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ANOMALOUS TEMPERATURE DEPENDENCE OF Cu NMR LINE WIDTH AND MAGNETIZATION IN YBa$_2$Cu$_3$O$_{7-\delta}$

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We report an anomalous temperature dependence of the magnetization and the NMR line width at the planar Cu(2) and oxygen sites in the mixed state of aligned YBa$_2$Cu$_3$O$_{7-\delta}$ powder at relatively high field ($\geq$ 30 kOe), where hysteresis of the magnetization due to flux pinning is not important. Both the magnetization and the NMR line width at all sites show a steep increase at low temperature. We found a much larger line width at Cu(2) sites than at oxygen sites when the magnetic field is applied perpendicular to the c-axis, indicating a very microscopic local field modulation.

In this paper we report an anomalous temperature dependence of the planar Cu NMR line width in the superconducting mixed state of aligned powder of YBa$_2$Cu$_3$O$_{7-\delta}$ (T$_c \approx$ 93 K), which seems to be closely related to the peculiar temperature dependence of the bulk magnetization found at relatively high field ($\geq$ 30 kOe). In order to compare Cu and O NMR line widths, we used the same ^{17}O enriched sample that was used for ^{17}O Knight shift measurements.[1] The powder was imbedded in epoxy and cured in a 42 kOe magnetic field to achieve alignment of the c-axis along the field.

Fig. 1 shows the ^{63}Cu central transition NMR spectra at the planar Cu(2) sites with the magnetic field applied perpendicular to the c-axis at several temperatures. These spectra were obtained at a fixed NMR frequency by sweeping (increasing) the magnetic field. The peak position is shifting to higher field, corresponding to a decrease of the Knight shift, as the temperature drops. This result agrees with our previous results.[2] The full width at half maximum (ΔH) is increasing below T$_c$, indicating an inhomogeneous distribution of the local field.

Generally there are three sources for the NMR

line broadening in the mixed state. First, the vortex lattice produces a distribution of the local field whose second moment is given as[3] $\langle \delta H^2 \rangle^{1/2} = \Psi_o / \lambda_L^2 (16\pi^3)^{1/2}$ in the field range H$_{c1} \ll$ H $\ll$ H$_{c2}$, where Ψ_o is the flux quantum and λ_L is the penetration depth. Second, the demagnetizing field is different from grain to grain and not uniform in a single grain. The equilibrium magnetization in the same field range can be expressed[4]

$$4\pi M_e = H_{c1} \frac{\ln (H_{c2}/B)}{\ln \kappa} = \frac{\Psi_o}{4\pi\lambda_L^2} \ln(H_{c2}/B) , \quad (1)$$

where κ is the Ginzburg-Landau parameter. $4\pi M_e$
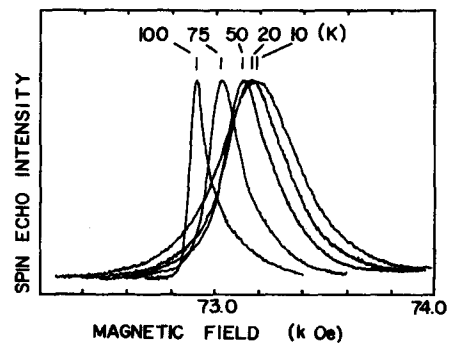

Figure 1. ^{63}Cu NMR spectra at the Cu(2) sites at different temperatures with magnetic field applied perpendicular to the c-axis. The peak positions are indicated by vertical bars.
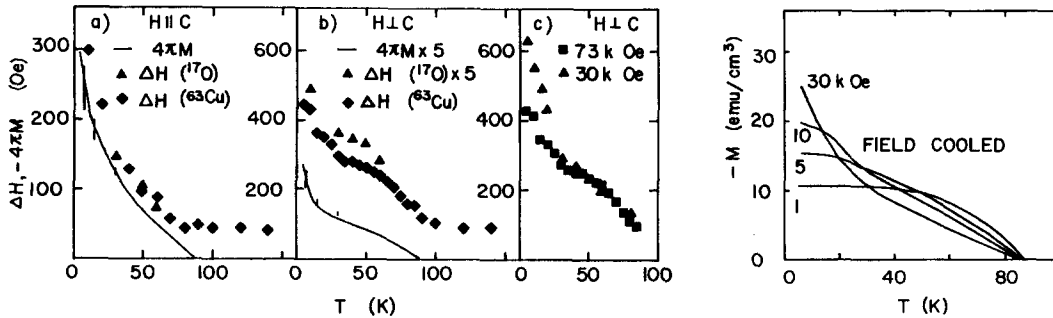
Figure 2. a), b): Temperature dependence of 4πM (warming at 50 kOe after zero field cooling to 5K), ΔH at Cu(2) and oxygen sites for two field directions. ΔH was measured at 73 kOe for Cu(2) and 69 kOe for oxygen. Vertical bars show hysteresis of 4πM at 45 kOe. c) Temperature dependence of ΔH$_{sup}$ at Cu(2) sites at diferrent fields. d) Temperature and field dependence of magnetization measured with increasing temperature.

has the same temperature dependence as ⟨δH⟩$^{1/2}$ and is larger by a factor $\sqrt{\pi}$ ln(H$_{c2}$/B). Third, when the external field is swept, vortex density gradients caused by flux pinning produce field a distribution. However, this effect is expected to be small in the present case because the hysteresis of the magnetization is small at high field (≥ 40 kOe). These general considerations lead to the prediction that NMR line widths due to shielding currents will be the same at all sites and have the same temperature dependence and similar magnitude as 4πM$_e$.

Fig. 2 a) and b) show the temperature dependences of 4πM and ΔH at the Cu(2) and oxygen sites for two field directions. ΔH for oxygen is obtained from the central transition spectra in which inequivalent oxygen sites are not resolved below about 70 K. We wish to point out several anomalous features of these data:

1) The magnetization at 50 kOe shows a steep increase at low temperatures (≤ 20 K) for both field directions. This is very peculiar since a much weaker temperature dependence is expected from eq. (1). This is observed only at high field (≥10 kOe) as shown in Fig. 2 d). The hysteresis of M is quite small at such fields (Fig. 2 a) and b)). Therefore, the rapid low temperature increase of M must be characteristic

of the thermal equilibrium magnetization.

2) For H ∥ c, ΔH at both Cu(2) and oxygen sites show similar temperature dependences and magnitudes as 4πM. Most surprisingly, ΔH at Cu(2) sites for H⊥c is larger than that for H ∥ c and is almost an order of magnitude larger than 4πM and ΔH at oxygen sites, indicating a huge microscopic field distribution within an interatomic distance. However, the temperature dependence is similar to that of the magnetization.

3) ΔH at Cu(2) starts to increase at T$_c$, clearly indicating that the line broadening is related to superconductivity. In Fig. 2 c), we plot the temperature dependence of ΔH$_{sup}$, the field distribution due to supercurrents obtained from the relation ΔH^2 = ΔH$_{norm}$^{2} + ΔH$_{sup}$^{2}, where ΔH$_{norm}$ is the line width at 100 K. ΔH$_{sup}$ decreases with increasing field below 30 K. This field dependence is again consistent with that of the magnetization and cannot be accounted for by magnetic impurities or quadrupolar effects.

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