Particle-size and temperature dependence of microwave noise in superconducting $YBa_2Cu_3O_{7-y}$: Evidence for random Josephson junctions

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The effects of particle size and temperature on the microwave noise and low-field microwave absorption in $YBa_2Cu_3O_{7-y}$ powders have been studied by the magnetically modulated microwave absorption technique. The results can be interpreted in terms of a network of random Josephson junctions in the individual superconducting grains but are not consistent with the thermally activated flux creep model. An estimate of the size of the Josephson junctions is also obtained from the variation of the microwave noise with particle size.

Soon after the discovery of high-temperature superconducting oxides, the superconducting glassy (SCG) state, akin to the spin-glass phase was postulated.[1] The theoretical underpinnings for the nature of the SCG phase were actually formulated[2,3] before the appearance of the high-T_c superconductors and much of the experimental data (relaxation of zero-field-cooled susceptibility,[1,4] torque measurements,[5] low-field peaks in microwave absorption,[6-8] etc.) on the glassy characteristics of these materials have been interpreted in terms of phase slippage in a system of random superconducting regions weakly coupled by Josephson junctions. Recently, however, it has been proposed[9] that many, if not all, the foregoing experimental results on superconducting oxides can be accounted for by thermally activated flux creep in type-II superconductors.[10,11] A possibility of distinguishing between the two mechanisms lies in investigating the dependence of various phenomena on particle size and temperature, the subject of the present study. For example, the SCG state is characterized by the white-noise spectrum of tunneling currents[12] which should be affected by the particle size. By reducing the particle size it may be possible to reach a point where the particles are too small to contain Josephson junctions so that the associated noise spectrum of tunneling currents disappears. Furthermore, Josephson-junction-related effects should be relatively temperature independent below the temperature needed to fully establish the superconducting state, whereas effects due to thermally activated flux creep should fall off at very low temperatures.

We have examined the particle size and temperature dependence of the microwave noise and low-field microwave absorption in superconducting $YBa_2Cu_3O_{7-y}$ using a relatively new microwave technique called magnetically modulated microwave absorption (MAMMA) which offers several advantages for studies of superconductivity.[13] The method is similar to electron-spin resonance (ESR) in that the quantity directly measured is the derivative with respect to magnetic field of the microwave power reflected from the cavity (MAMMA response). It has been shown elsewhere,[13] however, that in this case the response is due to magnetic-field-dependent changes in the resistivity of the superconducting sample rather than the microwave-induced electron-spin transitions of ESR. The essential operational difference between the MAMMA technique and the ESR method is that in the latter technique the field is varied and the temperature kept constant, while in the former technique, the converse procedure is followed. This technique sensitively detects not only the phase transition to the superconducting state, but reveals the presence of microwave noise and the broad low-field microwave absorption. A particular advantage of this method in the present case is that these effects are observed primarily as functions of temperature although their field dependences can also be determined. The presence of low-field microwave absorption observed around 8 to 50 G in field-swept experiments[7,8] on Y-Ba-Cu-O manifests itself in the MAMMA temperature spectra as an increase in signal amplitude below T_c, which increase sometimes levels off at the lowest temperatures.[7,8] This is illustrated in Figs. 1(a) and 1(b) which show spectra of a bulk sample in low (30 G) and high (1 kG) external magnetic fields, respectively. The peak at 94 K observed in all samples corresponds to the transition from the normal state to

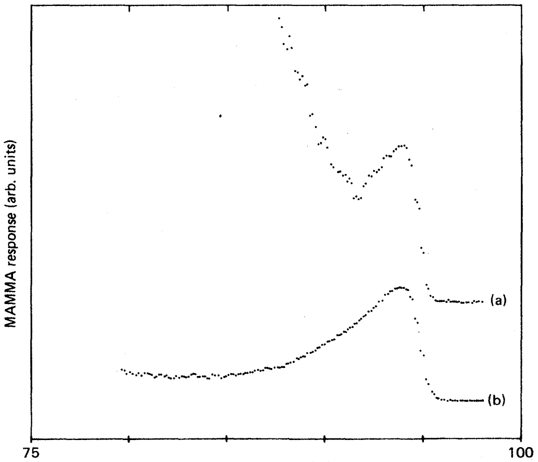

FIG. 1. MAMMA response vs temperature for Y-Ba-Cu-O. (a) Bulk sample in 30 G, and (b) bulk sample in 1 kG.

