Relaxation time of order parameter in YBaCuO single crystal

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The temperature dependence of the power of the radiation at the tripled frequency which arises upon the reflection of a microwave signal from a YBaCuO single crystal has been studied experimentally. A comparison of this behavior with a calculation based on the theory of Gor'kov and Éliashberg {Zh. Eksp. Teor. Fiz. **54**, 612 (1968) [Sov. Phys. JETP **27**, 328 (1968); **61**, 1254 (1971); **34**, 668 (1972)]} yields an estimate of the relaxation time of the order parameter.

The nonlinear properties of the high-T_c superconductors have been the subject of recent papers. An important question which arises immediately is that of the inertial properties of the order parameter Δ and of the relaxation frequency Ω_0 which is characteristic of Δ. This question cannot be resolved on the basis of linear electrodynamics, in which Ω_0 does not arise, and another frequency, Ω_1, is important. The latter frequency separates the region in which the field penetrates into the superconductor as a result of a skin effect from the region of the Meissner effect. The nonlinear response of a superconductor to an rf field, on the other hand, depends on both of these frequencies, Ω_0 and Ω_1. Gor'kov and Éliashberg showed that the relation $\Omega_0 = \Omega_1$ holds in a superconductor having a high concentration of paramagnetic impurities.[1] This situation was studied experimentally by Amato and McLean,[3] who found the relaxation time Ω_0^{-1} near the critical temperature T_c from the lineshape of the nonlinear response of an $La_{1-x}Gd_xSn_3$ alloy. In YBaCuO single crystals the relation $\Omega_1 < \Omega_0$ holds, as we will show below.

A convenient method for studying time-varying dynamic processes is to measure the intensities of the higher harmonics which arise upon the reflection of a microwave signal from the surface of the superconductor. In ceramic YBaCuO samples, the temperature dependence of the second-harmonic signal[4,5] or that of the third-harmonic signal[4] has two structural features: a maximum near the superconducting transition temperature T_c and a high and nearly constant signal level at $T \ll T_c$. The signal far from T_c is suppressed by a weak external field and depends in a nonmonotonic way on the power of the wave incident on the sample. These properties indicate a Josephson mechanism for the generation of this signal.

In this letter we are reporting a study of the temperature dependence of the microwave response of a $YBa_2Cu_3O_{6.9}$ single crystal at the tripled frequency.

A sample with approximate dimensions of $4\times4\times0.1$ mm and a resistivity $\rho \approx 50$ $\mu\Omega\cdot$cm at $T \approx T_c$ was held in a bimodal resonator tuned to the frequencies ω and 3ω. The single crystal was exposed to an electromagnetic wave at frequency $\omega/2\pi = 9.4$ GHz from a magnetron in pulsed operation with a pulse repetition frequency of 50 Hz and a pulse length of 2 μs. The maximum amplitude of the alternating magnetic field at the surface of the sample, $H_{\sim}^{\omega}$, could be varied from 4 to 20 Oe. To suppress the

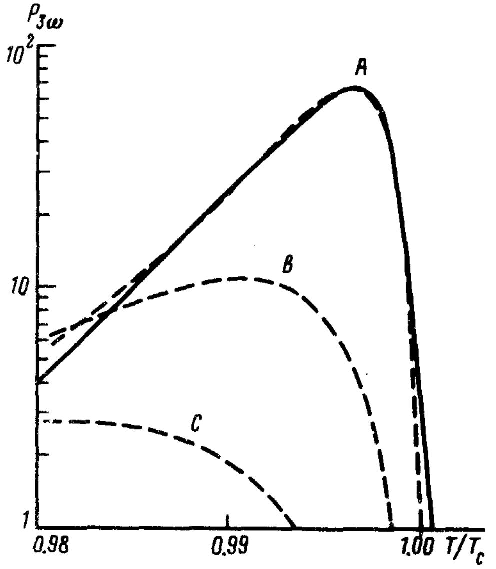

FIG. 1. The third-harmonic signal $P_{3\omega}$ versus the temperature T/T_c. Solid line—Experimental; dashed lines—theoretical for various values of $\omega\tau$. A) $\omega\tau = 0.003$; B) 0.008; C) 0.015.

harmonics of the magnetron, we used a system of absorbing filters. A superheterodyne receiver measured the pulsed signal power ($P_{3\omega}$) at the frequency 3ω. A $P_{3\omega}(T)$ signal was observed only near T_c, in contrast with the results on ceramic YBaCuO samples; i.e., Josephson junctions in the single crystal do not contribute to the nonlinearity. The temperature dependence of $P_{3\omega}$ is shown by the solid line in Fig. 1. Note that the signal $P_{3\omega}(T)$ is asymmetric. We observed the same $P_{3\omega}(T)$ lineshape near T_c in other YBaCuO single crystals. The $P_{3\omega}(T)$ signal did not change when we applied a static magnetic field in the direction parallel to the surface of the sample with a strength up to 7 kOe. It was established experimentally that the amplitude of the alternating field corresponding to the results in Fig. 1 ($H^{\omega}_{\sim} = 5$ Oe) lies in the interval for which the amplitude of the third-harmonic field, $H^{3\omega}_{\sim}$, is proportional to the cube of the field at the fundamental frequency:

$$H^{3\omega}_{\sim} \sim (H^{\omega}_{\sim})^3. \tag{1}$$

This situation means that one can use perturbation theory to describe the interaction of an intense electromagnetic field with the superconductor.

