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TITLE: TRANSVERSE- AND ZERO-FIELD μSR INVESTIGATION OF MAGNETISM AND SUPERCONDUCTIVITY IN $(Y_{1-x}PR_x)BA_2CU_3O_7$

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TRANSVERSE- AND ZERO-FIELD μSR INVESTIGATION OF MAGNETISM AND SUPERCONDUCTIVITY IN $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$

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Zero-field muon-spin-rotation (μSR) measurements on $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ [x = 1.0, 0.8, 0.6, and 0.54] show evidence for antiferromagnetic ordering of the Cu moments within the Cu-O planes, with Néel temperatures 285, 220, 35, 30, and 20 K, respectively. For x = 1.0 the local muon magnetic field is ~ 16 mT, but decreases to ~ 12 mT at 17 K, due to additional magnetic ordering. The zero-field data, in conjunction with transport data, allow construction of a complete phase diagram for this system. Transverse-field (1 kOe) μSR data for x = 0.2 (T_C = 75 K) show that the muon depolarization is determined primarily by the Cu nuclear moments for $T>T_C$, and by the vortex state for $T<T_C$. Fitting the superconducting-state data to a BCS model yields an extrapolated zero-temperature magnetic penetration depth of 2170 Å.

1. INTRODUCTION

Rare-earth R substitution for Y in $RBa_2Cu_3O_7$ does not affect superconductivity except for R = Ce, Tb, Pm and Pr. The Ce- and Tb-based compounds yield multiphase samples, and the Pm compound is radioactively unstable, making them all difficult to study. On the other hand, $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ exhibits both superconductivity and magnetism for particular values of x. It also retains the orthorhombic structure and is oxygen stable for all values of x /1/. These attributes make this an extremely attractive system for studying the interplay between superconductivity and magnetism in high-temperature superconductors (HTS).

2. EXPERIMENTAL

Utilizing both transverse- and zero-field μSR, we have investigated the magnetic and superconducting properties of $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ for $x = 1.0$, 0.6, 0.5, 0.4 and 0.2 in the former experiment, and for $x = 1.0$, 0.8, 0.6, 0.54, 0.50, and 0.40 in the latter experiment. Polycrystalline samples were fabricated using conventional solid-state reaction techniques /1/, with no evidence for phase separation /2/. X-ray and neutron-diffraction data showed that the samples crystallized in the orthorhombic structure with less than 2% impurity phases for all values of x.

The μSR experiments were conducted at the Los Alamos Clinton P. Anderson Meson Physics Facility using standard zero- and transverse-field μSR techniques. For the zero-field experiments the external field was nulled to ± 2 μT by trim coils. Transverse-field experiments were done in an external field of 1 kOe.

3. ZERO-FIELD RESULTS

Previous zero-field μSR data on the Pr-based compound has shown that for $x \geq 0.54$ there exists magnetic ordering of the Cu moments within the Cu-O *planes* /3/; similar conclusions have been derived from Mössbauer studies /4/. In addition to the Cu ordering there exists additional magnetic ordering at lower temperatures which has been attributed to the Pr moment, although the possibility of Cu *chain* ordering cannot be ruled out and is still a subject of controversy.

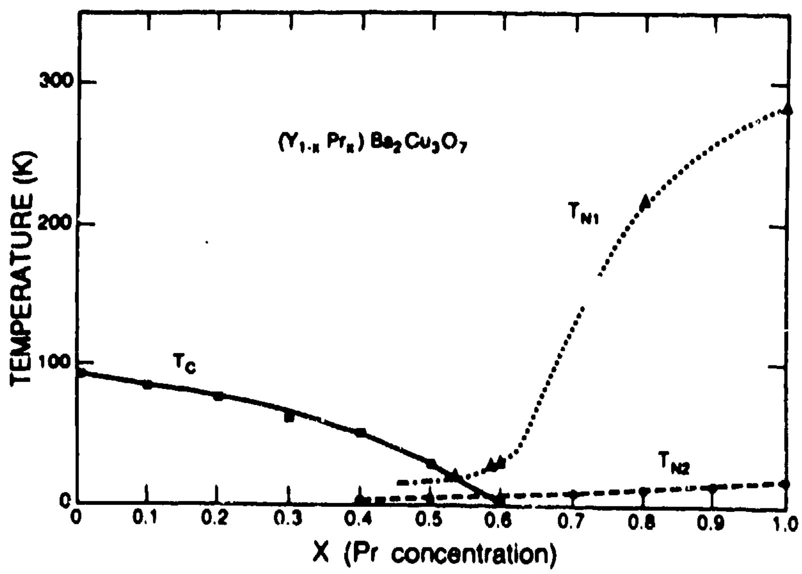

Fig. 1. Phase diagram for $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$. T_{N1} corresponds to antiferromagnetic ordering of Cu moments within the Cu-O planes. T_{N2} corresponds to either Pr-moment or Cu-chain ordering. Spin-glass-like magnetism occurs for $x < 0.54$ (dashed-dotted line).

