Coexistence of Antiferromagnetism and Superconductivity in Single Crystal Underdoped YBa$_2$Cu$_3$O$_{6+x}$

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Abstract

Muon spin rotation measurements in ultra clean single crystals of heavily underdoped superconducting YBa$_2$Cu$_3$O$_{6+x}$ ($x \approx 0.365$) are presented. The material shows a sharp superconducting transitions below $T = 15$ K. By field cooling and shifting the applied field, we show that the superconducting state pins magnetic flux and develops a flux lattice below $T_c$, indicating that the superconducting state exists throughout the sample on a microscopic scale. At the same temperature, a disordered magnetic state appears on a nanoscale with at least one well-defined internal field probed by the muon. These two states coexist on a nanometer lengthscale and over a narrow region of oxygen doping.

Key words: superconductivity, antiferromagnetism, YBCO, high Tc

1. Introduction

High temperature superconductors can be tuned from antiferromagnetism to superconductivity by varying the carrier concentration in the CuO$_2$ planes. In the case of YBa$_2$Cu$_3$O$_{6+x}$, oxygen doping away from the CuO$_2$ planes controls the carrier concentration in the planes and the magnetic and superconducting properties of the material. The proximity of the two phases in the phase diagram has long suggested that they may coexist in a single sample and that antiferromagnetic fluctuations may provide the binding mechanism for Cooper pairs. Early work by Brewer et al.[2] and Kiefl et al.[4] in YBa$_2$Cu$_3$O$_{6+x}$ powders suggested coexistence near $x = 0.4$. Later, Niedermayer et al. doped powdered YBa$_2$Cu$_3$O$_{6+x}$ with Ca ions and showed[5] conclusively that the two state were present in underdoped samples. More recently, Sanna et al. measured[6] a series of powdered YBa$_2$Cu$_3$O$_{6+x}$ samples and established the phase diagram in the heavily underdoped region, also reporting samples that were both magnetic and superconducting.

Establishing that the two states are present throughout the sample is not straightforward. For...

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instance, in the superconducting state, the magnetism tends to depolarize the muon polarization signal more rapidly than the effects of superconductivity, and therefore makes a measure of the superconductivity difficult. In this paper, we show that samples near the insulator/metal transition are both magnetic and superconducting at low temperatures, and report that the two states coexist over a very narrow oxygen doping range in clean single crystals.

2. Experimental results

These measurements were made in single crystals of heavily underdoped YBa$_2$Cu$_3$O$_{6+x}$ with $x \approx 0.365$. A description of the sample preparation technique and characterization is found in Ref. [7].

The transverse field muon polarization is sensitive to the magnetic transition and the magnetic volume fraction. Fig. 1 shows the $\mu$SR polarization signal above and below the superconducting transition in an applied field of $\mu_0 H = 5$ kG. The applied field is perpendicular to the muon polarization and parallel to the $c$-axis of the single crystals. At $T = 27$ K (circles in fig. 1), the relaxation is due to nuclear dipole moments and is well fitted with a Gaussian relaxation function. At $T = 3.7$ K (triangles) the relaxation has increased. This additional relaxation, as is shown below, is due in part to the presence of a vortex lattice in the superconducting state and mostly from internal fields in a magnetic state. The long-time polarization signal is a measure of the volume fraction, as shown by Brewer et al.[2]. The polarization at $t = 1 \mu$s decreases below $T = 20$ K, and drops to near zero below $T = 15$ K (fig. 3 a). This indicates that large internal magnetic fields occur throughout the sample in the magnetic state.

The magnetic state is clearly seen in the zero field $\mu$SR signal. The ZF polarization (fig. 2) relaxes slowly in zero field at $T = 100$ K (circles in fig. 2) due to nuclear dipoles (as seen in transverse field in fig. 1a). At $T = 3$ K, however, the zero field polarization signal is rapidly damped (triangles in fig. 2) due to the presence of large internal fields in the sample. The oscillation near $t \approx 0.25 \mu$s shows

![Fig. 1. Muon polarization in an applied field of $B = 5$ kG at $T = 27$ K (open circles) above the superconducting and magnetic transition and $T = 3.7$ K (closed triangles) below the transitions. The data are fit to a cosine with Gaussian relaxation.](image)

the presence of a magnetic state with a well defined local internal field at the muon site. The temperature dependence of the internal field is shown in fig. 3 b. The low temperature internal field is 273(5) G, about 90 % of the internal field in the parent compound[1,2,4]. This large internal field implies a high density of local moments and a bulk magnetic state.

In fig. 3 c, the magnetization is shown at low temperatures. The sample undergoes a superconducting transition at $T_c = 14.5$ K. $T_c$ varies strongly with $x$ in these samples, rising to 20 K for $x = 0.375$. This strong dependence of $T_c$ on $x$ and the small width of the transition shows that the oxygen doping in these single crystals is very homogeneous.

A more convincing demonstration of bulk properties is shown in fig. 4. A Fast Fourier Transform of the muon polarization signal at $T = 27$ K (dotted curve) and in an applied field of $\mu_0 H = 200$ G is compared to the FFT at $T = 3$ K in the same field (full curve). The applied field is then shifted to $\mu_0 H = 100$ G while in the superconducting state (dashed curve). Much of the signal remains at 200 G, indicating that the vortex lattice in a large fraction of the sample is pinned by defects.

In conclusion, in single crystals of heavily under-
Fig. 2. Muon Polarization in zero applied field. $T = 100$ K (triangles) and $T = 3$ K (circles). The rapid relaxation and oscillation at $T = 3$ K shows that the sample is in a magnetic state.

doped YBa$_2$Cu$_3$O$_{6+x}$, the superconducting state is present throughout the sample, similar to that in more highly doped YBa$_2$Cu$_3$O$_{6+x}$ $x = 0.5$ but with a reduced $T_c$. However, unlike at $x = 0.5$, at low temperatures the sample is also highly magnetic. The two phases coexist on a lengthscale of 20 Å or less, the lengthscale on which muons are sensitive to small fields[5] and over a small region of the phase diagram. For $x = 0.365$, the magnetic and superconducting transitions coincide. Coexistence between magnetism and superconductivity, shown in Ca-doped YBCO and powdered samples of YBCO, survives even in the cleanest single crystals of YBa$_2$Cu$_3$O$_{6+x}$.

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References


Fig. 3. a) Polarization at $t = 1.0$μs in a transverse field of $B = 5$ kG. The drop near $T = 15$ K is due to a transition to a magnetic state. b) Internal magnetic field vs. temperature, measured with zero field μSR. The fit is to $B_0 \propto (1 - T/T_c)^{\beta}$, with $\beta = 0.213$, $B_0 = 273$ G, and $T_c = 13.7$ K. c) Magnetization vs. temperature. The sharp transition shows the high quality of the single crystals. The superconducting transition occurs at $T_c = 14.5$ K.
Fig. 4. Fast Fourier Transform of the muon polarization signal in an applied field of 200 G at a) $T = 27$ K (dotted curve), b) $T = 3$ K (full curve), and $T = 4$ K after shifting the applied field to 100 G (dashed curve).