the superconducting state,[13,14] while the rising base line at temperatures below 94 K in the bulk sample at 30 G [Fig. 1(a)] is due to the low-field absorption. In Fig. 1(b), the same features are present but the rising base line is much less pronounced since at 1 kG we are well out on the wing of the strong low-field absorption which is believed responsible for the slight upturn in the base line at the low-temperature end of this spectrum. This upturn is clearly present in Fig. 2(a) where this system is examined at lower temperatures.

Samples of Y-Ba-Cu-O were prepared in a manner described previously,[14] and formed into powders of various particle sizes by crushing the bulk material and filtering the resultant powders through successive sieves. In this way, six samples were fabricated in which the particle sizes were in the range $<10-420$ μm. Particle sizes smaller than 10 μm were not prepared because the microwave noise relative to the baseline noise was essentially zero for the 10-μm particles. The microwave measurements were made in a closed 3-mm i.d. quartz tube within 1 h after the powdered samples were prepared to minimize changes in these high-surface-area samples due to reaction with atmospheric water, carbon dioxide, etc. These sample tubes are located in an Air Products Helitran flow-through cryostat designed to pass through the sample ports of our Varian rectangular cavity, and the sample temperature is varied by digitally controlled heating of cold helium gas en route from a liquid-helium reservoir to the cryostat. With this apparatus the only part of the system whose temperature is changed, apart from the sample itself, is a small piece of high-grade fused silica tubing in the center of the cavity. Consequently, the sensitivity of the spectrometer does not change as the sample temperature is varied. Typical operating conditions are 9.3-GHz microwave frequency, 1 mW of microwave power, and 2-G peak-to-peak magnetic field modulation amplitude.

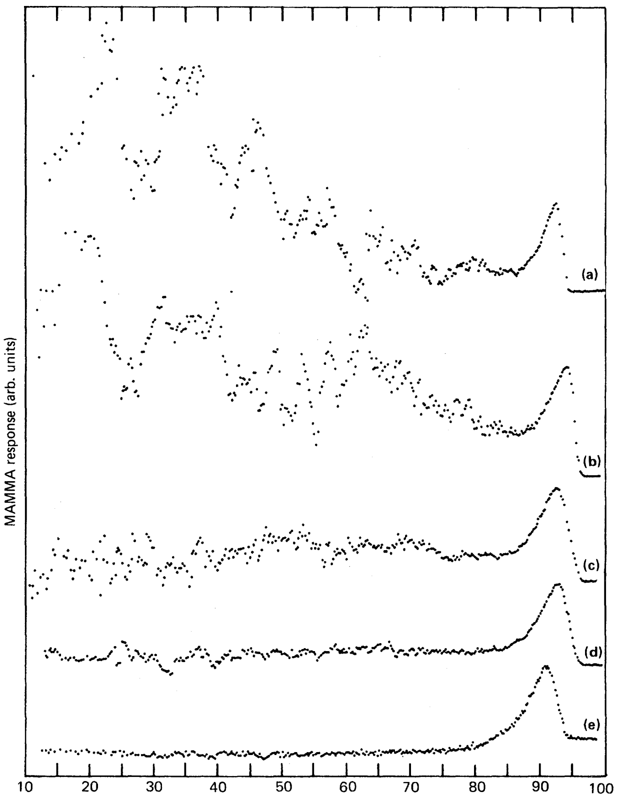

FIG. 2. MAMMA response vs temperature for Y-Ba-Cu-O powders of various particle sizes in an external magnetic field of 1 kG. The particle size S, for each curve is (a) bulk sample, (b) $425 > S > 330$ μm, (c) $S < 63$ μm, (d) $S < 38$ μm, and (e) $S < 10$ μm.

