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Ultrasonic-attenuation measurements in single-phased $YBa_2Cu_3O_7$

M-F. Xu, H-P. Baum, A. Schenstrom, Bimal K. Sarma, and Moises Levy
Physics Department, University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53201

K. J. Sun
NASA-Langley Research Center, Hampton, Virginia 23665

L. E. Toth,* S. A. Wolf, and D. U. Gubser
Naval Research Laboratory, Washington, D.C. 20375-5000

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Ultrasonic attenuation at 15 MHz has been measured between 300 K and liquid-helium temperatures on a single-phased $Y_1Ba_2Cu_3O_7$ sample with a 91-K superconducting transition temperature. The attenuation data show similarities to the behavior of heavy-fermion superconductors, with a local maximum just below T_c and a nearly quadratic dependence of the attenuation at lower temperatures. At higher temperatures there is evidence for a relaxation maximum at 252 K, with an effective relaxation time of 1.1×10^{-8} s.

Since the recent discovery of high-temperature superconductors (HTS), many questions have arisen concerning the nature of the interaction leading to superconductivity in these new materials, and many theories have been presented in an effort to answer them.[1-5] We have measured ultrasonic attenuation on a HTS polycrystalline sample, and have observed features reminiscent of the results obtained for heavy-fermion superconductors. These observations may provide a clue for revealing the nature of the interaction which produces superconductivity in the HTS perovskite system.

Our results of ultrasonic attenuation α as a function of temperature T do not exhibit a sharp drop at the transition temperature, as expected in a simple and well-behaved classical Bardeen-Cooper-Schrieffer (BCS) system, with a well-defined isotropic energy gap. However, the curve of $\alpha(T)$ presents a striking resemblance to a heavy-fermion system, having a local maximum slightly below T_c, and following a near-quadratic dependence down to liquid-helium temperatures.

The sample we studied comes from a batch prepared by mixing, grinding, pressing, and sintering powders to obtain 1–2 g pellets of $Y_1Ba_2Cu_3O_7$. The processing procedure and its relationship to crystal structure and transition temperature (T_c) have been reported earlier.[6] The sample used in this study is single phased and has a mass density of approximately 78% of the single-crystal density. These samples have also been investigated by x-ray diffraction and neutron scattering,[7] and by ultraviolet resonant photoelectron emission,[8] to assess their vibrational density of states, their atomic structure, and their valence band and electronic structure.

The sample, 0.295 cm thick, was first polished to a 3 μm finish, to plane two opposite faces parallel. An X-cut, 15-MHz fundamental frequency, quartz piezoelectric transducer was then bonded to one face with Epon Resin 815 epoxy. A MATEC Pulse Modulator and Receiver model 6600 in conjunction with a MATEC rf Plug-in model 760 was used to send longitudinal waves at the transducer's fundamental frequency through the sample and pick up the reflected signal. The temperature of the sample was swept between 300 and 7 K. Either a four-point probe resistance measurement, or a susceptibility assessment, both verified not to perturb the ultrasonic data, was concurrently monitored to position the superconducting transition. Although the sample was a pressed and sintered powder instead of a nonporous material, it was still possible to obtain one echo which could be measured.

The temperature dependence of the attenuation coefficient in the single-phased sample of $YBa_2Cu_3O_7$ is shown in Fig. 1. This sample has a density of 4.97 g/cm^3, which is 0.78 times the single-crystal perovskite structure density. The temperature range covered is from 7 up to 289 K. The resistance of the sample measured in the same temperature range on a different experimental run is also displayed in the figure. There is a smooth maximum

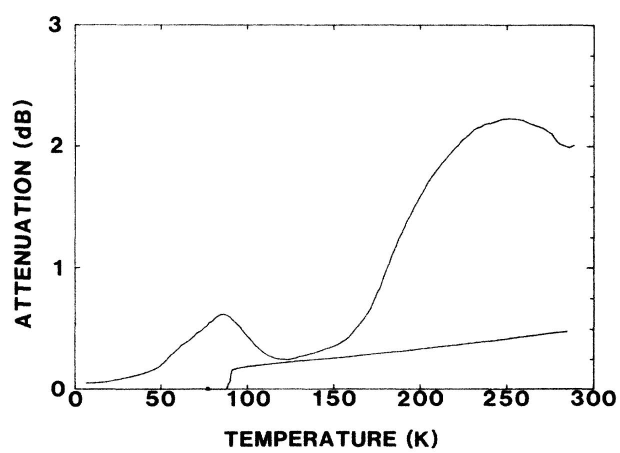

FIG. 1. The attenuation of 15 MHz longitudinal waves in a single-phased sample of $Y_1Ba_2Cu_3O_7$ in the temperature range from 7 to 289 K. The lower curve represents values for resistance measurements.

