size of a grain), where α is a constant which depends on the dimensions of the grains, their positions, and the demagnetizing factor. We also assume $\varphi_{ij}^0 \approx 0$ and that the size of the summation region is $L_{\varphi} \gg d$. We consider the case of high frequencies, at which the contributions from capacitances C_l to the admittance $\sigma(\tilde{x}_l)$ become comparable to the inductances of the Josephson

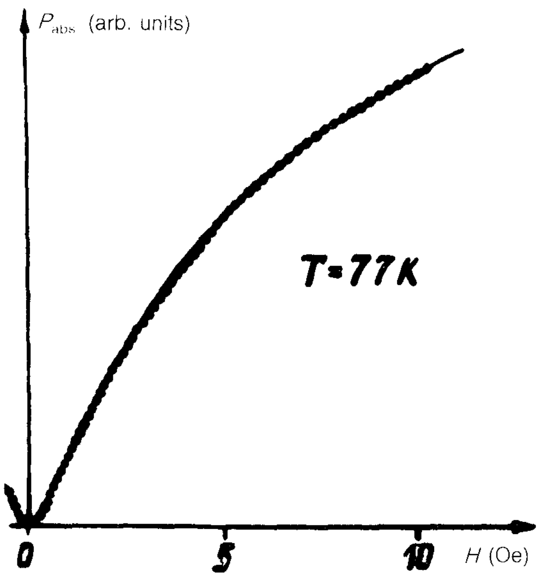

FIG. 3. Microwave absorption versus the magnetic field H. Points—Experimental; solid curve—theoretical [expression(4)]. There are two adjustable parameters here: the scale along the x axis and that along the y axis.

junctions. In this case the admittance $\sigma(\tilde{x}_l)$ is a complex number with a random phase which depends on the inductance and the capacitance C_l at loop $\tilde{x}_l$. In this case averages of the type in (3) are strongly suppressed because of the presence of a random phase $\Theta(x_l)$ in (1). If, however, we consider the change in the average of the modulus of I^ω_{ij} as a function of the magnetic field, the contribution of the product of $\Sigma_{\tilde{x}_l}$ and $(\Sigma_{\tilde{x}_m})^*$ becomes nonvanishing when an average is taken over realizations. The final expression is

$$\langle \Delta |I^\omega_{ij}|\rangle = \langle |I^\omega_{ij}(H)| - |I^\omega_{ij}(0)|\rangle$$

$$\approx \frac{e}{i\hbar\omega}\langle I_l\rangle \langle \sum_{\tilde{x}_\kappa, \tilde{x}_m} \exp i[\Theta(\tilde{x}_l) - \Theta(\tilde{x}_m)][\cos(\Phi_l/\Phi_0)\cos(\Phi_m/\Phi_0) - 1]\rangle V_\omega$$

$$\approx \frac{A}{2}\langle \sum_{\tilde{x}_\kappa}[\cos(2\Phi_\kappa/\Phi_l) - 1]\rangle \approx \frac{A}{2}\int_0^\infty e^{-x/L_\varphi}[\cos(2\frac{\alpha}{d}Hx) - 1]/x\,dx. \qquad (4)$$

We see that this expression is sensitive to a field H half that in (3).

In the microwave experiments, the sample was positioned at an antinode of the magnetic field; i.e., the microwave current through grains i and j was given. This situation leads to changes in the voltage across the junction, V_ω, as H is varied and thus in the absorption in it if, for example, it is shunted by a resistance R. Figure 3 compares the experimental and theoretical [expression (4)] results on the microwave absorption as a function of the magnetic field H. Using the measured demagnetizing factor (≈ 10) and 3 μm as the size of a grain, we find $L_\varphi \approx 50$ μm from Fig. (3) and expression (4).

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