Differentiating AC and DC Field Effects on the Magnetic Susceptibility of Bulk $YBa_2Cu_3O_{7-\delta}$

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ABSTRACT

A low field AC magnetic susceptibility has been measured for a superconducting bulk $YBa_2Cu_3O_{7-\delta}$ sample with an AC excitation field superimposed with a DC field. The effects on the susceptibility due to either type of field have been interpreted without any assumption regarding the presence of vortices in the material. From the in-phase susceptibility data, saturation values show that increasing the AC field strength causes a decrease in shielding ability and a persistence of intergranular losses to lower temperatures. The intergranular loss peaks in the out of phase susceptibility data show shifting to lower temperature in accordance with the in-phase data. Increasing the DC field strength does not cause the saturation values to decrease, but rather, saturation values remain at the same level for the in-phase susceptibility data, showing consistency in the sample's shielding ability. However, increasing DC field strength increases the peak height for the intergranular loss peaks, but the peak does not shift to lower temperatures, thus greater energy is expended to shield the DC excitation, but without causing losses to persist to lower temperatures.

Keywords: 74.25.Ha Magnetic properties, 74.62.-c Transition temperature variations, 74.72.Bk Y-based cuprates

INTRODUCTION

AC Magnetic Susceptibility is a widely used technique in characterizing electrical and magnetic properties of superconductors. The technique has been used to study frequency or field dependence of high temperature superconductor samples to allow for improvement in the application properties of these materials and the study of the physics such as investigating irreversibility lines (Deak, 1994), critical current densities (Bertman and Strongin, 1966), granularity (Couach and Khouder, 1991) and the pseudogap (Wang et.al., 2005). The principle of AC Susceptibility measurements is given by the sample's response to an external magnetic field. The magnetization M(ωt) of a material under a time dependent (sinusoidal) field, is given by:

$$H(\omega t) = H_{DC} + H_{AC}\,Re\left[\exp(i\omega t)\right] \qquad (1)$$

which can be expressed in a Fourier expansion:

$$M(\omega t) = \chi_o H_{DC} + H_{AC}\sum_{n=1}^{\infty} Re\left[\chi_n \exp(i n\omega t)\right] \qquad (2)$$

where $\chi_0 H_{DC}$ is the DC magnetization brought about by the superimposed DC magnetic field H_{DC} while the second magnetization term is the time-varying component (Yamamoto, et.al., 1992). In order to interpret susceptibility data, several frameworks are used (Couach and Khouder, 1991) such as Eddy current-based models, BCS Theory-based interpretation and Critical State models (T. Ishida and R.B.Goldfarb,1990, Enomoto and Okada, 1996). Critical state models are most common in interpreting susceptibility for type-II superconductor, although there is no delineation between the Meissner (vortex-free) and the mixed (superconducting state with vortices forming normal cores) states (Poole, Farach and Ceswick, 1995), despite requiring low values for the applied magnetic fields. In Critical State Models, the dependence of the critical current density and the field needs to be established.

In a previous study (Sarmago and Singidas, 2004), low field AC susceptibility, without DC field, in the absence of vortices, has been explained using an eddy-current loss model. The model is an alternative means of interpreting data without having to create a field and critical current density relationship for the system. The model has been found to be applicable for several superconducting samples such as $YBa_2Cu_3O_{7-\delta}$ (Sarmago and Singidas, 2004) and MgB_2 (Sarmago and Olbinado, 2004). In this present study, we have introduced the material YBCO to a superimposed DC field. We present susceptibility measurements using the parameters of the same range (Ishida and Goldfarb, 1996, Jeffries, et al., 1989, Shinde, et al. 1990) as that used in numerous studies that have utilized critical state models in data interpretation. These studies along with others (Chen, 1991, Qin et al. 1999, Xenikos and Lemberger 1989) have shown that the magnetic response of superconducting material to a DC magnetic field is different from its response to an AC field. In most of these works, Critical State Models have been employed in interpreting results. The addition of small amplitude DC fields to this work is aimed at identifying difference in behavior of susceptibility with either type of field and whether the additional DC field can drive the superconductor out of the vortex-free state. However, results show that the field strengths used are yet insufficient to drive the material out of the vortex-free state, thus the electrodynamic model by Singidas and Sarmago has been utilized in order to interpret magnetic susceptibility data obtained in this study.