in the attenuation at around 252 K. There are no shoulders or subsidiary maxima in this temperature range as reported on another sample of $YBa_2Cu_3O_7$.[9] We believe that this is evidence of the fact that the present sample is single phased (SP) and is not plagued by the other phase transitions that multiphased (MP) samples experience. We suggest that these maxima are produced by a relaxation mechanism where the attenuation is given by $\alpha \simeq \omega^2\tau^*/(1+\omega^2\tau^{*2})$ where ω is the angular frequency and τ^* is an effective relaxation time[10] which at the maximum is 1.1×10^{-8} s.

The most surprising data are obtained near the superconducting transition temperature, where the attenuation goes through a maximum and monotonically decreases. Figure 2 shows data obtained during a different experimental run which covered the temperature range between 7 and 120 K. The resistance of the sample was measured simultaneously. It goes to zero at 88 K with the midpoint of the transition located at 91 K. In this figure it is evident that the maximum in attenuation lies about 7 K below the midpoint of the superconducting transition. These data are similar to ultrasonic attenuation measurement obtained in the heavy-fermion superconductors, particularly UPt_3,[11-14] where a maximum in attenuation is observed at $T_m/T_c \simeq 0.96$, which is similar to the value obtained for the present sample, $T_m/T_c \simeq 0.92$. In order to determine the extent of the similarity, the data obtained in Fig. 2 were plotted on a log-log plot in Fig. 3. The slopes of the straight line portions yield T^n temperature dependences, where $n_1=2.1$ above 42 K and $n_2=1.6$ below 42 K. Again, this power dependence is very similar to that obtained for UPt_3 where values varying from $n=1$ to $n=3$ have been obtained.[11-14] Therefore, heavy-fermion models could be proposed for explaining the properties of the HTS, such as the Anderson-Brinkman-Morel (ABM) excitation spectrum with an anisotropic superconducting energy gap that vanishes at points on the Fermi surface, and which gives a T^2 dependence for the attenuation in the superconducting state.[15]

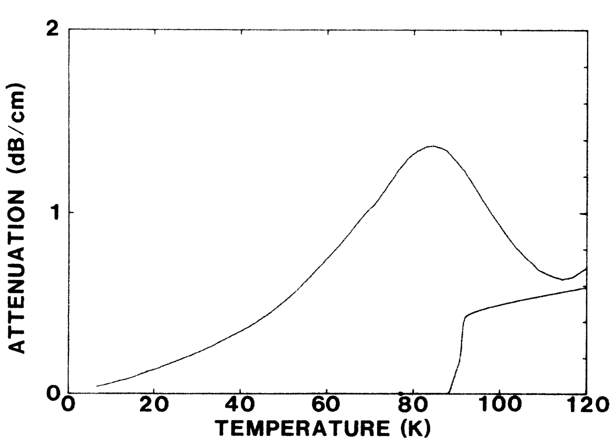

FIG. 2. Attenuation coefficient obtained during a different experimental run from the one displayed in Fig. 1 on the same sample of $Y_1Ba_2Cu_3O_7$. The temperature range covered was 7 to 120 K. The lower curve represents values for simultaneous resistance measurements.