The experimental curve of $P_{3\omega}(T)$ cannot be described by the theory derived in, for example, Refs. 1 and 6 on the basis of the BCS model.

A more appropriate approach for the high-T_c superconductors starts from Éliashberg's equations.[2] After an expansion in Δ/T_c and $\omega/T_c\,[(T_c - T)/T_c \ll 1)$, these equations become

$$\Delta_n Z_n = -\pi T \sum_{n'} \lambda(n-n')\left[-\frac{\Delta_{n'}}{|\epsilon_{n'}|} + \frac{\partial \Delta_{n'}/\partial t}{2Z_{n'}\epsilon_{n'}^2} + \left[\frac{E_F}{m^* c^2}\right]\frac{e^2 A^2 \Delta_{n'}}{Z_{n'}^2 |\epsilon_{n'}|^3} + \frac{\Delta_{n'}^3}{2|\epsilon_{n'}|^3}\right]$$

$$Z_n = 1 + \frac{\pi T}{\epsilon_n} \sum_{n'} \lambda(n-n')\frac{\epsilon_{n'}}{|\epsilon_{n'}|}\left[1 - \frac{\Delta_{n'}^2}{2\epsilon_{n'}^2}\right]. \tag{2}$$

Here $\Delta_n(t)$ is the gap, $\lambda(n-n') = 2\int_0^\infty d\omega[\omega\alpha^2(\omega)F(\omega)/\omega^2 + \omega_{n-n'}^2]$, α^2F is the Éliashberg function, $\varepsilon_n = (2n+1)\pi T$ and $\omega_n = 2n\pi T$. We also need an equation to describe the change in the vector potential **A** inside the superconductor;

$$\text{curl curl } \mathbf{A} = \frac{4\pi}{c^2}\left\{\frac{1}{\rho}\frac{\partial \mathbf{A}}{\partial t} + \frac{ne^2}{m^*(\pi T)^2}\sum_n \frac{\Delta_n^2 \mathbf{A}}{Z_n|2n+1|^3}\right\}, \tag{3}$$

where ρ is the resistivity, n is the density of holes, and m^* is the band mass of the holes. Incorporating an external magnetic field $H \ll H_{c2}$ in Eqs. (2) and (3) has no effect on the calculation of the response at the tripled frequency. Working from Eqs. (2) and (3), we find the following expression for the frequency, which is quite accurate near T_c:

$$\Omega_0 \approx 6T_c(1+\lambda)\left(1-\frac{T}{T_c}\right), \qquad \Omega_1 \approx \frac{2}{\tau(1+\lambda)}\left(1-\frac{T}{T_c}\right), \tag{4}$$

where $\lambda = \lambda(0)$ is a coupling constant, and $\tau = m^*/\rho n e^2$. For a numerical analysis of Eqs. (2) and (3), we selected the model of a phonon spectrum consisting of three Einstein oxygen modes[7] with frequencies of 200, 600, and 1000 K. As a result, we found both the correct value of T_c (at $\lambda = 1.4$) and the behavior $P_{3\omega}(T)$ shown by dashed line A in Fig. 1, which is the best fit of the experimental curve. Corresponding to line A is the parameter value $\omega\tau = 0.003$. With $\omega/2\pi = 9.4$ GHz and $\rho = 50$ $\mu\Omega\cdot$cm we find the ratio $m^*/nm_0 = 0.8\times10^{-21}$ cm^{-3} (for $\lambda = 1.4$). From (4) we find $\Omega_0 \approx 1.8\times10^{14}(1-T/T_c)$, and $\Omega_1 \approx 1.6\times10^{13}(1-T/T_c)$. Lines B and C in Fig. 1 correspond to $\omega\tau$ values of 0.008 and 0.015.

An alternative to the generation mechanism discussed above might be a mechanism based on a strong dependence of the impedance of the sample on the strength of the external magnetic field, $Z(H)$. A manifestation of this mechanism would be most understandable in type-I superconductors,[8] in which the resultant applied field $H + H^\omega$ is comparable to the critical field H_c, and the sample is in either the normal state or the superconducting state during a period of the incident wave. If the dependence $Z(H)$ involves a threshold, the reflected signal should have a nonharmonic shape, so a response should arise at all multiple frequencies with an amplitude proportional to H^ω. This conclusion does not correspond to experimental result (1). Furthermore, if the observed nonlinear effect were due exclusively to a $Z(H)$ dependence, then the amplitude of the $P_{3\omega}$ signal would vary with the strength of the external field, in contradiction of experiment.

We thus believe that the nonlinear response of a YBaCuO single crystal near T_c is a consequence of a time variation of the order parameter Δ under the influence of the rffield. The measured relaxation time Δ is $\Omega_0^{-1} \approx 5.6 \times 10^{-15}(1 - T/T_c)^{-1}$. Measurements of $P_{3\omega}(T)$ at a different frequency ω might show whether the nonlinearity mechanism which we have been discussing here is unique.

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