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Vortex lattice disorder in $YBa_2Cu_3O_{7-\delta}$ studied with β-NMR

H. Saadaoui [a,*], W.A. MacFarlane [b], G.D. Morris [c], Z. Salman [c], K.H. Chow [d], I. Fan [d], M.D. Hossain [a], R. Liang [a,e], A.I. Mansour [d], T.J. Parolin [b], M. Smadella [a], Q. Song [a], D. Wang [a], R.F. Kiefl [a,c,e]

[a] Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
[b] Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
[c] TRIUMF, Wesbrook Mall 4004, Vancouver, British Columbia, Canada V6T 2A3
[d] Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2G7
[e] Canadian Institute for Advanced Research, 180 Dundas Street West, Toronto, Ontario, Canada M5G 1Z8

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A B S T R A C T

In this paper, we report $^8Li^+$ β-NMR measurements in thin Ag films deposited on the surface of $YBa_2Cu_3O_{7-\delta}$ (YBCO) in the vortex state. The resonance in the Ag overlayer broadens dramatically below the superconducting transition temperature T_c, as expected from the underlying vortex lattice in the YBCO. However, the lineshape is much broader and more symmetric than expected for an ideal vortex lattice. These results indicate the observed field distribution in the Ag overlayer is dominated by extrinsic, long length scale disorder.

1. Introduction

The vortex state in high temperature superconductors (HTSC) has been a subject of intense investigation in the field of superconductivity [1,2]. In a perfect vortex lattice (VL) the internal field distribution $p(B)$ is a sensitive measure of both fundamental length scales, the London penetration depth (λ) and the coherence length (ξ) [3], as well as the unusual magnetic properties of the vortex cores [4,5]. There is also considerable interest in the structure and dynamics of the VL and how these may be connected to the anisotropic pairing and underlying crystal structure. However, structural defects are present in all superconductors, and these affect the arrangement of vortices and the resulting $p(B)$ [6], adding uncertainty to measurements of fundamental quantities like λ and ξ, since it is difficult to isolate extrinsic effects. It is also important for applications to understand the connection between the VL and the underlying crystalline structural imperfections since pinning of vortices determines critical current densities. Measurements of $p(B)$ in the vortex state are done using a variety of methods [7]. Until now, only low-energy muon-spin rotation (LE-μSR) has had the capability to measure $p(B)$ in a depth-resolved manner both above and below the surface [8]. However, LE-μSR is currently limited to relatively low magnetic fields. Recently we have shown that β-detected NMR (β-NMR) can also be used to measure $p(B)$ near the surface over depths of the order of few nm up to 500 nm [9–11]. Furthermore, β-NMR can be applied in high magnetic fields where the effects from disorder can be studied separately from the $p(B)$ associated with a perfect VL.

In this paper, we present measurements of the vortex state near the surface of three $YBa_2Cu_3O_{7-\delta}$ (YBCO) samples using low energy β-NMR to monitor $p(B)$ in a thin overlayer of Ag. In a high magnetic field, it is possible to quench the intrinsic broadening due to the ideal VL thereby isolating effects of disorder. Our results indicate that much of the disorder is due to pinning at twin boundaries, which results in a modulation of the vortex density on a long length scale. The resulting broadening is nearly Lorentzian and does not track changes in the superfluid density at low temperatures.

2. Experimental details

The measurements were carried on three near-optimally doped YBCO samples, two single crystals and a thin film, prepared using different techniques: (i) A twinned single crystal of $T_c \approx 92.5$ K, ~0.5 mm thickness, and an area of $\sim 2 \times 3\,mm^2$. (ii) A detwinned single crystal of $T_c \approx 92.5$ K, ~0.5 mm thickness, and area $\sim 3 \times 3\,mm^2$. (iii) A film of $T_c = 87.5$ K, 600 nm thickness, and critical current density $J_c = 2.10^6\,A/cm^2$, was grown by thermal co-evaporation on a $LaAlO_3$ substrate of $9 \times 8\,mm^2$ area. A 120 nm film of Ag (99.99% purity target) was evaporated on the crystals at room temperature using DC sputtering at an Ar pressure of 30 mTorr. The YBCO film was coated in situ with a 60 nm silver layer (99.99% purity). STM imaging of the surface morphology of the film showed a smooth surface with few pores due to a slight yttrium excess.