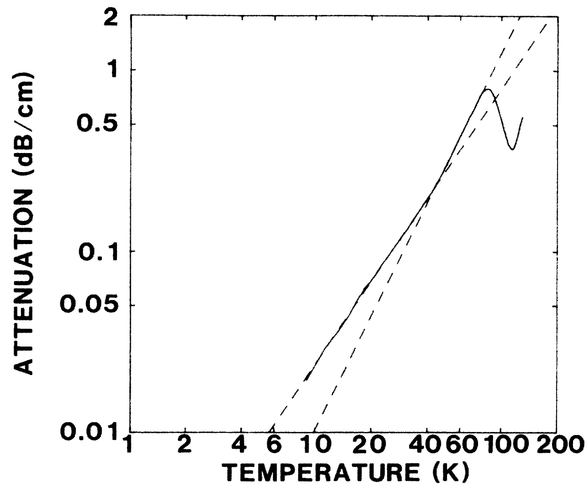

FIG. 3. Log-log plot of data in Fig. 2. The dashed lines yield T^n dependences in the superconducting state, where above 42 K $n_1=2.1$ and below 42 K $n_2=1.6$.

The sample is a pressed sintered pellet. Consequently there exists the possibility that the observed effects could be due to some sort of interference of echoes which follow different paths in the material. In order to minimize this possibility, the transducer was detached from the sample, the sample ends were repolished, and a new bond was made. Attenuation data could be obtained at the lower temperatures on the first, second, and third echoes. The data on the first echo looked the same as that which are shown in Fig. 2. The data on the second and third echoes also looked qualitatively similar to the data in Fig. 2, and for the second echo, the attenuation was about twice as large as for the first echo. Therefore, we are reasonably certain that the curves we are displaying represent attenuation in the sample and not some sort of interference phenomenon.

The total attenuation change in the superconducting state from the maximum near T_c to the lowest temperature is $\Delta\alpha \simeq 1.5$ dB/cm. This is the amount of attenuation that we could assume is being contributed by the electrons in the normal state. At this frequency this is several orders of magnitude larger than that which would be expected for a conventional superconductor. For instance, for vanadium with a resistivity ratio of 20,[16] one would expect $\Delta\alpha \simeq 1.5\times10^{-3}$ dB/cm. The attenuation is proportional to the electron mean free path and the Fermi velocity, and is inversely proportional to the density and to the cube of the sound velocity. These samples have a resistivity ratio of 3, and if we assume that the electron mean free path of the Y compound is comparable to that of V at room temperature, then the difference of resistivity ratios makes the attenuation 6.7 times smaller. The Fermi velocity of V, 1.8×10^7 cm/s is probably twice as large as that of the Y compounds. However, the sound velocity is 1.7 times larger for V. This contributes an increase of 4.9, and the difference in density contributes another increase of 1.2. Taking these factors into account, one would expect an attenuation coefficient of 6.6×10^{-4} dB/cm. Thus the observed change in attenuation is about three orders of magnitude larger than what would be expected for a normal superconductor.

One of the sources of measurable attenuation in a metal at low temperatures is electron-phonon interaction. When the electron mean free path l is smaller than the sound wavelength, the attenuation is proportional to l, since the energy imparted to the electrons during a collision is returned to the lattice out of phase with the sound wave by an amount that is proportional to l. In the superconducting state, the sound waves only interact with excited quasiparticles whose population in a BCS superconductor decays exponentially with temperature. In the present sample the attenuation does not decay exponentially but almost quadratically. This relationship would still be consistent with a superconductor that has an anisotropic energy gap such as that postulated for the heavy-fermion superconductors. And, in fact, there are estimates for the effective mass of the electrons in $YBa_2Cu_3O_7$ of about $100m_e$.[17] The maximum in attenuation that we observe slightly below the superconducting transition is consistent with observations made on the heavy-fermion superconductors UPt_3 and URu_2Si_2.[18] In these superconductors, the observed contribution of electron-phonon interaction to the attenuation is about what is observed in regular BCS superconductors whose effective electron masses are close to unity. Thus it does not appear that the value of the effective mass contributes a large factor to the attenuation. However, the attenuation change observed in our sample of $YBa_2Cu_3O_7$ is about three orders of magnitude larger than that which would be expected in a BCS superconductor. The possibility exists that the one and two dimensional CuO conducting planes,[19] in conjunction with the large effective electron masses, may account for this anomalous attenuation change. It should be noted though, that a two-dimensional electron gas would only contribute some geometrical factors to the electron-phonon interaction integrals, and could not account for this effect.[20] It may be possible that the one-dimensional nature of the CuO networks may contribute some fluctuations near the phase transition which could account for this anomalous attenuation. Another model that may account for this large effect could be the mean-field resonating valence bond (RVB) model[5] wherein boson holes Bose condense to make a superconductor. Although at present no predictions have been formulated for the interaction of such a system with sound waves, it seems reasonable to presume that such an interaction would involve all the bosons present as opposed to just the fermions at the Fermi surface. The ratio of these two quantities may yield the factor of 1000 which appears to be missing in the interaction.