YBCO is a ceramic superconductor and when fabricated in bulk, is treated as a network of grains connected by weak links (Muller, et al. 1987). Due to this granular nature of the sample, magnetic susceptibility often shows distinct features, first being the intrinsic or intragranular response, whereby the field acts on the individual grains of the sample and second when the grains achieve coherence, the sample acts as a singular body, thus the effects on the sample are referred to as intergranular (Y.Yang, et al. 1992). Typical coupling measurements have been presented by Goldfarb, et al. (1991) identifying intragranular and intergranular responses in AC Susceptibility measurements. Intragranular response coincides with the onset of the critical temperature, and when phase-coherence (Rose-Innes and Rhoderick, 1978) is achieved, the much larger intergranular response becomes evident. When phase coherence is achieved, it is reflected in the in-phase susceptibility (χ') as a second transition in the in-phase (Aksu, et al. 2003). The out of phase susceptibility (χ") may show two loss peaks. A smaller peak appears coinciding with TC, and is this loss peak is attributed to intragranular losses, meanwhile, the larger peak appearing at lower temperature corresponds to the intergranular losses. Depending on the strength of grain coupling, the peaks may be distinctly separated or may overlap.

METHODOLOGY

The behavior of bulk superconducting $YB_2Cu_3O_{7-\delta}$ (YBCO) was investigated using a Hartshorn-type Mutual Inductance Bridge (Hartshorn, 1925), shown in Figure 1. A mutual inductance bridge is composed of identical and coaxial pickup coils which are oppositely wound, enclosed by a primary coil. The primary coil supplies the applied field and a corresponding *emf* is induced in both the two pick-up coils. Placing a magnetic sample in one of the pick-up coils introduces an imbalance in the emf, which can be detected by a lock-in amplifier. The emf responses are proportional to the magnetization and susceptibility of the sample.

An additional coil was added in order to superimpose a DC field such that the total excitation field experienced by the sample is an AC field with an offset: $B=B_{DC}+B_{AC}\cos\omega t$. The DC coil is coaxial with the MIB such that B_{DC} is parallel to B_{AC}. The range of fields have been limited such that B_{DC} (2.04mT, 1.56mT, 0.72mT, 0.24mT and 0mT) and B_{AC} (0.512mT, 0.409mT,0.307mT and 0.205mT) are around the same order of magnitude as other published results. Susceptibility measurements are obtained via a lock-in amplifier that automatically decomposes the in-phase and out of phase components of the susceptibility $\chi=\chi'+i\chi''$, χ' being the in phase and χ" being the out of phase component. The excitation frequency for all measurements is 3200Hz. Two sets of magnetic susceptibility data were gathered. The first set contains magnetic susceptibility where B_{DC} is held fixed and B_{AC} is varied (0.512, mT, 0.409mT, 0.307mT and 0.205). The second set is a measurement of magnetic susceptibility responses for when B_{AC} is fixed and B_{DC} is then varied (2.04mT, 1.56mT, 0.72mT, 0.24mT and 0mT). These two sets will distinguish the response of the material to either type of field.

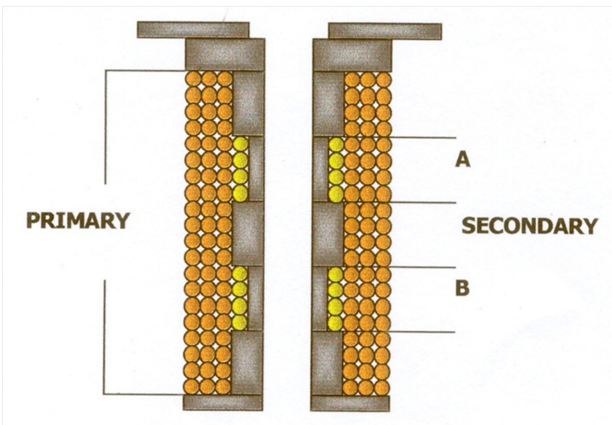

Figure 1. Hartshorn-type Mutual Inductance Bridge. An alternating current creates an alternating magnetic field through the primary coil, which induces emf across the two secondary pick-up coils A and B.

The YBCO sample was fabricated through standard solid-state reaction method for bulk sample fabrication, where powders of Y_2O_3, BaO, CuO are ground and pressed into pellets.. The resulting pellets are sintered twice at 900C and annealed in flowing oxygen. A 1mm × 1mm × 10mm bar was obtained from the produced YBCO pellet.

RESULTS AND DISCUSSION

Figure 2 shows the susceptibility of YBCO without a DC field (B_{DC}=0). The measurements were obtained still with the DC coil attached, but turned off. The in-phase susceptibility (χ') is characterized by a single transition, which broadens as B_{AC} is increased. The corresponding out-of-phase susceptibility (χ") shows a single peak reflecting intergranular losses. The absence of the intragranular loss peak indicates strong coupling in the sample, thus the in phase transition can immediately be associated to intergranular shielding. The saturation values of χ' (low temperature) decrease in magnitude as the field is increased, such that the shielding ability of the sample decreases as field strength increases. The corresponding intergranular loss peak broadens, decreases in magnitude and shifts to lower temperature as the field is increased.

