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The microscopic investigation of structures of moving flux lines by neutron and muon techniques

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Abstract. We have used a variety of microscopic techniques to reveal the structure and motion of flux line arrangements, when the flux lines in low T_c type II superconductors are caused to move by a transport current. Using small-angle neutron scattering by the flux line lattice (FLL), we are able to demonstrate directly the alignment by motion of the nearest-neighbor FLL direction. This tends to be parallel to the direction of flux line motion, as had been suspected from two-dimensional simulations. We also see the destruction of the ordered FLL by plastic flow and the bending of flux lines. Another technique that our collaboration has employed is the direct measurement of flux line motion, using the ultra-high-resolution spectroscopy of the neutron spin-echo technique to observe the energy change of neutrons diffracted by moving flux lines. The muon spin rotation (μSR) technique gives the distribution of values of magnetic field within the FLL. We have recently succeeded in performing μSR measurements while the FLL is moving. Such measurements give complementary information about the local speed and orientation of the FLL motion. We conclude by discussing the possible application of this technique to thin film superconductors.

Keywords. Flux lines; neutrons; SANS; NSE; muons; μSR.

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1. Introduction

All superconductors which are useful in high magnetic fields admit flux lines when the field is applied. If they are to have zero resistance, then the flux lines must be strongly pinned and not move under the influence of a transport current. This article is about type-II superconductors in a 'not useful' regime: when the flux lines are caused to move. The interest of this research is that the moving flux lines become organized *because* of their motion.

A variety of two-dimensional simulations of flux flow have been performed [1–3]. They all agree that moving flux lines tend to move one behind the other. If the pinning is not too strong, or the motion is fast enough to average out the pinning [4], this will result in a crystallization and alignment of the flux line lattice (FLL), so that the nearest-neighbor direction is on average parallel to the direction of flux line motion. There is great interest in confirming the results of these simulations and in whether we can observe the predicted structures in real three-dimensional samples.

A microscopic probe that can be used to observe flux lines inside superconductors is the neutron, which has a magnetic moment and can therefore be diffracted by the spatially-varying magnetic field in the flux line lattice. The spacing d of flux lines is typically $\sim$1000 Å at $B=0.2$ T. The wavelength of a 'cold' neutron is only $\sim$10 Å, and so Bragg's 2θ will be $\sim$0.01 rad or 0.6°. Hence the FLL causes small-angle neutron scattering (SANS). Further details of the possibilities of the technique are given for instance in [5]. SANS can be used to observe the arrangement of flux lines *while they are in motion*.

There is another way in which the scattering of neutrons can be used to study the *motion* of flux lines: by measuring the change in neutron energy that occurs when the neutron is 'reflected' by moving Bragg planes. The energy change is exceedingly small, but can be detected using the high-resolution 'neutron spin-echo' (NSE) technique [6]. Further details of these results will be reported below.

Another microscopic probe, capable of measuring magnetic effects inside superconductors, is the positive muon. This is produced in nuclear reactions with its spin antiparallel to its momentum. The muon decays with mean lifetime $\sim$2.2 μs, emitting a positron preferentially in a direction parallel to the muon spin. Thus, by detection of the decay positrons, the muon polarization may be measured, and in particular the precession rate of the muon spin in the magnetic field at its site. This technique is known as 'muon spin rotation' (μSR), and has been extensively used to measure the distribution of field values (i.e. the spectrum of muon precession frequencies) in the FLL in a superconductor into which muons have been implanted [7]. When the flux lines are set in motion, the field *at the muon site* will vary with time and the muon may detect a 'motionally averaged' value or distribution of field. The deductions that may be made from this kind of measurement are also described below.

2. SANS observations

Initial measurements have been reported in [8,9]. The results show that in a metallurgically polycrystalline Pb–In sample, the FLL initially formed on cooling in a constant field is also polycrystalline. On passing a transport current exceeding the critical current, the moving FLL tends to become aligned as predicted. However, the alignment is never quite perfect. The bending of the flux lines, due to the extra field arising from the transport current, is also observed. If the current is *slowly* reduced to zero, the FLL becomes polycrystalline again. We believe that this arises from *plastic deformation* of the FLL which is expected to occur just above the critical current [1,2].

3. Neutron spin echo measurements

Details of the experimental setup and results are given in [6,10]. According to Josephson [11], when flux lines move, an electric field E is produced, which depends on their average velocity v_L and the average induction B via $v_L = E/B$. B is known and E may easily be measured by voltage contacts on the sample. Since the neutron energy change measured by NSE is directly proportional to v_L [6], these measurements have allowed a direct check of the Josephson relationship. In addition, we have also demonstrated that one can detect a *spread* of flux line speeds, which macroscopic measurements of E would not reveal.

4. μSR measurements

If flux lines are moving sufficiently fast, and if the FLL nearest-neighbor direction is orientated randomly with respect to v_L, then the time-average of the magnetic field at any point would be the average induction B. Thus, muons, implanted at random positions over the area of the sample, would all precess at the same average rate and a very narrow distribution of field values would result. However, if an ordered FLL is moving with a nearest-neighbor direction aligned exactly with v_L, then complete motional averaging would not occur. This is because the flux line cores would travel only along the lines joining nearest neighbors, whereas the field minima would travel along other lines half way between the former. Detailed simulations [12] indicate that a *two*-peaked field distribution would result. Our experiments [12] show a *single* peak at high flux flow rates. This confirms that the FLL alignment in real polycrystalline samples is not as perfect as suggested by the two-dimensional simulations. It may be that in order to test the predictions exactly, we need to use thin amorphous samples. This would require the use of low energy muons [13], which can be deposited in samples only ~1000 Å thick.

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References

[1] C J Olson, C Reichhardt and F Nori, *Phys. Rev. Lett.* **81**, 3757 (1998)
[2] S Spencer and H J Jensen, *Phys. Rev.* **B55**, 8473 (1997)
[3] G W Crabtree *et al*, *Phys. Rev.* **B61**, 1446 (2000)
[4] T Giamarchi and P Le Doussal, *Phys. Rev.* **B57**, 11356 (1998)
[5] E M Forgan, in *Neutron scattering in layered copper oxide superconductors* edited by A Furrer (Kluwer, Dordrecht, 1998)
[6] E M Forgan *et al*, *Phys. Rev. Lett.* **85**, 3488 (2000)
[7] C M Aegerter and S L Lee, *Appl. Mag. Res.* **13**, 75 (1997)
[8] C Goupil, E M Forgan *et al*, *Physica* **C341**, 999 (2000)
[9] S L Lee, E M Forgan *et al*, *Physica* **B276–8**, 752 (2000)
[10] E M Forgan *et al*, *Physica* **B268**, 115 (1999)
[11] B D Josephson, *Phys. Lett.* **126**, 242 (1965)
[12] D Charalambous *et al*, *Phys. Rev. Lett.* (submitted) (2001)
[13] T J Jackson, E M Forgan *et al*, *Phys. Rev. Lett.* **84**, 4958 (2000)