It is obvious that attempts should be made to measure the attenuation in single crystals of $YBa_2Cu_3O_7$, and at higher frequencies. These measurements might yield information which will be necessary for interpreting the present measurement and understanding the mechanisms which produce superconductivity in these systems. After submitting this paper we received a copy of the unpublished work of Bhattacharya *et al.*[21] Their attenuation measurements are qualitatively similar to those reported in this paper.

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[1]V. Kresin, Phys. Rev. B **35**, 8716 (1987).

[2]J. Ashkenazi, C. G. Kuper, and R. Tyk, Solid State Commun. **63**, 1145 (1987).

[3]P. W. Anderson and E. Abrahams, Nature **327**, 363 (1987).

[4]J. Yu, S. Massida, A. J. Freeman, and D. D. Koeling, Phys. Lett. A **122**, 203 (1987).

[5]P. W. Anderson, G. Baskaran, Z. Zou, and T. Hsu, Phys. Rev. Lett. **58**, 2790 (1987).

[6]L. E. Toth, E. F. Skelton, S. A. Wolf, S. B. Qadri, M. S. Osofsky, B. A. Bender, S. H. Lawrence, and D. U. Gubser (unpublished).

[7]J. J. Rhyne, D. A. Neumann, J. A. Gotaas, F. Beech, L. Toth, S. Lawrence, S. A. Wolf, M. Osofsky, and D. U. Gubser (unpublished).

[8]R. L. Kurtz, R. L. Stockbauer, D. Mueller, A. Shih, L. E. Toth, M. Osofsky, and S. A. Wolf, Phys. Rev. B **35**, 8818 (1987).

[9]K. J. Sun, M. Levy, B. K. Sarma, P. H. Hor, R. L. Meng, Y. Q. Wang, and C. W. Chu (unpublished).

[10]K. J. Sun, R. S. Sorbello, M. Levy, M. B. Maple, and M. S. Torikachvili, in *Proceedings of the IEEE 1986 Ultrasonics Symposium* edited by B. R. McAvoy (IEEE, New York, 1986), p. 1123.

[11]D. J. Bishop, C. M. Varma, B. Batlogg, E. Bucher, Z. Fisk, and J. L. Smith, Phys. Rev. Lett. **53**, 1009 (1984).

[12]V. Muller, D. Maurer, E. W. Scheidt, Ch. Roth, K. Luders, E. Bucher, and H. E. Bommel, Solid State Commun. **57**, 319 (1986).

[13]B. S. Shivaram, Y. H. Jeong, T. F. Rosenbaum, and D. G. Hinks, Phys. Rev. Lett. **56**, 1078 (1986).

[14]Y. J. Qian, M-F. Xu, A. Schenstrom, H-P. Baum, J. B. Ketterson, D. Hinks, M. Levy, and B. K. Sarma, Solid State Commun **63**, 599 (1987).

[15]J. P. Rodriguez, Phys. Rev. Lett. **55**, 250 (1985).

[16]J. A. Waynert, H. Salvo, Jr., and M Levy, Phys. Rev. B **10**, 1859 (1974).

[17]V. Z. Kresin and S. A. Wolf, in *Novel Mechanisms,* edited by S. A. Wolf and V. Z. Kresin (Plenum, New York, 1987), p. 287.

[18]M. Levy, A. Schenstrom, K. J. Sun, and B. K. Sarma, in *Novel Mechanisms,* edited by S. A. Wolf and V. Z. Kresin (Plenum, New York, 1987), p. 243.

[19]F. Herman, R. V. Kasowski, and W. Y. Hsu, Phys. Rev. B **37**, 2309 (1988).

[20]R. Sorbello (private communication).

[21]S. Bhattacharya, M. J. Higgins, D. C. Johnston, A. J. Jacobson, J. P. Stokes, J. T. Lewandowski, and D. P. Goshorn (unpublished); and S. Bhattacharya (private communication).