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Neutron scattering from the flux-line lattice in $Bi_2Sr_2CaCu_2O_{8+y}$

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Abstract

Neutron small-angle diffraction has been used to investigate the flux-line lattice structure within single crystals of the high-temperature superconductor $Bi_{2.15}Sr_{1.95}CaCu_2O_{8+x}$. The diffracted intensity goes rapidly to zero as the magnetic field or the temperature is increased. Melting at low fields as a function of temperature coincides with the appearence of finite resistance within the superconducting state. At low temperatures the diffracted intensity disappears in fields greater than ~70 mT, probably due to the decomposition of the flux-line lattice into randomly pinned 2d "pancake" vortices.

1. Introduction

The mixed state of a type-II superconductor corresponds to magnetic flux being inside the superconducting sample. This magnetic flux is quantised and distributed in the form of flux-lines which are situated on a lattice. This lattice structure is usually hexagonal. This flux-line lattice corresponds to a periodic distribution of magnetic induction throughout a sample and can be sampled through the Bragg diffraction of neutron beams. For details see Ref. [1]. The large spacings of the flux-line planes requires that long wavelength neutron beams be used for such experiments and the diffracted beam be observed at relatively small scattered angle. Small-angle scattering (SAS) instruments are necessary for such measurements. The properties of the high-temperature cuprate super-conductors are very different in a number of ways from conventional superconductors. In particular the higher critical temperatures (T_c), the presence of large anisotropies due to CuO_2 planes and the low carrier concentration mean that thermal fluctuations are considerably more important than for low-T_c materials. These fluctuations are clearly observable in the properties of the flux-lines in the mixed state [2]. One particular example of the role of fluctuations is provided by the "irreversibility" line in the phase diagram of the mixed state. Above this line flux-lines move in response to external forces giving rise to reversible magnetisation curves and finite electrical resistance to the flow of current. Below this line the flux-lines become pinned, trapped by defects in the samples, and cannot be moved easily resulting in irreversible behaviour in the physical properties. In the anisotropic, high-T_c materials this irreversibility line exists at temperatures considerably lower than T_c. This paper describes some recent neutron

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investigations of the flux-line structure in a single crystal of $Bi_{2.15}Sr_{1.95}CaCu_2O_{8+x}$ which demonstrate the changes which occur as function of applied magnetic field and temperature in such an anisotropic superconductor. Details of our previous measurements for this system are to be found in Ref. [3].

2. Experimental details

The neutron diffraction experiments were performed using the SAS instrument at Risø National Laboratory. At the lowest magnetic field used in these experiments, 20 mT, the flux-line spacing is ~3500 Å, so an incident neutron wavelength of 19.5 Å was used to produce sufficiently large scattering angles. The area detector was placed at 6 m behind the sample in the evacuated flight path. An electromagnet was used to generate the applied magnetic field. This magnetic field was aligned parallel to the incident neutron beam to allow several of the lowest-order Bragg reflections from the flux-line lattice to be observed for one position of the sample. Most of the measurements were made with the magnetic field also parallel to the c-axis of the crystal. In all cases the flux-line lattice was grown by cooling the crystal in an applied magnetic field from above T_c to the temperature of measurement. Backgrounds at high temperature ($T > T_c$) and at low temperatures in zero magnetic field were taken to remove the contributions from grain boundaries and other features, which provide substantial small-angle scattering, from the observed scattered distribution on the detector. At low temperatures and at low magnetic fields a well-defined sixfold diffraction pattern was observed as illustrated by Fig. 1. The intensities of the Bragg reflections in this pattern were found to decrease as either the temperature or the magnetic field were increased, and eventually to disappear entirely. An examination of the field/temperature variation of the Bragg intensity allows the production of a phase diagram for the region of existence of the flux-line lattice which is presented as Fig. 2. The open circles which mark the loss of intensity in a set of scans at constant magnetic field map onto the irreversibility line as measured by magnetisation. The actual shape of these plots of intensity against temperature depends on the heat treatment given to the sample prior to measurement. The flat dashed region which indicates the loss of intensity as a function of field at constant temperature is rather sample dependent. The width of the Bragg reflections as a function of