* Corresponding author. Tel.: +1 604 222 1047x6194; fax: +1 604 222 1047.
E-mail address: saadaoui@phas.ubc.ca (H. Saadaoui).

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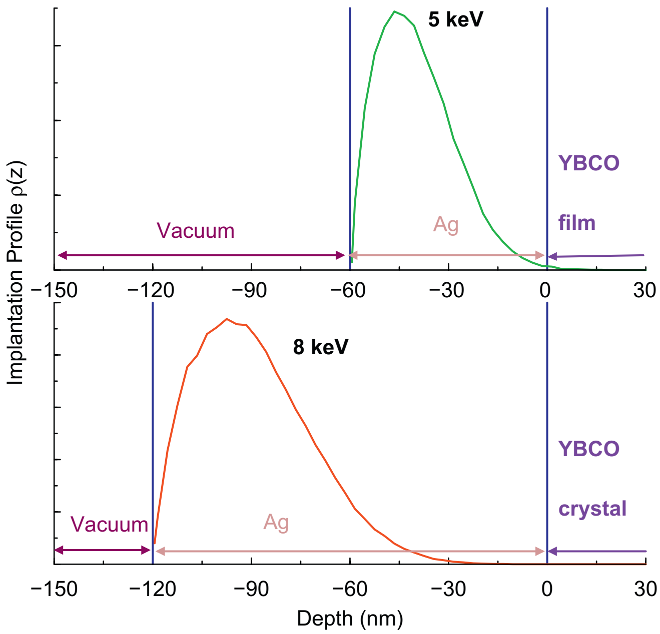

Fig. 1. TRIM simulation [13] of the stopping profile of $^8Li^+$ with implantation energies of 5 keV into 60 nm of Ag with the mean depth at 40 nm away from YBCO film (top figure), and 8 keV into 120 nm of Ag with the mean depth 90 nm away from YBCO crystal (bottom figure).

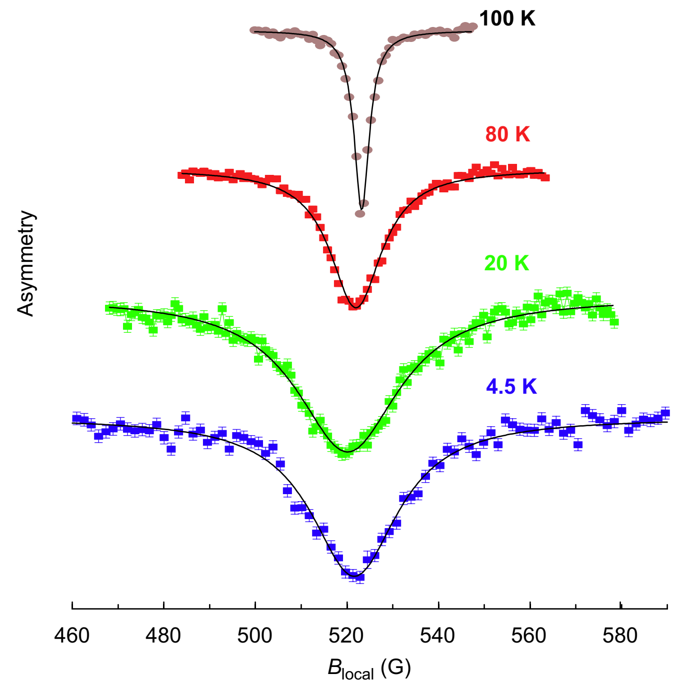

Fig. 2. β-NMR lineshapes in Ag/YBCO (twinned crystal) at various temperatures in a magnetic field $H_0 = 523$ G applied along YBCO c-axis and perpendicular to the surface. The solid curves are best fit using a Lorentzian field distribution.

