Field (Direction) Dependence of AF Magnetism in YBCO Vortex States: a MaxEnt-µSR study

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Abstract. Muon-spin-resonance (µSR) data of YBa₂Cu₃O₇₋δ (YBCO) vortex states are analyzed to determine the field dependence of observed antiferromagnetism (AF). YBCO vortex states are investigated at low magnetic fields. Field distributions are obtained from µSR data using Maximum-Entropy (ME) analysis. Well below T_c, the vortex signal in the magnetic field distribution is best fitted by a Lorentzian, indicating AF in and near the vortex cores. Earlier we reported that the field dependence of the YBCO AF Lorentzian width is approximately linear. ME-µSR analysis of c-axis-oriented YBCO data indicates a field-direction dependence, suggesting three-dimensional AF. The relevance of an AF presence in and near YBCO vortex cores to a potential magnetic origin of cuprate superconductivity is discussed.

1. Introduction
The understanding of magnetism in cuprate superconductors is still developing. Observed antiferromagnetism (AF) in YBa₂Cu₃O₇₋δ (YBCO) vortex states would support theories indicating a magnetic origin of high-T_c superconductivity. [1] Our ME-µSR studies have indicated evidence of AF in and around these vortex cores below half T_c. [2-4] Earlier [2] we found a positive linear correlation of the AF Lorentzian width with applied field. A muon-spin-resonance (µSR) study has revealed magnetic anisotropy in YBCO. [5] In this AF-vortex investigation, we address the AF field-direction dependence.

The original µSR study [5] of c-axis-oriented YBCO was performed using curve fitting (CF) and Fourier transformation (FT). Using maximum entropy (ME), we analyze these µSR vortex data to further study the field-direction dependence of AF in the YBCO vortex state. ME-µSR analysis has produced more reliable field-distribution results than CF&FT [6] since the ME-Burg algorithm can partly remove Poisson noise without any (FT) truncation effects. We address the question if AF is observed in and near the vortex cores in c-axis-oriented YBCO, and investigate its field-direction dependence. Our results to date show contradictions to the original CF&FT analysis. [5]

2. YBCO sample characterization
The sample used for data collection at LAMPF is a disk of c-axis-oriented YBCO powder embedded in epoxy. This disk has been prepared at Case Western Reserve using their magnetic alignment technique. [7] The resulting c-axis alignment is within one degree, with reasonable isolation of
individual grains due to the volume packing ratio of 20% YBCO. All data are taken on the same YBCO sample ($T_c = 92$ K) at 5 K with a 5-kOe transverse field. The three data sets have c-axis orientations perpendicular, parallel, and at a 60° angle ($\theta$) to the applied field. [5]

3. YBCO ME-µSR analysis and results

The YBCO vortex data are analyzed by using a Gaussian filter to give more statistical weight to earlier times. To maximize the vortex signal to the grainboundary (GB)/epoxy signal [5,6] ratio, a 1-µs filter time ($T_f$) appears to be optimal. Due to the large overlap between the vortex and GB/epoxy signals, we filter out as much of the long-lived GB/epoxy signal as possible.

Figure 1. ME-µSR transforms for YBCO vortex data recorded at 5 K with the c-axis oriented parallel, 60 degrees with, and perpendicular to, the applied field of 5 kOe. $T_f = 1$ µsec. The GB/epoxy peak is at about 67.1 MHz. The overall asymmetric nature reflects vortex signal behavior. The lines through the data are guides to the eye. Clearly, a field-direction dependence can be seen.

ME-Burg analysis is used to determine the frequency distribution of the µSR signal. The GB/epoxy peak significantly overlaps the high frequency side of the vortex peak. In the obtained ME-µSR transforms [Fig 1] the vortex peak is not distinguishable from the reduced GB/epoxy peak. Several fits of the ME-µSR transforms have been performed. A Lorentzian for the vortex peak with a Gaussian for the GB/epoxy peak (LG) fits better than (a single Gaussian or) two Gaussians (GG) in the perpendicular [Fig 2] and parallel orientations. See Tables 1 and 2. The average $\chi^2(GG)/\chi^2(LG)$ for these two orientations is 2.3. This average matches that previously reported for Bi2212 and Tl2223 below 0.4 $T_c$ [3] and supports AF in and beyond the vortex cores. For the 60° c-axis orientation, the $\chi^2(GG)/\chi^2(LG)$ is 0.85 suggesting the GG fits slightly better than the LG fit.

In the LG fit, the average Gaussian relaxation rate ($\sigma = 0.20(2)$ MHz) for the GB/epoxy signal is equal (within error) to $\sigma$ of the blank epoxy sample at 5 K, and to the reported CF muon-spin-
relaxation rate of the blank epoxy signal. [5] The Gaussian $\sigma$’s in the GG fits are ~30% smaller than expected.

The LG and GG fit parameters for the Lorentzian and Gaussian signals are reported in Tables 1 and 2. We do not see the same trend in our vortex signal width ($\kappa$) as Lichti et al reported for their CF relaxation rates, yet we observe similar frequency behavior. [5] Notably, the $\kappa$’s for the perpendicular and parallel orientations are about equal. The $\kappa$ ($\theta = 60^\circ$) is about a factor of two smaller than for the $0^\circ$ and $90^\circ$ c-axis orientations. Note that in these fits, the amplitude $A_L$ and Lorentzian width $\kappa$ are highly correlated, so caution should be taken.