For $x = 1.0$, the local magnetic field at the muon site reaches a maximum value (near 20 K) of 16 mT, and then decreases to approximately 12 mT below 20 K. As stated above, it is unclear whether this reduced magnetism is due to Pr-moment or Cu-chain ordering. Nevertheless, these results, in conjunction with transport data /1/, allow us to construct a complete phase diagram for $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ which is shown in Fig. 1. Notice that for $x < 0.54$ (intersection of the T_{N1} and T_c *vs* x curves) we show a dashed-dotted line indicating that spin-glass-like magnetism rather than antiferromagnetism is observed in this region, as discussed in previous work /3/.

The region near $x = 0.50$ corresponds to a crossover of the ground state from magnetism to superconductivity. Muon depolarization for $x = 0.5$, taken at 5 K, is characterized by a fast-relaxing component in addition to a long-time tail, indicative of spin-glass-like magnetism /5/. We conclude, therefore, that *antiferromagnetism* and superconductivity do not simultaneously coexist in this system, in agreement with the conclusion of Felner et al. /4/, but that superconductivity and *spin-glass-like magnetism* do coexist.

4. TRANSVERSE-FIELD RESULTS

Transverse-field µSR data were taken for $x = 1.0$, 0.60, 0.50, 0.40, and 0.20 in an applied magnetic field of l kOe.

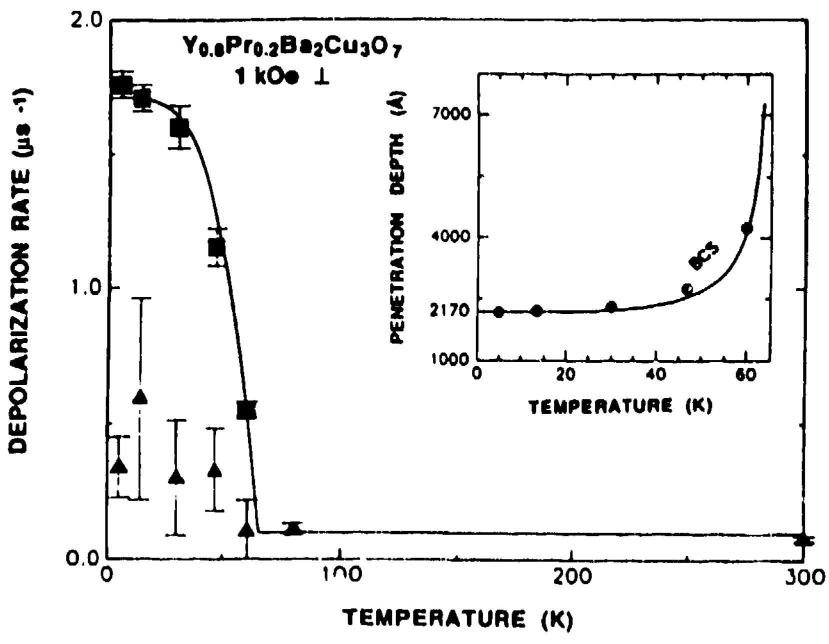

Fig. 2. Muon depolarization rates for $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_7$ taken in a 1- kOe transverse field. The squares correspond to muons which have stopped in superconducting regions and the triangles to muons which have stopped in normal-conducting regions. The inset shows the magnetic penetration depth as determined by BCS theory.

For large x the measured muon depolarization rates are high (> 8 μs^{-1}) and the data are difficult to analyze. On the other hand, for small x (0.20) the sample is superconducting (T_c = 75 K) with the muon depolarization rates being determined primarily by the Cu nuclear moments for $T > T_c$, and by the vortex state for $T < T_c$, as shown in Fig. 2. Note that two distinct depolarization signals are observed, one corresponding to the superconducting vortex state (squares) and the other to the normal-conducting state (triangles). All data were taken in the applied field as the sample was cooled. Similar results have been obtained in Eu- and Gd-based superconductors /6,7/. The data are fitted to a two-frequency Gaussian depolarization rate given by $G(t) = \exp[-1/2(\sigma^2 t^2)]$, where σ is the depolarization rate and is related to the second moment of the local-field distribution.

The observed muon precessional frequencies ($\gamma_\mu = 2\pi \times 13.55$ MHz kOe^{-1}) which correspond to the depolarization rates of Fig. 2 are shown in Fig. 3. Both data sets are consistent with the notion that some fraction of the implanted muons stop in superconducting regions of the sample, thereby yielding an increased depolarization rate and a decreased precessional frequency due to the inhomogeneous magnetic field distribution. The normal-state value of the precessional frequency (13.40 MHz) corresponds to a magnetic field at the muon site of 989 Oe. In the superconducting state the frequency is near 13.14 MHz at 5 K, which corresponds to a local field of 970 Oe.

