NMR Lineshape in the Vortex Lattice State of Near-Optimally Doped $YBa_2Cu_3O_{7-\delta}$

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Abstract

NMR measurements of the linewidth of planar ^{17}O in near-optimally doped $YBa_2Cu_3O_{7-\delta}$ (YBCO) in the vortex lattice state are reported. We find that the lineshape, *i.e.* magnetic field probability distribution, is much broader than what is expected based on the calculated distribution arising from the vortex supercurrents. We can qualitatively account for this anomalously large NMR linewidth measured at low temperatures by postulating that the broadening is caused by antiferromagnetism in the vortex core.

Key words: Vortex Lattice; Antiferromagnetism in the Vortex Core; $YBa_2Cu_3O_7$

1. Introduction

The magnetic field penetrates a strong type II superconductor in the form of quantized flux lines which tend to form a regular lattice resulting in a spatial distribution of magnetic fields, reflected in the NMR spectrum. Consequently, one can obtain information about the nuclei spatially located at well-defined distances from the vortex center as was recently demonstrated by NMR measurements of Mitrović *et al.*[2,1] and Kakuyanagi *et al.*[3] and μSR lineshape measurements of Miller *et al.*[4].

In our previous work we reported on spatially-resolved measurements of the nuclear spin-lattice relaxation rate, $1/T_1$, in the mixed state [2,1]. We found that both magnetic field and temperature dependences of $(^{17}T_1T)^{-1}$ exibit different behaviour in two different regions of the NMR spectrum, which we identify as regions inside and outside of the vortex core. Furthermore, we associate the observed temperature dependence of $(^{17}T_1T)^{-1}$ in the vortex core with antiferromagnetic (AF) spin fluctuations. It is interesting to question whether, along with AF spin fluctuations, static AF order can be induced in the vortex core. To try answering this question we quantitatively examine the NMR lineshape measured in the vortex lattice state.

2. NMR Lineshape Arising from Vortex Supercurrents

We calculated the spectra using Brandt's algorithm [5], convoluted with the the normal state spectrum to get a realistic assessment of what might be expected under ideal circumstances with no AF interactions. The result is compared to the measured spectrum in Fig. 1, where we find that the measured spectra are more then a factor of two broader then the convoluted spectra at T = 11 K. This is surprising since these calculations can account for the spectra measured on single crystals of YBCO by μSR [6] and an aligned powder of optimally doped YBCO by ^{89}Y NMR [7]. We will attempt to account for the excessive broadening of the ^{17}O NMR spectra but first we discuss some of the constraints on possible broadening mechanisms. The measured spectra are broadened asymmetrically,

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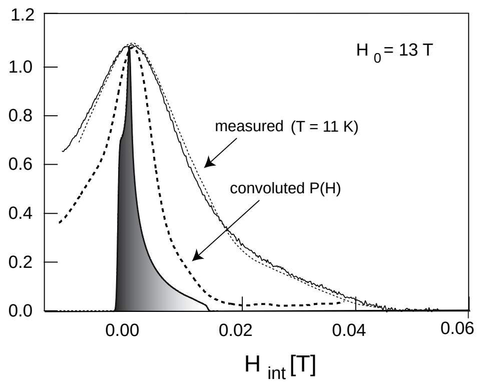

Fig. 1. Comparison between the calculated vortex lattice lineshape (for a 80° lattice with a penetration depth of $\lambda = 1500$ Å) and the measured spectrum at 11 K. The dashed curve is the normal state spectra convoluted with the calculated vortex lattice lineshape (shaded in gray), at $H_0 = 13$ T. The measured $(-\frac{1}{2} \leftrightarrow -\frac{3}{2})$ transition spectra, obtained by subtracting the $(-\frac{3}{2} \leftrightarrow -\frac{5}{2})$ transition spectra, at 11 K are shown. $H_{int} = \omega / {}^{17}\gamma - H_0$ where ${}^{17}\gamma$ is the gyromagnetic ratio for oxygen and the spectrometer frequency, ω, is set to resonance at the peak frequency. The light dotted line is calculated from our proposed model agreeing well with the measured spectrum.

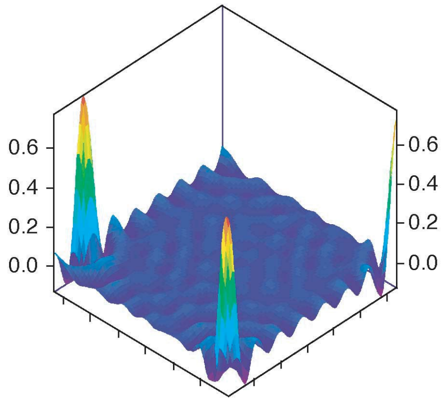

Fig. 2. Distributions of the local magnetic field in real space, in units of Tesla, from antiferromagnetic cores for the vortex lattice with $\alpha = 80°$ at $H_0 = 13$ T. The peaks are the vortex cores.

which excludes the possibility of impurity broadening as the dominant mechanism. Disorder of the vortex lattice as discussed by Brandt [8] is not nearly sufficient to account for the anomalous broadening. The mechanism must preserve the average field since the first moment of the measured lineshape is consistent with the calculation. To be compatible with the μSR and ^{89}Y NMR results, we require that the extra broadening of ^{17}O NMR be caused by local magnetic fields generated by interactions involving the conduction electrons, to which μSR and ^{89}Y NMR are not as sensitive as compared with NMR of planar ^{17}O. We propose a simple model where the field gradients are caused by antiferromagnetism induced in the vortex cores coupled to ^{17}O via hyperfine interactions with electrons on the Fermi surface.

3. NMR Lineshape Broadening by Antiferromagnetic Vortex Cores

We assume that antiferromagetism in the vortex core leads to a net magnetic moment localized near the center of the core which can act similar to an impurity polarizing the environment via the spin-susceptibility. In the latter case, the polarization partially screens the magnetic moment at the impurity site as a result of which the nearby copper atoms can develop magnetic moments. We consider the extra magnetic moment as a perturbation and calculate[9] the induced local magnetic field around it via the spin susceptibility, which is peaked around $\mathbf{q} = (\pi, \pi)$, reflecting the AF behavior.

In Fig. 2 we show the real space distribution of the local field from AF cores from which the corresponding field probability distribution is then calculated. To obtain the total lineshape we calculate, at each point of the vortex lattice unit cell, the local field arising from the supercurrents outside the cores and the local field from the AF vortex cores. We assume that we can simply add these two fields. The resulting field distribution is then convoluted with an intrinsic normal state lineshape to give the total NMR lineshape in the vortex state. The calculation agrees with the observed spectra shown in Fig. 1, adjusting only the strength of the effective moment to be $\approx 1\mu_B$.

In summary, we can account for the the low temperature NMR spectrum of the planar ^{17}O by considering that the spectra arise from supercurrents outside the core and a local field from a static moment in the vortex core.

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