ELSEVIER

Synthetic Metals 120 (2001) 1015–1016

SYNTHETIC METALS

www.elsevier.com/locate/synmet

μSR studies of the flux vortex phases in a BEDT-TTF superconductor

F.L. Pratt[a,b*], S.L. Lee[c], C.M. Aegerter[d], C. Ager[c], S.H. Lloyd[e], S.J. Blundell[b], F.Y. Ogrin[c], E.M. Forgan[e], H. Keller[d], W. Hayes[b], T. Sasaki[f], N. Toyota[g], S. Endo[g].

[a] *RIKEN-RAL, Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK.*
[b] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK.*
[c] *School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife KY16 9SS, UK.*
[d] *Physik-Institut der Universitat Zurich, CH-8057, Zurich, Switzerland.*
[e] *School of Physics and Space Research, University of Birmingham B15 2TT, UK.*
[f] *Institute for Materials Research, Tohoku University, Sendai 980-77, Japan.*
[g] *Department of Physics, Tohoku University, Sendai 980-8578, Japan.*

Abstract

μSR has been used to probe the structure and stability of the flux vortex array in the organic superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$. At temperatures below 5 K and fields below 5 mT the internal field distribution is found to closely match that expected for a three dimensional (3D) Abrikosov flux line lattice (FLL). Careful studies in this 3D-FLL regime have enabled an improved measurement of the temperature dependence of the superconducting penetration depth to be made. A linear term is found in the temperature dependence of the penetration depth, suggesting the presence of line nodes in the gap parameter and d-wave pairing.

Key words: Organic superconductors, Superconducting phase transitions, μSR

Muon spin rotation (μSR) spectroscopy has demonstrated itself to be a powerful probe of the the complex vortex phase behaviour in highly anisotropic superconductors such as the layered BEDT-TTF (ET) charge transfer salts[1]. The rich vortex behaviour is the result of competition between electromagnetic and Josephson intervortex interactions and thermal excitations and defect pinning processes[2]. It is important to have a good understanding of these effects if experimental techniques such as μSR are to be used to shed light on problems such as the symmetry of the superconducting order parameter in ET salts, a topic which has been under debate for some considerable time now.

The μSR measurements reported here were carried out on the GPS instument at the Paul Scherrer Institute with the field perpendicular to the plane of a mosaic sample of κ-(ET)$_2$Cu(SCN)$_2$ crystals. This simpler 90° geometry is in contrast to the 45° case on which we focused earlier for this system[1]. Analysis of flux vortex field distributions was carried out using both maximum entropy methods and direct fitting to model field distributions. The internal field profile of the vortex structure is distributed about a most probable value B_{pk} and is characterised by the RMS linewidth

$$B_{RMS} = \sigma/\gamma_\mu = < (B - B_{pk})^2 >^{1/2}$$

and the skewness parameter

$$\beta = \frac{< B - B_{pk} >}{B_{RMS}},$$

which takes on a value for a static 3D FLL that is characteristic of the lattice geometry.

The field dependence of β at 2 K is shown in Fig.1a. The crossover from 3D FLL to decoupled layers occurs in the region between 5 and 8 mT as

---

[*] Corresponding Author. E-mail: pratt@riken.nd.rl.ac.uk

PII: S0379-6779(00)01002-X

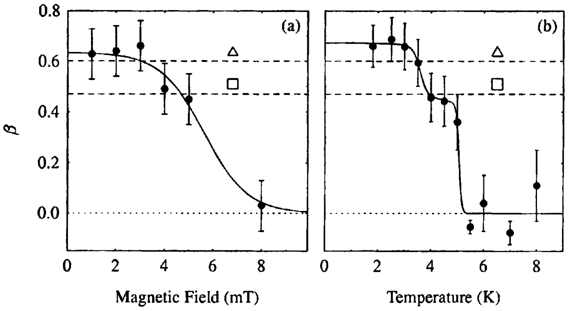

Fig. 1. Measurement of β in $(ET)_2Cu(SCN)_2$ for field perpendicular to the ET layers: (a) field dependence at 2 K and (b) temperature dependence in 3 mT. Expected β values are shown for the triangular and the square 3D FLL cases.

reported previously[1]. The value of β at fields below 4 mT is entirely consistent with the value of 0.60 calculated for a triangular Abrikosov vortex structure. We note that β values at 4 and 5 mT are close to the square lattice value (0.47), however the current data are insufficient to distinguish a possible change in the vortex lattice geometry from the onset of the dimensional crossover. Recent flux decoration experiments[3] have confirmed that the triangular lattice is present at low fields but no data have been reported above 1 mT. It is however clear from Fig.1a that the low field phase is fully established at 3 mT and below. A study of the temperature dependence of β at 3 mT is shown in Fig.1b. The value of β for temperatures up to 4 K is again consistent with the triangular lattice. Above 5 K β falls to zero, reflecting the breakup of interlayer order between the pancake vortices making up the vortex line at the temperature T* [1,4]. In the 4-5 K region there appears to be a plateau around the square lattice value, again suggesting the possibility of an intermediate vortex state before decoupling occurs.