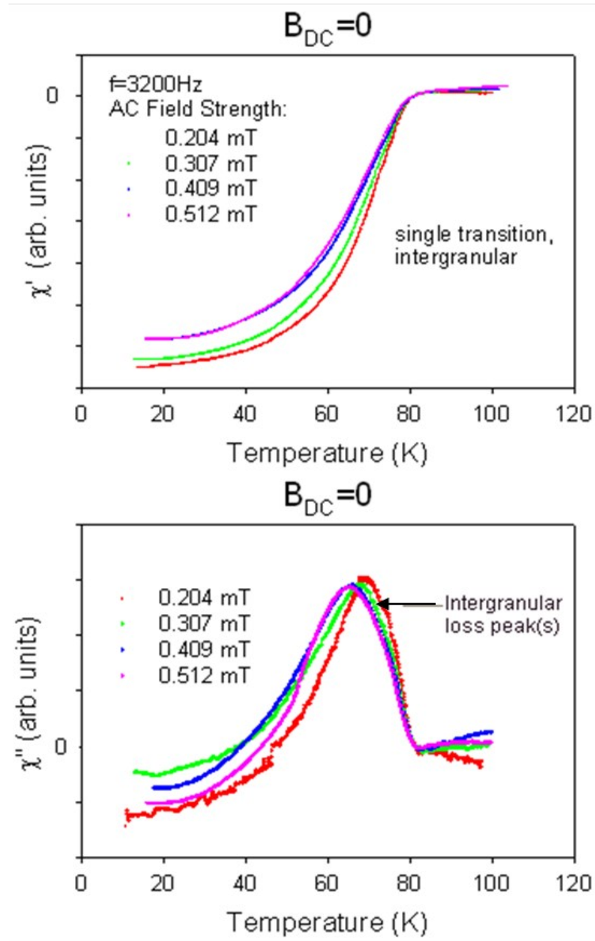

Figure 2. In phase susceptibility χ' and out of phase susceptibility χ" measured at 3200Hz. DC field is turned off and the AC field amplitude is varied from 0.512mT to 0.204mT.

Fixed DC field, Varying AC

To illustrate the effects due only to the AC field, we gathered a set of data where in the DC field is held constant, while the AC field is varied for each value of the DC field. The data is shown in Figures 3-6.

Figure 3 shows the susceptibility data for upon the addition of a DC field (B_{DC}=0.24 mT). The χ' behaves similar to the case where no DC field is applied. The transition temperature is ~81K. The single transition broadens as B_{AC} is increased. And χ” has a single loss peak which broadens, decreases in magnitude and shifts to lower temperature as the AC field is increased.

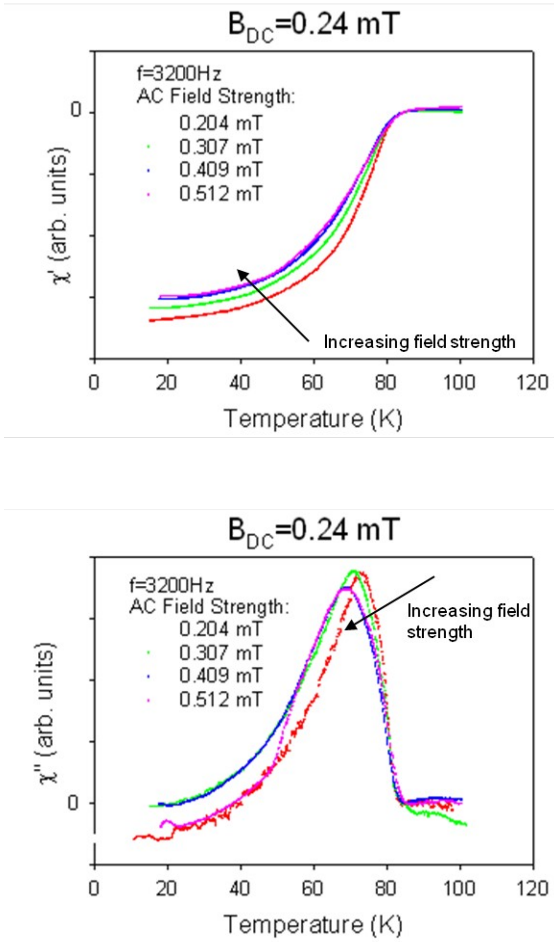

Figure 3. AC Susceptibility measurements at 3200Hz. The DC field strength is fixed at 0.24 mT while B_{AC} is varied.