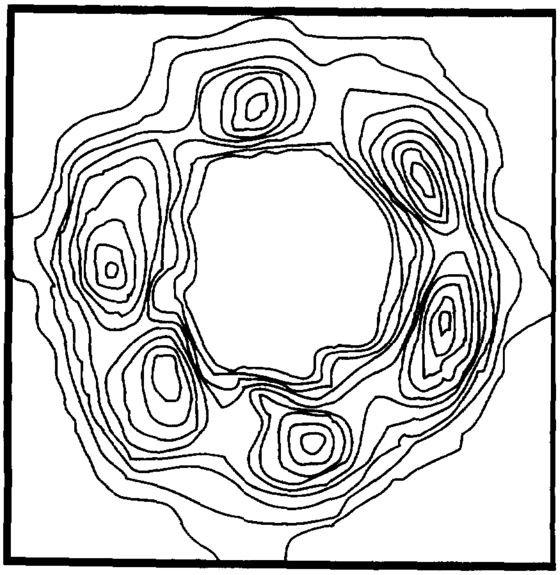

Fig. 1. Contours of equal intensity for the scattered intensity from the flux-line lattice in $Bi_{2.15}Sr_{1.95}CaCu_2O_{8+x}$ at $B = 50$ mT and $T = 1.5$ K. This image was measured with the magnetic field applied parallel to the c-axis of the single-crystal sample.

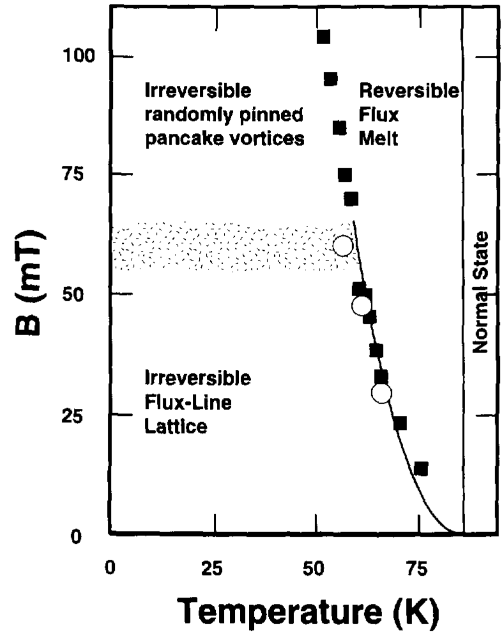

Fig. 2. Magnetic field versus temperature phase diagram for a sample of $Bi_{2.15}Sr_{1.95}CaCu_2O_{8+x}$. The circles indicate the loss of Bragg intensity in constant-field measurements as a function of temperature. The squares mark the boundary between reversible and irreversible behaviour, the irreversibility line, for the sample magnetisation measured using a vibrating-sample magnetometer. The hashed line denotes the loss of Bragg intensity from a series of measurements with constant temperature and varying magnetic field.

rotation of the sample remains constant, within experimental accuracy, for all measurements in these regions. These features will be discussed below.

3. Conclusion and discussion

These measurements show clearly that a flux-line lattice only exists in a restricted corner of the B–T phase diagram. The Bragg intensity and hence a periodic distribution of magnetic induction disappears at the irreversibility line. The horizontal line on the phase diagram corresponds to the transition from flux-lines to individually pinned "flux-pancakes" in the CuO_2 planes again leading to a loss of the well-defined distribution of magnetic induction. This line marks the position where the inter-plane attractive interaction between pancakes is dominated by the intra-plane repulsive interaction. The exact heat treatment given to the sample is very important in defining the actual position of this feature. This line moves to lower values of magnetic field as the anisotropy of the superconductor is increased. The exact form of the temperature dependence of the integrated intensity for the Bragg reflections at constant magnetic field is also dependent on the state of the sample. This would be expected since we are changing the number and possibly the type of pinning centres. Higher-T_c samples show a more linear dependence with a sharp drop at the irreversibility line and little or no plateau in intensity at low T. A similar temperature dependence has been observed for the flux-line lattice in $YBa_2Cu_3O_7$ [4]. This temperature dependence is faster than would be expected. It may indicate increasing amplitude in the vibration of the flux-lines about their mean position or a quasicontinuous redistribution in the actual positions of the flux-lines relative to their appropriate lattice sites.

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References

[1] E. M. Forgan et al., Nature 343 (1990) 735; E. M. Forgan et al., Physica C 185–189 (1991) 247; M. Yethiraj et al., Phys. Rev. Letts. 70 (1993) 857.
[2] D. A. Huse et al., Nature 358 (1992) 553.
[3] R. Cubitt et al., Nature 365 (1993) 407.
[4] D. McK. Paul et al., Physica B 192 (1993) 70.