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Conf-910903--

Neutron Scattering from the Flux Lattice in High Temperature Superconductors

CONF-910903--10

DE91 017947

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Keywords: *High Temperature Superconductivity, Neutron Diffraction,
Magnetic Structures*

Neutron scattering has been used to observe diffraction from the flux-line lattice in high temperature superconductors. This technique is particularly useful in such systems as it allows observations to be made over a wide range of temperature and magnetic field. Experiments on the systems $K_{0.4}Ba_{0.5}BiO_3$ and $YBa_2Cu_3O_{7-x}$ will be described with applied magnetic fields of up to 4 Tesla and for temperatures from 2K to T_c .

Introduction

In the mixed state ($H_{c1} < H < H_{c2}$) of a type II superconductor the magnetic flux penetrates the body of the superconductor. The superconductor attempts to minimise its free energy by distributing

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this magnetic flux on a lattice of flux-lines parallel to the applied field; each flux-line contains one flux quantum. The magnetic field profile around a flux-line peaks at the flux-line core (a normal region of ~ 2 coherence lengths(ξ) in diameter) and decays in magnitude away from the core with a length scale of the penetration depth (λ).

Observation of the Flux-Line Lattice

NMR and μ SR are microscopic probes of the magnetic field in the mixed state but are only capable of providing a measure of the field distribution and any extraction of further information is model-dependent.

The ends of the flux-lines may be decorated with magnetic particles and this method has proved to be very successful in providing a real space visualisation of the flux-line lattice.¹ However such a method is restricted to very low magnetic fields, and only reveals the distribution of flux-lines at the surface which may not reflect the behaviour in the bulk of the material.

The neutron, with its magnetic moment, is a useful probe of the modulated magnetic field in the mixed state. The neutrons scatter coherently from the magnetic field distribution and Bragg diffraction may be observed. The positions of the diffracted peaks are determined by the lattice structure adopted by the magnetic flux and the intensities relate to the variation of the magnetic field within the flux-line unit cell. For most systems there is little absorption of the neutron beam and therefore neutron diffraction is a *direct* method of measuring the spatial distribution of the magnetic flux within the bulk of a sample^{2,3,4}.

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Experimental Methods

Typical lattice spacings for the flux-line lattice are large (of the order of a few hundred to a few thousand Å) and this requires long wavelength neutrons (10-15 Å) to be used in such experiments to produce reasonable scattering angles (~ 0.5 - 3°). For high κ ($\lambda \gg \xi$) superconductors, such as the high- T_c superconductors, the integrated intensity of the diffracted beam is $\propto 1/\lambda^4$ and hence the predicted intensity of the scattering in these systems is much less than for more conventional superconductors⁵. This weak intensity must also be detected at angles where there is a large contribution to the background scattering from twin boundaries and other defects often found in crystals of these materials. The experiments described in this paper have been performed using the D11 and D17 instruments of the Institut Laue-Langevin, Grenoble. These instruments provide a large flux of long wavelength neutrons with variable collimation and sample to detector distance which permits the experiment to be optimised for each material and range of magnetic field. The scattering geometry adopted for all experiments was with the magnetic field aligned approximately along the incident beam; this setup is preferred in situations where a non-perfect flux lattice may be produced. Experiments have been performed with applied magnetic field of up to 4 Tesla, this upper limit is fixed by interactions between the stray magnetic field and the instrument rather than by any intrinsic limitation from the technique. For all experiments the flux-lattice was produced by cooling the superconductor from above T_c to the lowest temperature of measurement with the appropriate magnetic field applied; the temperature was then varied if required. The figures 1,2 display

the intensity contours on the multidetector used to detect the scattered neutrons; the figures have backgrounds (obtained at $T > T_c$) subtracted and are composites of measurements at several different sample angles, which were chosen to bring each of the diffracted beams into the Bragg scattering condition.