Figure 4 shows the susceptibility when B_{DC} is 0.72 mT, the in phase susceptibility (χ’) is still seen to broaden as the AC field is increased. However at this DC field, the in phase response begins to show two transitions. Immediately after TC (~83K), a short temperature range of ~5-8K appears, before a second (intergranular) transition occurs. The first transition is associated with the shielding of individual grains (intragranular), and is observed to broaden slightly with increasing AC field strength. The second transition is brought about by the coupling of grains, enabling the sample to act as a single grain (intergranular). The out of phase susceptibility still displays a single loss peak which broadens, decreases in magnitude and shifts to lower temperature with increasing field.

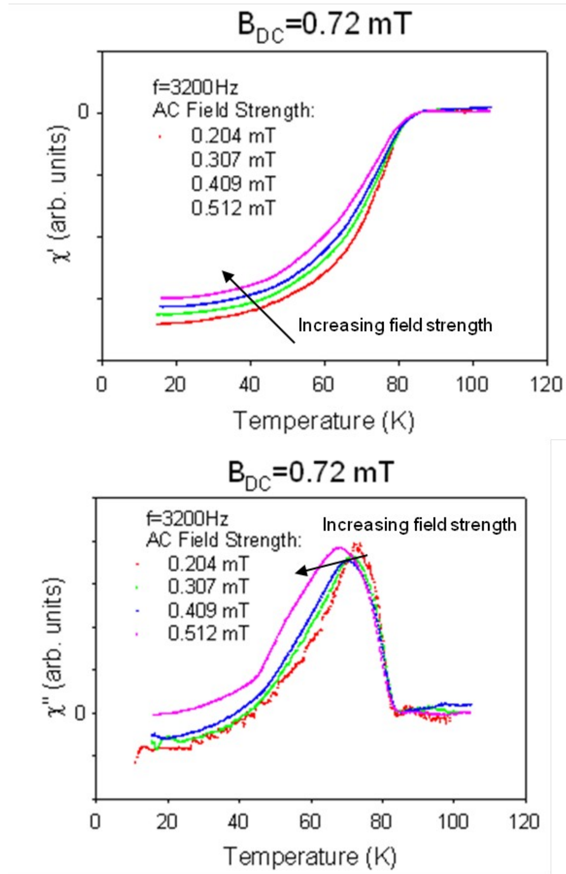

Figure 4. AC Susceptibility measurements at 3200Hz. The DC field strength is fixed at 0.72 mT while B_{AC} is varied.

Figure 5 shows the susceptibility data when B_{DC} is 1.56mT, the in phase susceptibility shows two transitions. The first transition, occurring at TC (~84K), is seen to broaden with increasing field, such that the second transition occurs at a lower temperature when the AC field is greater. The second (intergranular) transition is also seen to broaden with increasing field, as seen in the inset. The out of phase behavior is still consistent as before.

Figure 6 shows the susceptibility data at the highest B_{DC} of 2.04mT, the slopes are at their broadest in the data set. As the AC field is increased both transitions in the in-phase susceptibility broaden, and is most apparent for 0.512mT, the highest AC field. While the out of phase susceptibility again follows the trend as before of decreasing in magnitude, broadening of the peak and shifting to lower temperature as the field is increased. The second transition appears 6.5K after T_C, and slightly broadens with increasing field strength as shown in the inset.

