Paramagnetic vortex state in $Pr_{2-x}Ce_xCuO_4$ single crystals

J.E. Sonier [a,1], K.F. Poon [a], G.M. Luke [b], P. Kyriakou [b], R.I. Miller [c], P. Fournier [d], R.L. Greene [e]

[a] *Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6*
[b] *Department of Physics & Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
[c] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[d] *Départment de Physique, Université de Sherbrooke, Québec, Canada J1K 2R1*
[e] *Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, MD-20742, USA*

Abstract

Transverse-field muon spin rotation (TF-μSR) measurements of the internal magnetic field distribution of $Pr_{2-x}Ce_xCuO_4$ single crystals reveal a large increase in the magnitude of the average field in the vortex state under field-cooling conditions. The observed increase in the average internal magnetic field measured by μSR indicates that vortices play an important role in the paramagnetic Meissner effect.

Key words: paramagnetic vortex state; electron-doped cuprate; μSR

1. Introduction

Although the diamagnetic Meissner effect is one of the defining properties of a superconductor, an unusual paramagnetic response is sometimes observed in small superconducting samples when cooled in a weak magnetic field below the critical temperature T_c. The origin of this phenomenon, often called the paramagnetic Meissner effect (PME), is not known for certain. Over the years there have been several theoretical proposals to explain the PME. In high-T_c superconductors the PME was argued to be a consequence of *d*-wave pairing [1]. However, the observation of the PME in conventional superconductors points to other explanations. A possible origin is the formation of a 'giant vortex'. In this scenario, magnetic flux becomes trapped when the surface of the sample becomes superconducting while the bulk is still in the normal state. This can arise from inhomogeneous cooling [2] or the existence of a surface critical field H_{c3} [3]. Upon further cooling of the sample the superconducting region at the surface grows inward, compressing the trapped flux and giving rise to a net paramagnetic moment. More recently it has been shown from self-consistent solutions of the Ginzburg-Landau equations for a finite size superconductor that the PME can arise from the presence of vortices [4]. In this model, the circulating currents that screen the field within a vortex flow in opposite directions to the diamagnetic currents at the sample perimeter that screen the external field. The total magnetization of the sample thus consists of competing paramagnetic and diamagnetic contributions. For certain intervals of applied field, the paramagnetic contribution dominates..

Here we report on transverse-field (TF) μSR measurements of the internal magnetic field distribution in the vortex state of superconducting $Pr_{2-x}Ce_xCuO_4$ (PCCO) single crystals. The results reveal a *paramagnetic* vortex state, in which the magnitude of the average internal field exceeds that in the normal state.

[1] Corresponding author. Present address: Department of Physics, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, Canada V5A 1S6. E-mail: jsonier@sfu.ca

2. Experimental

The experiments were performed on the M15 and M20B beam lines at TRIUMF, Vancouver, Canada. TF-μSR time spectra were taken below T_c after field cooling in a magnetic field applied parallel to the $\hat{c}$-axis. The single crystals of PCCO were grown by a directional solidification technique in Al_2O_3 crucibles using a CuO-based flux [5]. Oxygen reduction was achieved by encapsulating the crystal in polycrystalline PCCO in the presence of flowing Ar at 900-1000 °C [6]. Here we report results on one single crystal, noting that qualitatively similar results were obtained on two others having different T_c values. The single crystal was 0.07 mm thick, with an $\hat{a}$-$\hat{b}$ surface area of $\sim$6.5 mm^2 and a mass of 3.74 mg. Resistivity and dc susceptibility measurements gave T_c values of 25(1) K and 23.8(1.0) K, respectively — indicating that the crystal is near-optimally doped.

3. Results

Figure 1 shows the temperature dependence of the average internal magnetic field at the μ^+ site in PCCO, B_μ, plotted relative to its value above T_c. Below T_c there is a substantial increase in the magnitude of B_μ, which decreases with increasing applied field. The μ^+ stopping site has previously been identified in the parent compound Pr_2CuO_4 as near an O atom midway between adjacent CuO_2 layers [7]. We note, however, that this site is random on the large scale of the vortex lattice.

The TF-μSR measurements above T_c display a μ^+ Knight shift, that is defined by

$$K_\mu = \frac{B_\mu - B_{\mathrm{Ag}}}{B_{\mathrm{Ag}}} \tag{1}$$

where B_{Ag} is the average internal field in a reference Ag sample. Between 25 and 70 K we find that $K_\mu \approx -3300(40)$ ppm, which is likely due to a small magnetic moment on the Pr ions. Above T_c at 9 mT this corresponds to a difference between B_μ and the applied field of approximately -0.03 mT. Since the increase of B_μ below T_c greatly exceeds 0.03 mT, the effect cannot be explained by the modification of the static spin susceptibility due to the formation of Cooper pairs. Additional μSR measurements carried out in zero external field do not show any evidence for the onset of magnetic order below T_c. Furthermore, the amplitude of the TF-μSR signal does not change upon cooling below T_c. Thus, we also do not attribute the increased field to the presence of magnetic moments.

The paramagnetic field shift observed here is in stark contrast to the diamagnetic shift typically observed by μSR in studies of the vortex state in type-II superconductors. Our μSR results on a single crystals cannot be explained by the d-wave pairing model of Ref. [1], which was developed for granular superconductors. Furthermore, the increased average field and the width of the measured asymmetric field distribution measured by μSR appears to be incompatible with giant vortex models. On the other hand, our μSR results appear to be consistent with a paramagnetic vortex state of the kind proposed in Ref. [4].

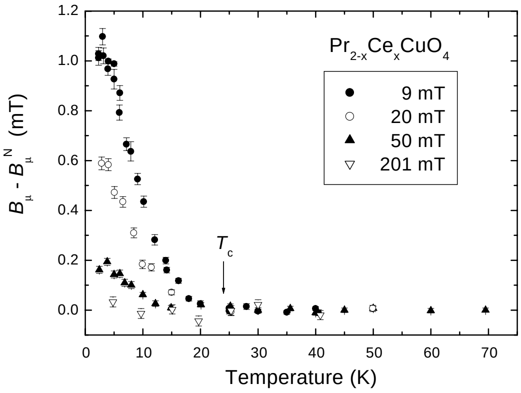

Fig. 1. Temperature dependence of the average internal magnetic field B_μ relative to its value B_μ^N above T_c.

Acknowledgements

This work was partially supported by the Canadian Institute for Advanced Research, the National Science and Engineering Research Council of Canada and the National Science Foundation of the USA.

References

[1] M. Sigrist, T.M. Rice, Rev. Mod. Phys. **67** (1995) 503.

[2] A.E. Koshelev, A.I. Larkin, Phys. Rev. B**52** (1995) 13559.

[3] V. V. Moshchalkov, X. G. Qiu, V. Bruyndoncx, Phys. Rev. B**55** (1997) 11793.

[4] G.F. Zharkov, Phys. Rev. B **63** (2001) 214502.

[5] J.L. Peng, *et al.*, Physica C **177** (1991) 1238.

[6] M. Brinkmann, T. Rex, H. Bach, K. Westerholt, J. Crystal Growth **163** (1996) 369.

[7] G.M. Luke *et al.*, Phys. Rev. B **42** (1990) 7981.