The MAMMA response spectrum in the temperature range 10–100 K and with an external magnetic field of 1 kG for a bulk sample (4.5 mg) is shown in Fig. 2(a). The peak at 94 K corresponds to the superconducting phase transition, and following which the noise rapidly increases with decreasing temperature until about 65 K after which the noise level is temperature independent. The upward displacement of the baseline with decreasing temperature is due to the low-field microwave absorption. Figures 2(b)–2(e) show corresponding results for powder samples of various particle sizes. In these measurements equal amounts of each sample and identical spectrometer operating conditions were used to facilitate comparison of the resulting spectra. Variations in T_c for the various samples are within the experimental error. The peak height in each case is proportional to the mass of sample which is in the superconducting state at temperatures below T_c. In Fig. 2(b), the particle size is bracketed between two limits, while in the remainder of the figure, an upper bound for the particle size is indicated in each case. Because the data in Fig. 2 were taken with an external magnetic field of 1 kG, the effect of particle size on the low-field peak is less pronounced. One sees, however, a marked reduction in the noise below T_c with decreasing particle size. Furthermore, and especially significant, the microwave noise observed below T_c in these samples is *temperature independent down to 10 K.* It should also be noted that the temperature scans in the experiments described in Fig. 2 required approximately 20 min each, during which time sudden changes in the noise level were not observed. Furthermore, the noise is also time independent in that abrupt changes in the noise level with time at constant temperature are not observed.

Figure 3 shows the MAMMA response with the sample in a field of 30 G for three different particle size groups and dramatically shows how absorption decreases with particle size. Again, it should be noted that the amplitude of the noise also decreases with particle size and at 10 μm, is essentially equal to the baseline noise above T_c.

These results generally support the hypothesis that the microwave noise and low-field microwave absorption in Y-Ba-Cu-O are due to intrinsic Josephson junctions. The decrease in the noise with decreasing particle size is consistent with previously discussed expectations for a Josephson junction model. Although thermally activated flux creep could have a similar particle size dependence, the observed temperature independence of the noise argues strongly against this latter mechanism. Equally significant is the decrease in the low-field microwave ab-

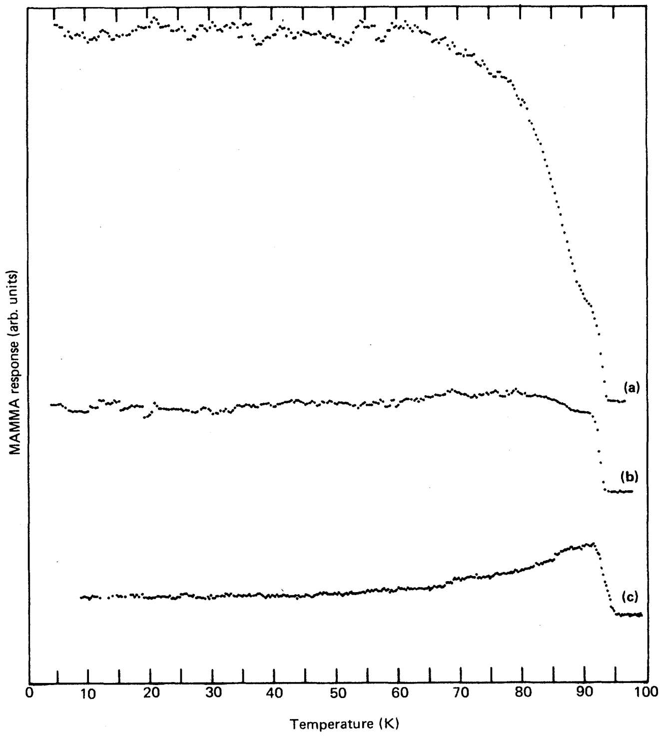

FIG. 3. MAMMA response vs temperature for Y-Ba-Cu-O powders of various particle sizes in an external magnetic field of 30 G. The particle size S for each curve is (a) $S < 63$ μm, (b) $S < 38$ μm, and (c) $S < 10$ μm.

sorption with decreasing particle size. In the likely event that the microwave noise is due to Josephson junctions then the similar particle size dependence of the low-field absorption argues for the same mechanism. In addition, it should be noted that the noise which occurs in the bulk sample is comparable to that occurring in the sample with particle sizes 330–425 μm. Consequently, if the bulk material contains clusters of Josephson junctions then the average size of such clusters should be of the order 300–400 μm. This implies that the samples with particle sizes less than this contain, on the average, a single cluster of interacting Josephson junctions, and, therefore, reducing the particle size results in a corresponding reduction in the cluster size. Assuming the noise level is proportional to the number of junctions per cluster, which in turn scales with cluster size, the microwave noise should decrease with particle size, as observed.