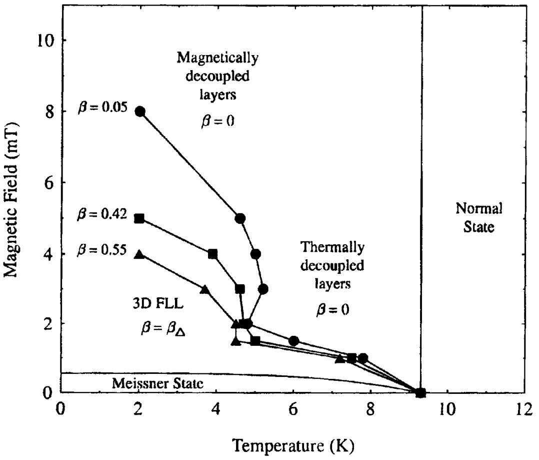

Fig. 2. The superconducting vortex phase diagram for $(ET)_2Cu(SCN)_2$ derived from the μSR studies.

Following field and temperature scans such as these, the basic features of the vortex phase diagram can be built up (Fig.2). From this phase diagram the optimum field and temperature range can be chosen for studying the superconducting penetration depth as a function of temperature. For field, the value 3 mT was chosen to be well separated from both the Meissner state and the decoupled layer phase. For temperature, the range below 4 K has β consistent with a triangular FLL and thus the expression $\sigma^2 = 0.00371\Phi_0\lambda^{-4}$ [5] has validity in this range and can be used to derive λ from σ. The results of this measurement are shown in Fig.3. The penetration depth at the lowest measured temperature is consistent with our earlier measurements at 90°[1]. However there is clearly a linear term present in $\lambda(T)$. This linear dependence, in a region where the vortex structure has been confirmed to be well-defined and stable, is strong evidence for the presence of line nodes in the order parameter, as would be expected for d-wave superconducting pairing symmetry.

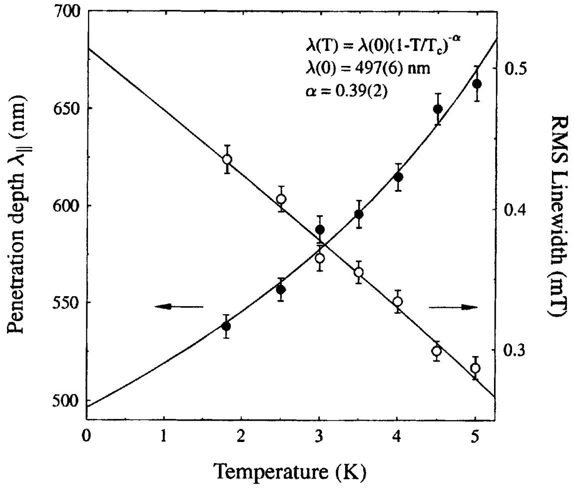

Fig. 3. Open circles show the temperature dependence of the measured superconducting RMS linewidth B_{RMS} in $(ET)_2Cu(SCN)_2$ measured for a field of 3mT. Filled circles show the corresponding penetration depth for a triangular 3D FLL, with temperature dependence fitted as shown.

References

[1] S.L. Lee, F.L. Pratt, S.J. Blundell, C.M. Aegerter, P.A. Pattenden, K.H. Chow, E.M. Forgan, T. Sasaki, W. Hayes, H. Keller, Phys. Rev. Lett. 79 (1997) 1563.

[2] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I.Larkin and V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125.

[3] L.Ya. Vinnikov, T.L. Barkov, M.V. Kartsovnik and N.D. Kushch, Phys. Rev. B 61 (2000) 14358.

[4] J.R. Clem, Phys. Rev. B 43 (1991) 7837.

[5] E.H. Brandt, Phys. Rev. B 37 (1988) 2349.