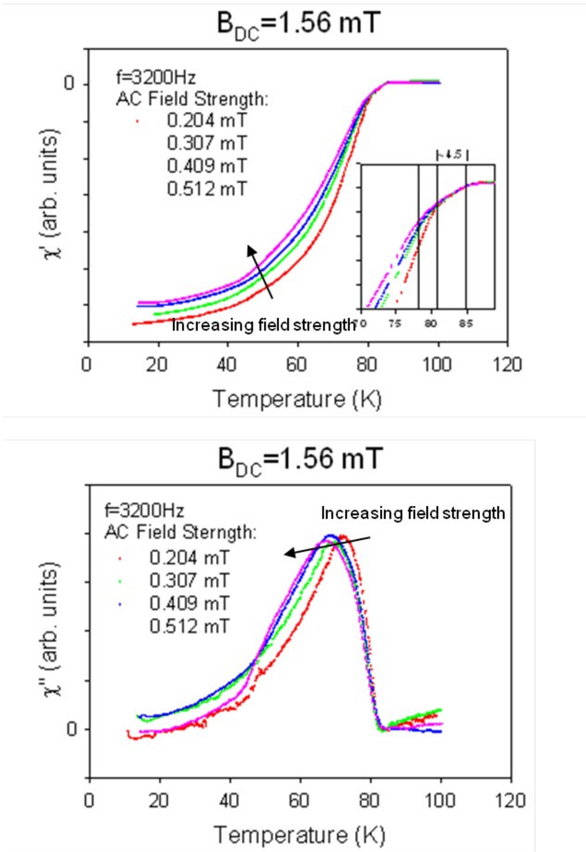

Figure 5. AC Susceptibility measurements at 3200Hz. The DC field strength is fixed at 1.56 mT while B_{AC} is varied. The inset for χ' shows a closer inspection of the transition that appears at T_C. The first transition width broadens.

For all fixed values of the DC field, it has been consistently observed that increasing the AC field strength causes the intergranular transition to broaden and the saturation values to become less negative, as seen from the in-phase susceptibility. The intergranular loss peak on the other hand, decreases in magnitude, broadens and shifts to lower temperature as the B_{AC} is increased, as seen from the out-of-phase susceptibility curves.

Fixed AC field, varying DC field

In the second data set, we focus on the behavior due to the DC field. In the same respect, the AC field is held fixed while the DC field is varied (0, 0.24mT, 0.72mT, 1.56mT and 2.04mT) for every fixed AC field value.

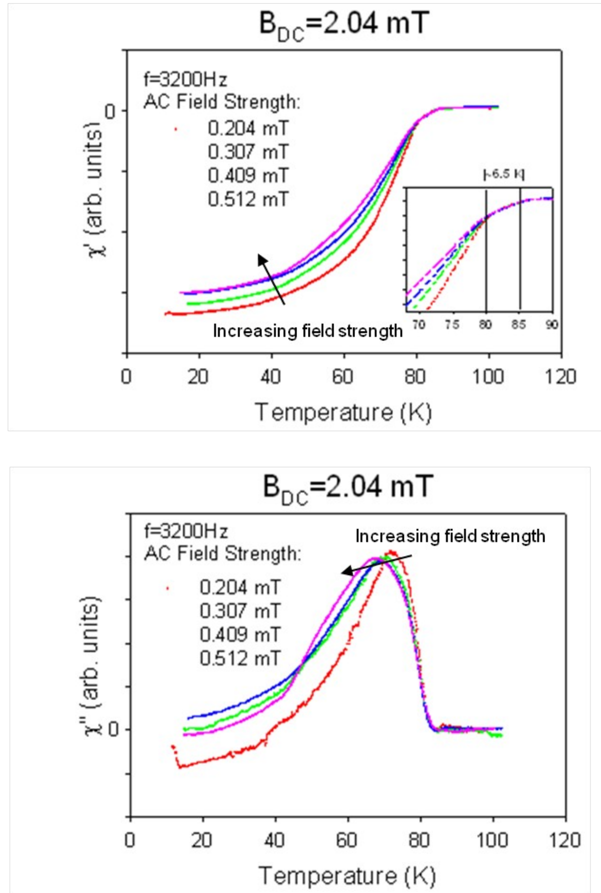

Figure 6. AC Susceptibility measurements at 3200Hz. The DC field strength is fixed at 2.04 mT while B_{AC} is varied. The inset shows a closer look at the first transition appearing near TC. The first transition width is approximately 6.5K .

Figure 7 shows the susceptibility data at B_{AC}=0.204mT. The in phase susceptibility (χ') shows two transitions for those at higher DC fields, the first transition (TC ~85K) confined in a very short temperature range. As the DC field is increased, only slight broadening is observed. The corresponding out of phase (χ") shows a single loss peak. As the DC field is increased, hardly any shifting of peaks to lower temperatures nor changes in behavior can be seen.

Figure 8 shows susceptibility data for when B_{AC} is 0.307mT. χ' shows two transitions for those at higher DC fields. Both the first (TC~84K) and second transitions broaden with increasing applied field. While the corresponding χ" has a single loss peak, showing slight broadening, but no decrease in magnitude and no shifting to lower temperature as the DC field is increased.