The experiment was performed at the ISAC facility in TRIUMF, Canada, using a low energy beam of $^8Li^+$ which was polarized in flight via optical pumping [9]. The 70% nuclear spin polarized beam of about 10^6 ions/s was guided electrostatically to the high field spectrometer installed on a high voltage (HV) platform. Applying a high positive voltage to the platform slows down $^8Li^+$ from about 28 to 1 keV [10]. In this work, the mean stopping depth was adjusted so that the $^8Li^+$ stops entirely within the Ag overlayer as shown in Fig. 1. The β-NMR measurements were carried out in the presence of a static external magnetic field H_0 (0.1–60 kG) and a small transverse RF magnetic field H_1 (maximum ~1 G) at frequency ω. The geometry is such that H_0 is perpendicular to the surface and parallel to the YBCO c-axis and the initial spin polarization of $^8Li^+$. The power broadening due to H_1 is less than 1 G [12]. The beam is delivered continuously while monitoring the time averaged longitudinal polarization through the forward–backward asymmetry of the emitted betas. Those $^8Li^+$ spins within γH_1 of ω are effectively depolarized, where $\gamma(^8Li) = 0.63015$ kHz/G is the gyromagnetic ratio of $^8Li^+$. Since there is no quadrupolar splitting for $^8Li^+$ in Ag [10], the resulting lineshape is a direct measure of the internal $p(B)$ experienced by ^8Li. In all cases the samples were field-cooled through T_c to achieve a uniform flux lattice.

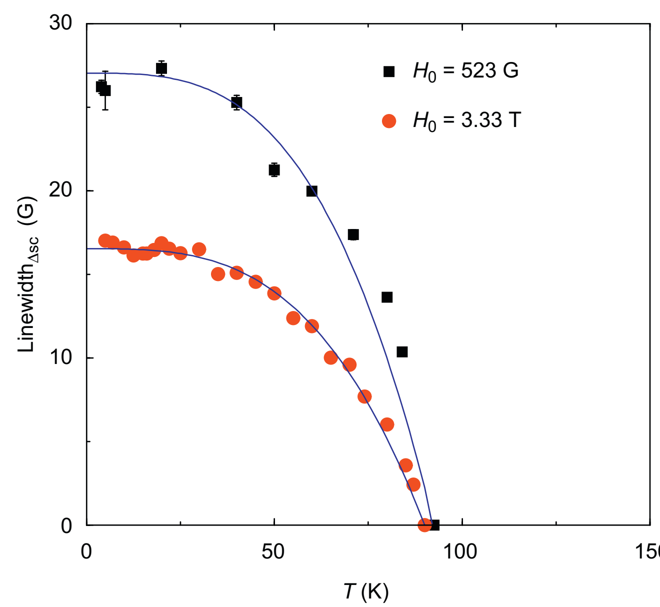

Fig. 3. The additional broadening below T_c, $\Delta_{sc}(T) = \sqrt{\Delta_T^2 - \Delta_{NS}^2}$ in the twinned YBCO crystal in 523 G and 3.33 T. Solid lines are fits to $\Delta_{sc}(0)(1-(T/T_c)^{3.16})$.

3. Results and discussions

Fig. 2 shows example lineshapes in the twinned crystal at various temperatures in an applied field of $H_0 = 523$ G. Above T_c (e.g. 100 K) there is a T-independent linewidth due to nuclear dipole moments in the Ag and RF power broadening. Below T_c, $p(B)$ broadens as expected from the magnetic field inhomogeneities due to the VL emerging from the surface of a superconductor. The lineshape is very symmetric and fits well to a simple Lorentzian. This is very different than the asymmetric lineshape which characterizes a uniform flux lattice [8]. In particular there is no indication of a high field tail from the vortex cores or a cusp frequency from the saddle point. This is evidence for a disordered VL which can lead to both a broader and more symmetric $p(B)$ than an ideal VL [14,15]. Note the overlayer linewidth is expected to be much narrower than deep inside the bulk of the superconductor and falls to zero rapidly when the mean distance d from the interface exceeds the spacing between vortices a [8]. On the other hand, if the disorder is characterized by a much longer length scale D, then the resulting broadening will not be suppressed until d exceeds D. Thus measuring outside the sample in the Ag allows one to isolate long length scale disorder in the VL.