Morphology of the Flux Lattice

Unfortunately only the lowest order Bragg reflections can be observed from the flux lattice in high T_c superconductors due to the restricted magnetic field contrast arising from the large value of penetration depth but this still gives enough information to discuss the structures adopted by the flux-lines. For the cubic $K_{0.4}Ba_{0.6}BiO_3$ system a hexagonal lattice was observed for all temperatures and magnetic fields (but see next section for limitations). In $YBa_2Cu_3O_{7.6}$ a more complicated situation is evident due to the presence of twinning planes in this orthorhombic material. Figures 1 and 2 show the diffraction pattern observed at 10K in a field of 0.6 Tesla when the field is applied parallel to the c-direction or with the c-axis rotated 10° from the field direction. With the field along c the pattern observed resembles that expected for a square lattice, however the data at other orientations suggest that this pattern is produced by two domains of a hexagonal lattice, aligned at 90° to each other. When the crystal was rotated 10° away from c about the vertical axis in Fig. 1 and the flux-lattice regrown the hexagonal pattern of Fig. 2 was found. The strongest peaks in this pattern are from those flux lattice planes aligned along a 110 direction, corresponding to the direction of the twinning planes. These two figures provide evidence that the growth of the flux lattice in this system is

strongly influenced by the presence of the twinning planes. The weak spots in Fig. 2 are slightly further from the centre of the pattern than the strong spots, this distortion from a pure hexagonal lattice arises from the large anisotropy in λ . The weakness of these spots is probably because the flux lattice planes are less well formed in directions which are not parallel to twin planes.

Intensity of the Bragg Reflections from the Flux-Lattice

In extreme type II superconductors a simple model of the integrated intensities of the Bragg reflections as a function of temperature and magnetic field may be written⁶. Such a model would predict the integrated intensity of a Bragg reflection to vary as $1/\sqrt{B}$ at constant temperature and as $(1-(T/T_c)^4)^2$ for a fixed magnetic field. Neither of the systems investigated in these experiments obey these rules.

For $\text{YBa}_2\text{Cu}_3\text{O}_{7.3}$ an approximately linear dependence of intensity on temperature is observed, i.e. the intensity disappears more quickly than predicted by the model, however the field dependence up to 4 Tesla is approximately that expected from the simple model.

For $\text{K}_{0.4}\text{Ba}_{0.6}\text{BiO}_3$ ($T_c \approx 32\text{K}$), the disagreement with the model is much greater; the integrated intensities of the Bragg reflections show a rapid decrease as a function of magnetic field at constant temperature and at fixed field the intensity becomes very small well below T_c . At 0.22 Tesla little intensity could be measured above 25K, while at higher fields this "cut-off" shifted to lower temperatures. Above 2 Tesla, ($\ll H_{c2}$), it was not possible to observe the flux lattice at any temperature in this system.

Conclusion

In the cubic superconductor $K_{0.4}Ba_{0.6}BiO_3$, the flux lattice adopts the conventional Abrikosov triangular structure but with a field and temperature dependence which differs greatly from that expected in simple models. In $YBa_2Cu_3O_{7.8}$, the flux lattice morphology is strongly influenced by twin planes. These observations are part of a continuing series of experiments on the flux-line lattice in high T_c systems which may well be of importance in studying both flux lattice pinning and also the nature of the superconducting state in these materials.

Figure 1. Contours of extra neutron scattering intensity for a single crystal of $YBa_2Cu_3O_{7.8}$ cooled from above T_c to 10K in a magnetic field of 0.6 Tesla aligned along the c-axis. The degree of shading within each contour is proportional to the observed intensity.

Figure 2. Contours of extra neutron scattering intensity for a single crystal of $YBa_2Cu_3O_{7.8}$ cooled from above T_c to 10K in a magnetic field of 0.6 Tesla aligned at 10° to the c-axis. The preferred alignment of the flux lattice planes to the twin planes is also indicated on this diagram.

References

- ¹ G.J. Dolan, F. Holtzberg, C. Field and T.R. Dinger, Phys. Rev. Lett., **62**, 2184 (1989)
- ² D. Cribier, B. Jacrot, L. Madhav Rao and B. Farnoux, Phys. Lett., **9**, 106 (1964)
- ³ J. Schelten, G. Lippmann and H. Ullmaier, J. Low Temp. Phys., **14**, 213 (1974)
- ⁴ D.K. Christen, F. Tasset, S. Spooner and H.A. Mook, Phys Rev. B, **15**, 4506 (1974)
- ⁵ E.M. Forgan, D. McK. Paul, H.A. Mook, P.A. Timmins, H. Keller, S. Sutton and J.S. Abell, Nature, **343**, 735 (1990)

flux lattice
planes
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twin planes
direction