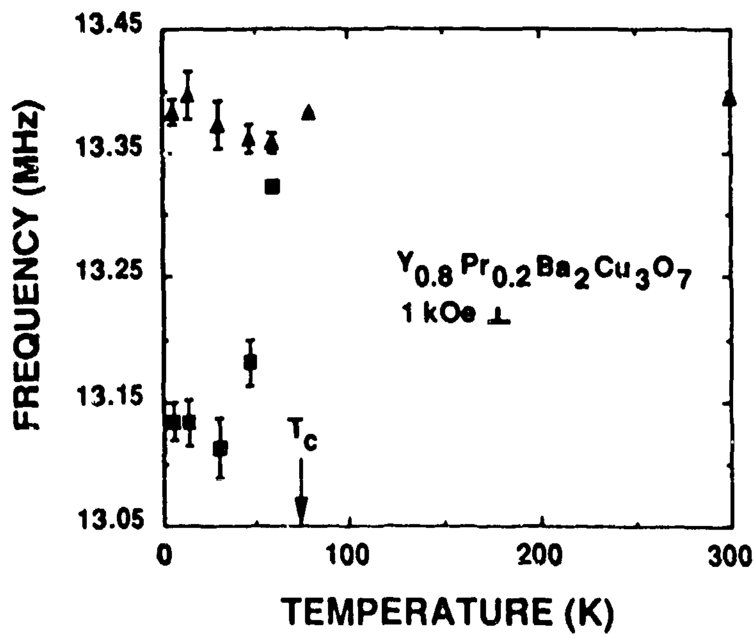

Fig. 3. Muon precessional frequencies for $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_7$ taken in a 1- kOe transverse field. The data correspond to the depolarization rates shown in Fig. 2. The normal-conducting state is depicted by triangles and the superconducting state is given by squares.

From the observed muon depolarization rates shown in Fig. 2, it is possible to deduce the magnetic field penetration depth for the x = 0.20 sample. Assuming a square Abrikosov lattice (a triangular lattice only changes the result by approximately 4%) for the vortex state we have for the magnetic field inhomogeneity

$$\left\langle |\Delta H|^2 \right\rangle = \frac{H_{app}\phi}{4\pi\lambda^2}\left[1+\frac{4\pi^2\lambda^2 H_{app}}{\phi}\right]^{-1} = \frac{\sigma^2}{\gamma_\mu^2} \quad , \qquad (1)$$

where σ is the muon depolarization rate, γ_μ is the muon gyromagnetic ratio, λ is the magnetic field penetration depth, and ϕ is the flux quantum (2×10^{-7} Oe cm^2). By extrapolating σ to zero Kelvin and subtracting the constant relaxation rate 0.1 μs^{-1}, we find $\sigma(0)$ to be 1.63 μs^{-1}. Substituting this value into Eq. (1) yields the magnetic field penetration depth at zero Kelvin, $\lambda(0)$ = 2170 Å. Invoking the usual empirical relation to describe the temperature dependence of the penetration depth /8/, $\lambda(T) = \lambda(0)[1-(T/T_c)^4]^{-1/2}$, with $\lambda(0)$ given above, we obtain the solid line shown in the inset of Fig. 2. T_c obtained from the fit to the depolarization rate data is 65 K rather than 75 K as determined from transport measurements. The doping of 20% Pr into $YBa_2Cu_3O_7$ increases $\lambda(0)$ from 1400 Å /9/ to 2170 Å.

Substitution of the empirical expression for $\lambda(T)$ into Eq. (1) gives, to a first approximation, $\sigma(T) \propto [1-(T/T_c)^4]$. Therefore we fitted the muon depolarization data of Fig. 2 to an expression of the form $\sigma(T) = a[1-(T/T_c)^4] + b$. The solid line in Fig. 2 shows that for $T > T_c$, $\sigma(T) = 0.1$, and for $T<Tc$, $\sigma(T) = 1.63[1-(T/T_c)^4] + 0.1$, with T in Kelvin and σ in μs^{-1}. The best fit is obtained for T_c = 65 K. The depolarization rate above T_c (0.1 μs^{-1}) is the same as that obtained in $YBa_2Cu_3O_7$ /9/.

5. CONCLUSIONS

Zero-field µSR data show that antiferromagnetic ordering occurs in $(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ for $x > 0.54$, which is attributable to ordering of the Cu ions within the Cu-O planes. There exists a crossover region in the phase diagram near $x = 0.50$ where spin-glass-like magnetism and superconductivity coexist. Additional magnetic ordering is observed for $x \geq 0.40$, which is due to either Pr-moments or to Cu within the chains. Unambiguous elucidation of the mechanism responsible for this low-temperature ordering remains an important and unresolved issue.

Transverse-field results for $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_7$ show that two distinct muon stopping sites are observed, one corresponding to the superconducting state and the other to the normal-conducting state, similar to previous results reported for Eu- and Gd-based HTS. The extrapolated zero Kelvin magnetic field penetration depth is 2170 Å, considerably higher than that obtained in $YBa_2Cu_3O_7$ (1400 Å).

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