Finally, the average particle size for which the Josephson effects are largely eliminated (~ 10 μm according to our results) can provide information about the size of the Josephson junctions or, alternatively, the London magnetic field penetration depth λ. Josephson effects involve quantized changes in flux through the junction where the elementary flux quantum, $\phi_0 = 2\times 10^{-7}$ G cm^2, is given by the expression[15]

$$\phi_0 = 2H_{c1}^J S \cong 2H_{c1}^J d\lambda .$$

Here, H_{c1}^J is the Josephson critical field which can be much smaller than H_{c1}, and S is the area of the junction, which is approximately the product of λ and the width of the junction d, where d is less than or equal to the average particle size. Since H_{c1}^J has been experimentally determined to be roughly 10 G,[6,7] (which is consistent with our observation that the low-field microwave absorption is largest at the lowest field obtainable in our apparatus which is the 30-G residual field of the electromagnet pole faces and decreases rapidly with increasing field) an area $S \cong 1$ μm^2 is required to support a Josephson junction, which for $d = 10$ μm requires, in turn, $\lambda = 0.1$ μm or 1000 Å. This value is consistent with results of muon-spin-relaxation measurements[16] but is lower than the results from low-field magnetization measurements,[17] which differences may reflect differences in how various measurement methods respond to the magnetic field distributions within these superconductors. This estimate of the size of the Josephson junctions also agrees with results obtained from microwave measurements as a function of dc magnetic field strength.[18]

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[1] K. A. Müller, M. Takashige, and J. G. Bednorz, Phys. Rev. Lett. **58**, 1143 (1987).

[2] C. Ebner and D. Stroud, Phys. Rev. B **31**, 165 (1985).

[3] S. John and T. C. Lubensky, Phys. Rev. Lett. **55**, 1014 (1985).

[4] G. Deutscher and K. A. Müller, Phys. Rev. Lett. **59**, 1745 (1987).

[5] C. Giovannella, G. Collin, P. Rouault, and I. A. Campbell, Europhys. Lett. **4**, 109 (1987).

[6] K. W. Blazey, K. A. Müller, J. G. Bednorz, W. Berlinger, G. Amoretti, E. Buluggiu, A. Vera, and F. C. Matacotta, Phys. Rev. B **36**, 7241 (1987).

[7] K. Khachaturyan, E. R. Weber, P. Tejedor, A. Stacy, and A. M. Portis, Phys. Rev. B **36**, 8309 (1987).

[8] J. Stankowski, P. K. Kahol, N. S. Dalal, and J. S. Moodera, Phys. Rev. B **36**, 7126 (1987).

[9] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).

[10] P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962).

[11] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. **131**, 2486 (1963).

[12] S. John and T. C. Lubensky, Phys. Rev. B **34**, 4815 (1986).

[13] B. F. Kim, J. Bohandy, K. Moorjani, and F. J. Adrian, J. Appl. Phys. **63**, 2029 (1988).

[14] K. Moorjani, J. Bohandy, F. J. Adrian, B. F. Kim, R. D. Shull, C. K. Chiang, L. J. Swartzendruber, and L. H. Bennett, Phys. Rev. B **36**, 4036 (1987).

[15] P. G. de Gennes, *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966), p. 240.

[16] D. R. Harshman, G. Aeppli, E. J. Ansaldo, B. Batlogg, J. H. Brewer, J. F. Carolan, R. J. Cava, M. Celio, A. C. D. Chaklader, W. N. Hardy, S. R. Kreitzman, G. M. Luke, D. R. Noakes, and M. Senba, Phys. Rev. B **36**, 2386 (1987).

[17] J. R. Cooper, C. T. Chu, L. W. Zhou, B. Dunn, and G. Grüner, Phys. Rev. B **37**, 638 (1988).

[18] M. Perić, B. Rakvin, M. Prester, N. Brnicević, and A. Dulcic, Phys. Rev. B **37**, 522 (1988).