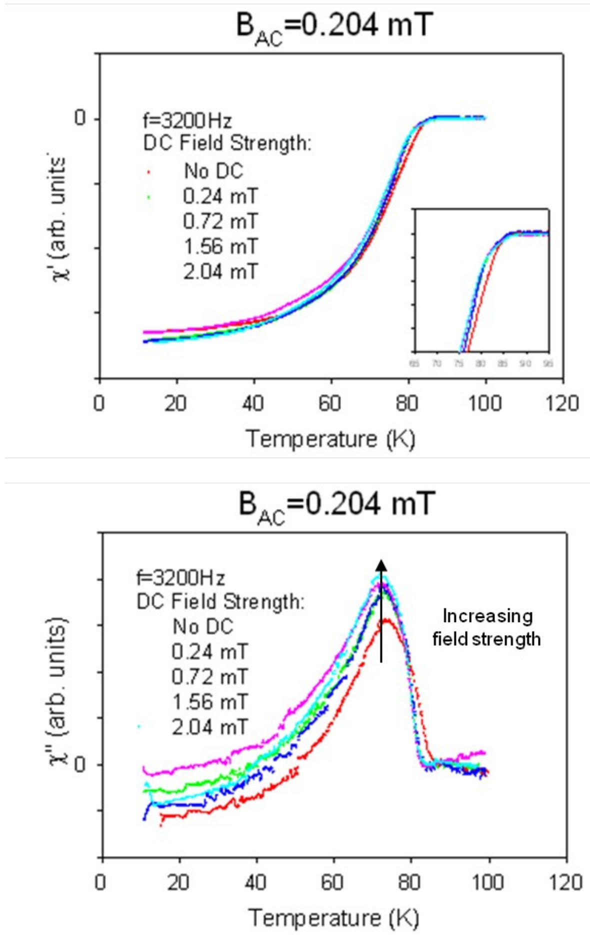

Figure 7. AC Susceptibility measurements at 3200Hz. The AC field strength is fixed at 0.2047mT while B_{DC} is varied. The inset for χ' shows two transitions for all measurements with the DC field is turned on.

Figure 9 shows the susceptibility data at B_{AC}=0.409mT. The slope of the first transition (χ', T¬C~84K) shows broadening as the DC field is increased, such that at higher DC fields, the second transition occurs at lower temperature. The second transition also broadens with increasing DC field. The intergranular loss peak (χ") on the other hand, displays slight broadening, slight decrease in magnitude but barely any shifting to lower temperature as the DC field is increased.

Figure 10 shows the susceptibility data at B_{AC}=0.512mT. The in phase susceptibility now shows two transitions for all values of the DC field. The first (TC~84K) and second transitions are seen to broaden significantly with increasing DC field. The out of phase response on the other hand shows an increase in magnitude, but no broadening and no shifting to lower temperature as the DC field is increased.

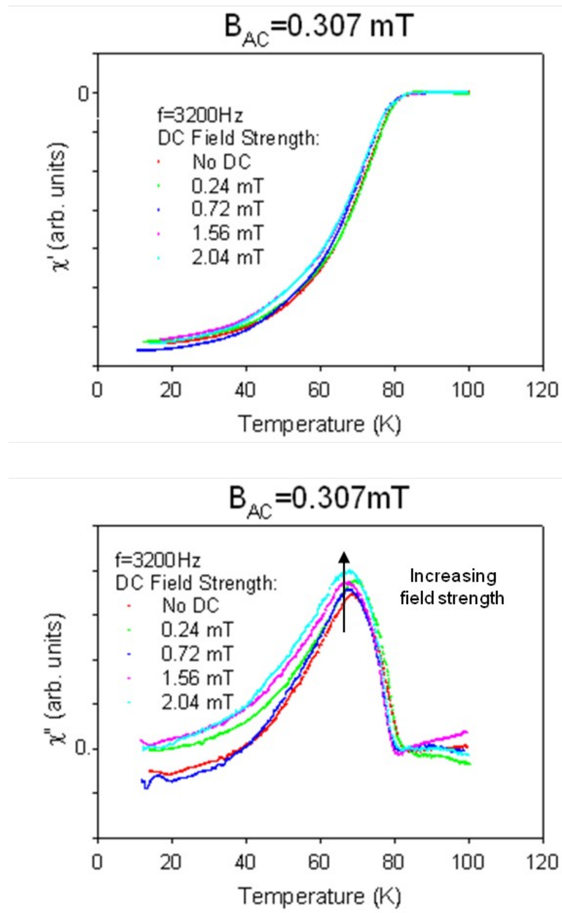

Figure 8. AC Susceptibility measurements at 3200Hz. The AC field strength is fixed at 0.307 mT while B_{DC} is varied. The χ' curves at higher DC field shows slight signs of developing an intragranular transition.

Differentiating the Effects of B_{AC} from B_{DC} on the behavior of magnetic susceptibility

The behavior of the magnetic susceptibility data with increasing B_{AC} and B_{DC} is summarized in Table1.

