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Small-angle scattering from the vortex lattice in high-T_c and other superconductors

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Abstract

Small-angle neutron scattering (SANS) is an extremely powerful probe of the vortex state in type II superconductors. The technique may be further enhanced by the use of polarised neutrons and the application of the neutron spin-echo method. We discuss some recent applications of these techniques to the study of both conventional and unconventional superconducting materials, and describe the unique information which SANS can provide on the vortex state. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the mixed state of type II superconductors the flux vortices form a flux-line lattice. The typically large separation of vortex lines in the lattice $d \sim 100$–1000 Å requires the use of long wavelength neutrons and small-angle neutron scattering (SANS). Since the pioneering experiments of Cribier et al. (1964) [1] experiments have been performed on a wide variety of systems including conventional superconductors [2], moving lattices [3,4], a heavy Fermion system [5], high-T_c materials [6–11] and the magnetic superconductors RE-Ni_2B_2C [12,13]. In this paper we shall discuss some recent results from measurements on a variety of different systems, using several approaches to SANS including the use of polarised neutrons and the neutron spin-echo (NSE) technique.

2. Measurement of the transverse field components in $YBa_2Cu_3O_{7-\delta}$

Using the IN15 spectrometer at the ILL we have recently been able to use polarisation-analysed SANS (PA-SANS) to observe the components of the internal flux density transverse to the applied field direction. In an isotropic superconductor all components of the internal flux density are parallel to the applied field, and this is also true in an anisotropic system in which the field is directed along one of the principal-axes of the effective mass tensor [14]. However, in an anisotropic system transverse components may develop. In the high-T_c's this reflects the preference of the supercurrents to flow in the CuO_2 planes, which are not perpendicular to the average induction if the applied field is at an angle to the

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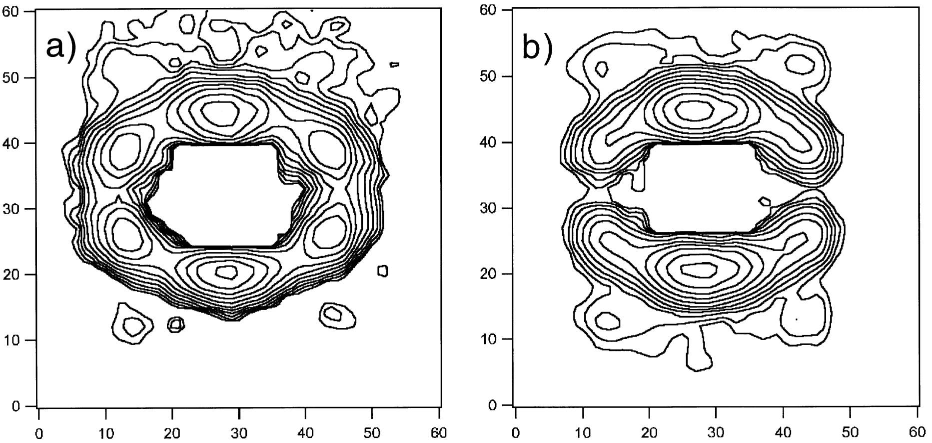

Fig. 1. Contour plot of the diffraction pattern from the flux line lattice in an untwinned $YBa_2Cu_3O_{7-\delta}$, after cooling to 5 K in a field of 0.5 T applied at 55° to the c-direction. (a) Intensity arising from non-spin flipped neutrons, (b) from spin-flipped neutrons. Data taken from above T_c have been subtracted from the patterns.

c-direction. This gives rise to a spatially varying local field with components transverse to the direction of flux quantisation. These components give rise to spin-flip transitions of scattered neutrons, and are thus detectable using PA-SANS [15]. It is worth noting that these transverse components are not observable in bulk macroscopic measurements, since they average to zero over the flux lattice unit cell.

To describe the high-T_c material $YBa_2Cu_3O_{7-\delta}$ (YBCO) we follow the analysis of Thiemann et al. [14] which uses the London model with a uniaxial effective mass tensor characterised by an effective mass ratio γ^2. For YBCO $\gamma = \lambda_c/\lambda_{ab} \sim 4 \rightarrow 8$ [10,16], where λ_c, λ_{ab} are the superconducting penetration depths for currents flowing parallel and perpendicular to the c-direction, respectively. We thus assume the current distribution in the ab-plane to be isotropic. For the field parallel to the c-direction the lattice is triangular, but on tilting the field away from c by an angle θ (for fields not too close to H_{c_1}) the six diffraction spots fall on an ellipse of axial ratio given by [17]

$$(\text{minor/major}) = (\cos^2\theta + \gamma^{-2}\sin^2\theta)^{1/2}. \qquad (1)$$

Even for systems of modest anisotropy such as YBCO, the distortions over a large range of angles from c essentially follow a simple $\cos\theta$ dependence. In reality there is a small in-plane anisotropy between the a- and b-axis ~ 1.2, discussed in more detail elsewhere [8,16]. Thus, with the field parallel to c in an untwinned crystal the diffraction pattern from the flux lattice is slightly distorted.