Table 1. Lorentzian and Gaussian (LG) fit results for ME-µSR transforms of YBCO 5K vortex data for three orientations of the c-axis with the field at 5 kOe. The $\chi^2$ for the three LG fits reflects the goodness of fit.

| $\theta$ (B, c) | $A_L$  | $\kappa$ [MHz] | $f_L$ [MHz] | $A_G$ | $\sigma$ [MHz] | $f_G$ [MHz] | $\chi^2$ 10$^2$ |
|----------------|--------|----------------|-------------|-------|----------------|-------------|-------------|
| 0$^\circ$      | 0.16(1)| 0.45(4)        | 66.62(5)    | 0.76(4)| 0.18(1)        | 67.06(1)    | 0.42        |
| 90$^\circ$     | 0.19(1)| 0.43(1)        | 66.81(2)    | 0.80(2)| 0.19(1)        | 67.12(1)    | 0.04        |
| 60$^\circ$     | 0.15(1)| 0.23(2)        | 66.59(2)    | 0.98(2)| 0.23(1)        | 67.06(1)    | 0.27        |

Table 2. Two-Gaussian (GG) fit results for ME-µSR transforms of YBCO 5K vortex data for three orientations of the c-axis with the field at 5 kOe. The $\chi^2$ for the three GG fits reflects the goodness of fit.

| $\theta$ (B, c) | $A_{G1}$ | $\sigma_1$ [MHz] | $f_{G1}$ [MHz] | $A_{G2}$ | $\sigma_2$ [MHz] | $f_{G2}$ [MHz] | $\chi^2$ 10$^2$ |
|----------------|----------|-------------------|----------------|----------|-------------------|----------------|-------------|
| 0$^\circ$      | 0.14(1)  | 0.70(2)           | 66.64(6)      | 0.28(2)  | 0.13(1)           | 67.06(1)      | 0.59        |
| 90$^\circ$     | 0.14(1)  | 0.69(2)           | 66.81(2)      | 0.32(1)  | 0.14(2)           | 67.10(1)      | 0.14        |
| 60$^\circ$     | 0.17(3)  | 0.51(2)           | 66.66(9)      | 0.36(5)  | 0.15(1)           | 67.10(2)      | 0.23        |

4. Discussion and conclusive remarks
For the parallel and perpendicular c-axis orientations, we confirm that a Lorentzian fits the vortex signal better than a Gaussian. The 60$^\circ$ c-axis orientation is close. Overall, the LG fits better than the GG fit by a factor of 1.9(8). Thus, our results are consistent with earlier studies [2-4] where AF magnetism in and near cuprate vortex cores is found. Clearly we observe a field-direction dependence (Fig 1). Our earlier study [2] has shown a positive linear correlation with applied field.
Our ME-µSR analyses should be repeated with a higher frequency resolution. Note, in Fig 1 the 60° and 90° c-axis orientation overall signals look similar. Here, the frequency resolution is four times the one used for the fits. A more complete ME-µSR analysis would include fitting the GB/epoxy signal in time space and then subtracting this signal from the histograms before applying the ME transformation. [2]

Our YBCO µSR analysis thus far does not completely match the findings of Lichti et al. [5] This is partly due to substantial differences in data analysis technique: CF vs ME-µSR. The likely existence of a low field tail [6] contributes to a systematic error in CF analysis. [2] Examination of Fig 1 at frequencies below 66 MHz indicates the low field tail is the strongest for the c-axis parallel to the applied field. The induced supercurrents create fields parallel to the c-axis, reducing and broadening the local fields at the muon sites. This broadening will substantially increase the effective muon-spin-relaxation rate in timefits.

Lake et al [8] have performed a dimensionality study of the field-induced magnetism in LSCO superconductor using neutron diffraction. Their setup accommodates orientations of the magnetic field with the CuO$_2$ planes. [8] The field-induced AF is shown to be of a three-dimensional nature [8] consistent with our field-direction dependence of AF magnetism in YBCO vortex states. Consideration should be given to the possible temperature dependence of the vortex-core charge in cuprate superconductors. [9] If indeed the vortex cores are negatively charged, the µ will preferentially probe in and near the vortex cores, and thus be more sensitive to the AF probing in the vortex state. Another effect to be considered are the supercurrents in the CuO-chain layers below 25 K. [6, 10] These supercurrents, which appear to produce the low field tail, may lead to field-induced three-dimensional AF.

We conclude that AF is most likely present in the vortex states of c-axis oriented YBCO. A field-direction dependence is observed. The AF related to the cuprate vortex cores appears to be three-dimensional. Our low field YBCO ME-µSR study confirms that AF must be also present outside the vortex cores, consistent with the LaBCO neutron results. [8] The AF seen in and near the YBCO vortex cores supports theories [1] substantiating a magnetic origin of cuprate superconductivity.

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