From the first data set (fixed DC, varying AC), we can identify the behavior of susceptibility data due to increasing the AC field. The behavior of the susceptibility when the DC field is increased can also be identified from the second data set (fixed

AC, varying DC). When increasing the AC field strength, the intergranular transition (in-phase) broadens and becomes less negative. Only when the fixed DC field is applied does the intragranular transition appear. The intragranular transition is seen to be independent of the AC field strength. On the other hand, increasing the AC field strength causes the intergranular loss peak (out-of-phase) to decrease in height, broaden and shift to lower temperature. This behavior is consistent with the observed behavior of the intergranular loss peak in other studies (Ishida and Goldfarb, 1990, Sarmago and Singidas, 2004, Shinde, et al., 1990). From this observation, it appears that the phase coherence between order parameters of individual grains is affected by the amplitude of the applied magnetic field.

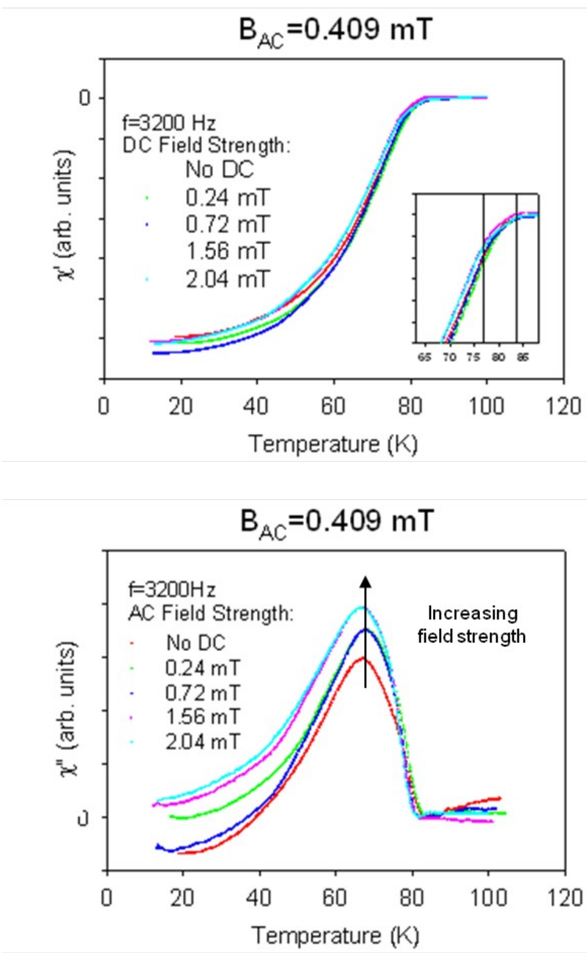

Figure 9. AC Susceptibility measurements at 3200Hz. The AC field strength is fixed at 0.409 mT while B_{DC} is varied. The inset for χ' shows two transitions for susceptibility measurements obtained for B_{DC}>=1.56mT

When the DC field is varied, the susceptibility data behaves differently. As DC field strength is increased, the intergranular transition (in-phase) does not broaden significantly and the saturation values do not become less negative. Increasing the DC field strength causes an increase in height and broadening, but no shifting to lower temperature of the intergranular loss peak (out-of-phase). The lack of sensitivity of the intergranular loss peak to the DC field has also been observed in other studies (Couach and Khoder, 1991)

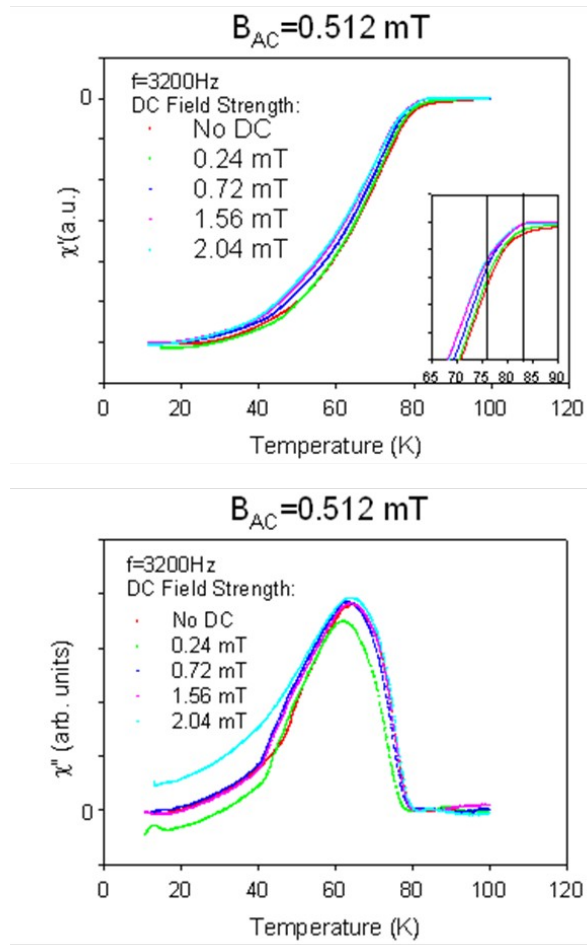

Figure 10. AC Susceptibility measurements at 3200Hz. The AC field strength is fixed at 0.512 mT while B_{DC} is varied. The inset for χ' shows two transitions for measurements done at B_{DC}>=0.72mT.