An example of a diffraction pattern from an untwinned YBCO single crystal is given in Fig. 1, for the field directed at 55° to the c-direction. The field has been rotated about the vertical axis, which is the y-axis in the notation of Ref. [14]. In Fig. 1a, the pattern arises from non-spin flipped (NSF) neutrons, where one sees the distorted hexagonal lattice arising from the tilted field geometry (and a small amount of basal plane distortion). This pattern arises from components of the local field parallel to the applied field (the z-direction in Ref. [14]). Fig. 1b shows the pattern for spin-flipped (SF) neutrons, which arise only from the transverse components of the field. For these components there is the analogue of the 'moment orientation factor' seen in magnetic systems. This is essentially a consequence of $\nabla \boldsymbol{B} = 0$, which means that transverse components parallel to the scattering vector must be zero. This fact, coupled with the absence of y components of the field at reciprocal lattice points for which $G_y = 0$ [14], leads to the lack of scattering at the equator in Fig. 1b. More details of these cross-sections are given in Ref. [18]. The relative intensities of the different diffraction spots and their angular dependence are in good qualitative with the predictions of London theory, details of which are found elsewhere [19].

There is an interesting feature of the SF scattering which comes from the fact that a flipped neutron changes its potential energy U_B in the average flux density B. Since the scattering process is elastic, there must be a corresponding change in the kinetic energy of the neutron. Although this energy change is very small, ~ 60 neV (around 10^{-4} of the neutron kinetic energy), it cannot be neglected. In fact, due to the small scattering angle the shift in kinetic energy has a measurable effect on the Bragg angle required for diffraction to occur. This is illustrated in Fig. 2, where the shift in the centre of the rocking curve can be seen for SF neutrons compared to the NSF case.

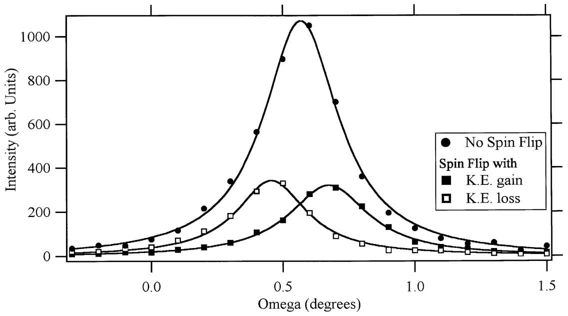

Fig. 2. Rocking curves for the flux lattice Bragg peaks in untwinned YBCO, showing the different Bragg angles for SF neutrons compared to NSF neutrons.

3. Observations of moving vortex lattices

There is currently much interest in the behaviour of the vortex lattice under the influence of a driving current, e.g. Ref. [20], although SANS experiments of this type were first performed many years ago [21], and more recently on the conventional anisotropic material $NbSe_2$ [4]. We have recently performed measurements on polycrystalline ribbons of Nb–Ta and other alloys, in which the vortex lines are caused to move by the passage of a sufficiently large driving current which exerts a Lorentz force on the vortices.

Due to developments in instrumentation and the high flux on the IN15 spectrometer at the ILL, it is now possible to perform *inelastic* measurements on a moving vortex lattice using the neutron spin-echo technique (NSF). It is possible to measure the change in energy ΔE of the neutron on diffraction from the moving lattice, which may be represented as a reflection from a moving mirror: $\Delta E = hv_f/d$, where v_f is the speed of the flux line planes and d is their spacing. The speed is related to the induction B and the electric field E via $v_f = E/B$, which is typically $< 1\ \mathrm{ms}^{-1}$. The resultant energy change leads to a phase shift ϕ in the spin-echo: $\phi = (\Delta E/\hbar)t = (2\pi v_f/d)t$ where t is the Fourier time of the precession, which is proportional to the line-integral of the spin-echo precession field.

Some representative results are shown in Fig. 3, which demonstrate that the average speed of the vortex lines may be measured using the SE technique. The amplitude of the NSE signal is also affected by the vortex motion, and gives information on the distribution of speeds within the specimen. Further details of such measurements are given elsewhere [22].

A variety of interesting dynamically induced transitions of the vortex state are predicted theoretically, examples of which are found in the numerical simulations of Ref. [20]. The phase diagrams include regions of plastic vortex flow, smectic phases and moving vortex lattices, which depend upon field, driving current and temperature [20]. Using the D11 spectrometer at the ILL we have recently investigated these phenomena in conventional superconducting alloys such as NbTa. An example of the diffraction pattern from a sample cooled in an applied field is given in Fig. 4a. One can see that the signal is characteristic of an extremely disordered vortex arrangement, with an amorphous or polycrystalline structure factor with no clearly discernible Bragg peaks.

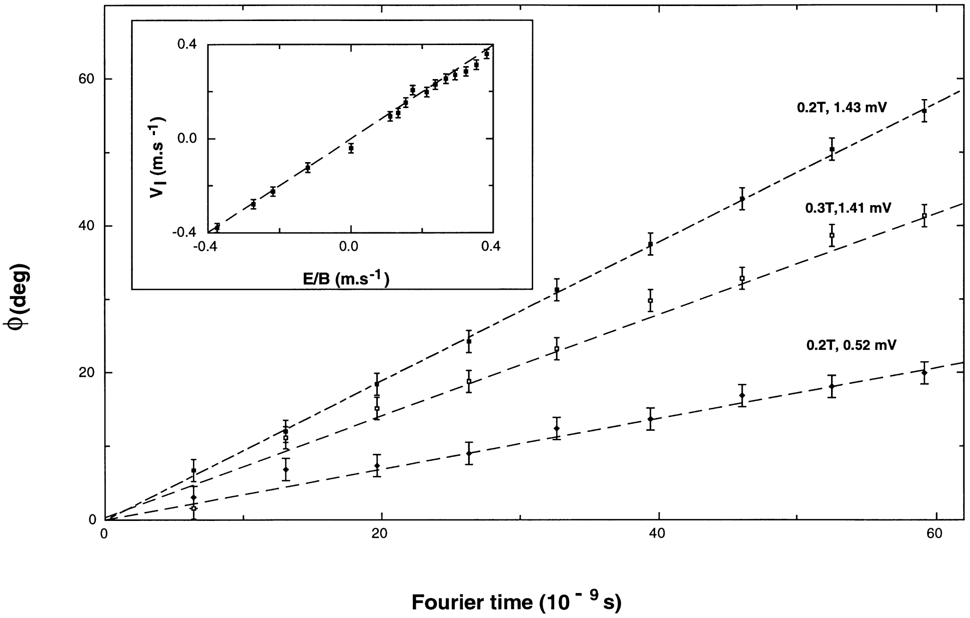

Fig. 3. Spin-echo phase shift as a function of Fourier time for various values of E/B in a Nb–Ta sample.

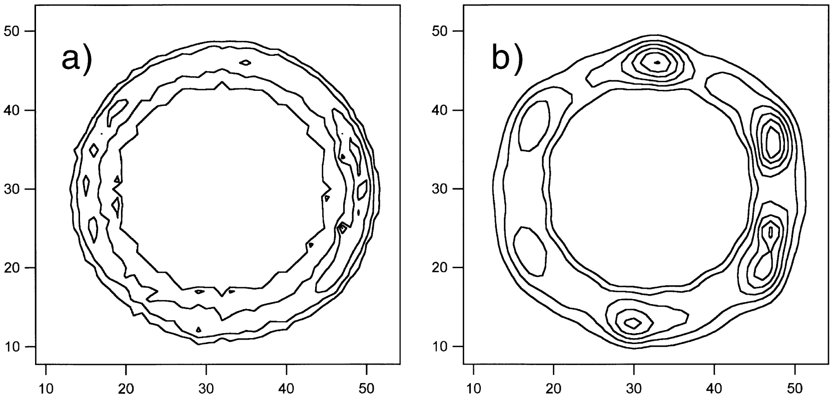

Fig. 4. Diffraction pattern from a conventional superconducting alloy (a) cooled to 2 K in an applied field of 0.2 T and a zero current, (b) prepared as in (a), but followed by the application of a current of 20 A along the vertical direction in the figure.

Fig. 4b illustrates the effect of passing a sufficiently large DC current through the sample so that the vortices begin to flow. The current is passed along the vertical direction, and causes the vortices to form a well-ordered lattice with one set of planes parallel to the direction of vortex flow. The creation of a preferred direction is in good agreement with simulations [20], and illustrates the unique information which can be revealed directly by SANS experiments compared to other methods such as *V–I* characteristics. Further results of these experiments will be described elsewhere [23].

Acknowledgements

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