The decrease in saturation values in the in-phase susceptibility reflects the material's decreased ability in expelling the applied magnetic field. Increasing the AC field strength reduces the material's ability to shield its interior. Increasing the DC field strength however does not cause the same effect. Essentially superimposing a DC field

Table 1. Susceptibility behavior with increasing DC and AC fields

	In Phase (χ')	***Out of Phase (χ'')***
Increasing AC Field Strength (Constant DC Field)	-intergranular transition broadens -saturation values decrease	-peak height decreases -FWHM increases -Peak moves to lower temperature
Increasing DC Field Strength (Constant AC Field)	-intragranular transition widens in temperature -intergranular transition broadens (slightly) -saturation values are constant	-peak height increases -FWHM slightly increases -Movement of peak to lower temperature less significant

introduces an offset in the applied field and the sample is still able to shield its interior by the same amount despite the range of DC field strength values applied. The corresponding out-of-phase reflects the material's losses incurred during the transition from normal to superconducting. Increasing the AC field strength causes the intergranular losses to persist into lower temperatures. The material loses energy to expel the field even at the lower temperatures. Other studies (Couach and Khoder, 1991) have postulated that as B_{AC} increases, shielding breaks down when the induced currents needed to shield out B_{AC} exceeds the critical currents of the intergranular weak links. The field thus penetrates more of the volume of the sample. The currents induced in the grains contribute to the dissipation. Eddy currents travel through the surface of the material, shielding the interior. When eddy currents traverse through the normal surface material, it crosses grain boundaries when it achieves sufficient phase coherence. The weak links (provided by the grain boundaries) act as resistance encountered by the eddy current. Increased resistance translates to increased heating in the material (Quirion, et al. 2004). Increasing the DC field strength on the other hand, increases the intergranular loss peak. Although the energy loss increases, the intergranular loss peak does not persist to lower temperature. This and the saturation values that have no dependence on DC field strength, show that the material utilizes more energy to expel the DC field, but is able to shield its interior by the same amount.

However, using the range of fields used in this study, the effects caused by the AC and DC fields have shown no concrete delineation between the Meissner and Mixed States. An eddy current model may be best suited to interpret the data presented. The behavior of the intergranular transitions and loss peaks are gradual. Previous studies (Singidas and Sarmago, 2004, Torralba and Sarmago, 2004 Olbinado and Sarmago, 2004) have utilized an eddy-current based model for YBCO, without a superimposed DC field. The eddy current model previously proposed (Sarmago and Singidas, 2004) has been successful in explaining the behavior of the susceptibility in the absence of vortices. The addition of the DC field in this experiment has not deviated from the predictions of the model. This suggests that for this range of fields, it is not necessary that vortices be assumed present and that an electromagnetic framework is sufficient in explaining susceptibility behavior.

CONCLUSION

AC Suceptibility data gathered for a YBCO sample shows that when the DC excitation field is fixed, increasing the AC field strength causes the in phase susceptibility saturation values to decrease. The in-phase susceptibility reflects the sample's ability to shield its interior from the excitation field, at larger fields, greater area of the sample is penetrated. Meanwhile, the out of phase susceptibility reveals that the intergranular loss peak broadens, decreases in peak height and shifts to lower temperature. The out of phase susceptibility reflects the sample's losses incurred in shielding its interior. Increasing the AC field strength causes losses to persist to lower temperature.

However, when the DC field strength is varied and the AC field strength is fixed, susceptibility data behaves differently. The in-phase susceptibility shows constant saturation values, indicating that the sample is able to shield the same amount of material from the total excitation field, despite increasing the

DC field strength. The out of phase susceptibility data show that the intergranular loss peak increases in peak height, maintains its width and shows no shifting to lower temperatures. This indicates that energy needed to shield the sample by the same amount increases. The increase in field strength does not cause losses to persist to lower temperature.

It is recommended that an electromagnetic (eddy current based) framework be utilized in order to gain more insight in the mechanism by which AC field strength effects differ from DC field strength effects.

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