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Vortex studies in heavy-ion irradiated $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ probed by μSR and small-angle neutron scattering

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Abstract

μSR and small-angle neutron scattering (SANS) have been used to probe the vortex arrangement in single crystals of the high-T_c superconductor $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ which have been irradiated with heavy ions to produce columnar defects. The influence of these pinning sites on the spatial arrangement of the vortices is discussed, and the results are compared with numerical simulations. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the high-T_c and other anisotropic superconducting systems the vortex lattice may be highly susceptible to positional fluctuations [1]. These may originate from pinning sites in the material which anchor the vortex lines to produce static distortions, or from thermal agitation which causes dynamic fluctuations. The detailed inter-play of vortex–vortex interactions, vortex–pin interactions and thermal fluctuations is pivotal to understanding the magnetic phase diagram of these materials. In highly anisotropic systems the situation is further complicated by the extreme flexibility of the vortex lines. In the more extreme case an appropriate representation of such a system is a stack of two-dimensional 'pancake' vortices which are coupled by Josephson currents and/or electromagnetic interactions [1,2]. In the layered high-T_c materials the pancakes are confined to the CuO_2 planes. The vortex–vortex interaction then has inter-plane and intra-plane components, the relative strengths of which also have a profound influence on the vortex behaviour.

The susceptibility of the vortex system to thermally induced vibrations is detrimental to potential applications since this enhances the mobility of the vortices. An applied current may thus more easily cause the motion of a vortex giving rise to a voltage and hence destroying the property of zero resistance. The role of pinning is therefore crucial to

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applications, since vortex motion is inhibited. This is also true of the conventional low-T_c isotropic alloys used in commercial wires for superconducting-magnet construction.

One method to dramatically enhance the pinning in high-T_c materials is to irradiate them with high-energy heavy ions. The ions are to penetrate the sample where they cause amorphous tracks of damage which act as extended anisotropic pinning defects. These columnar defects (CD) can act as particularly effective pins, especially if their density is greater than that of the vortices. It is convenient to introduce the concept of the matching field B_Φ, which is the field at which the density of the vortices equals that of the CD. The influence of CD on vortex behaviour was investigated theoretically by Nelson and Vinokur [3,4], who mapped the system onto one of boson localisation in two dimensions. At low temperature and at fields $B < B_\Phi$, a 'Bose-glass' (BG) phase is predicted, with flux lines localised on the columnar pins, with a sharp phase transition at higher temperature to an entangled liquid of vortex lines.

A great deal of experimental data has been interpreted within the Bose glass theory, yet one can question whether the existence of a true BG phase is realistic in a CD sample. In reality several of the assumptions in the BG model are difficult to realise experimentally. In particular, even below B_Φ the positions of the vortices may not be random, but there may exist spatial correlations in a plane perpendicular to the field, which is demonstrated in numerical simulations by Täuber and Nelson [5]. These correlations are believed to originate from two sources: firstly, a random distribution of defects will naturally contain some areas where they are closely spaced, such that vortex–vortex interactions will make it energetically unfavourable for all of them to be occupied, even at the matching field. Secondly, for a sample cooled in an applied field at which vortex–vortex interactions are significant (strongly overlapping vortices) at the depinning temperature, the vortices will already be correlated as they enter the irreversible region. As they become localised onto tracks, significant vortex–vortex correlations are thus frozen in [6]. Here we present some muon and neutron results which throw light on some of these issues.

2. Experimental

The $Bi_{2.15}Sr_{1.85}Ca_1Cu_2O_{8+\delta}$ (BSCCO) crystals were grown using a floating zone technique [7]. Since a μSR experiment requires samples of large area and a thickness of at least 200 μm, the sample consisted of a mosaic of crystals of typical dimension 5 mm × 3 mm × 400 μm. The irradiation was carried out at GSI (Darmstadt, Germany) using 17.7 GeV U ions, as described in Ref. [8]. The μSR experiments were carried out on beamline πM3 at the Paul Scherrer Institute (PSI), Switzerland and at the ISIS MUSR facility at the Rutherford Appleton Laboratory (RAL), UK, using experimental arrangements as described in Refs. [9,10] (PSI) and [11] (RAL). A transverse geometry was used, and the samples were backed by an Fe_2O_3 plate, to rapidly depolarise, outside of the observable time window, any muons not hitting the sample. The neutron measurements were carried out at the Institut Laue Langevin (ILL), Grenoble, France, using instrument D11 and an arrangement similar to that described in Refs. [9,12].

3. μSR line shapes of irradiated $Bi_{2.15}Sr_{1.85}Ca_1Cu_2O_{8+\delta}$

By Fourier transforming the muon decay spectra one obtains the line shape which closely reflects the probability distribution of internal flux density $p(B)$ of the superconductor. For a conventional vortex-line lattice $p(B)$ the shape of this distribution is highly asymmetric with a tail extending to fields above the average, due to muons stopping in or near the narrow vortex cores (see e.g. Ref. [13]). The width of the distribution, which is measured by the second moment of $p(B)$, is given for fields not too close to H_{c_1} as

$$\langle \Delta B^2 \rangle = \frac{0.00371\Phi_0^2}{\lambda^4}, \tag{1}$$

where λ is the superconducting penetration depth. The high-field tail will also be present when a vortex line is pinned to a columnar defect, but the line shape will be influenced by the disorder introduced into the vortex lattice by the presence of the columnar defects. It was shown by Brandt [14] that distortions of a flux lattice composed of rigid vortex lines generally lead to smearing of the field distribution, which convolutes the ideal lattice field distribution with that due to the disorder [14]. In this instance the width of the distribution, which is measured by the second moment of $p(B)$, $\langle \Delta B^2 \rangle$, will always be *greater* than that of the ideal lattice. For the case of an ideal Bose-glass system with perfect pinning and a field equal to the matching field, such that each vortex is trapped by a defect, the positions of the vortices would be random in a plane perpendicular to the applied field. This case has been treated analytically in Ref. [15]. In this case the width of the distribution is given by

$$\langle \Delta B^2 \rangle = \frac{B_{\mathrm{app}} \Phi_0}{4\pi\lambda^2}. \tag{2}$$

These two extremes are illustrated in Fig. 1a, where we compare the numerically simulated line shape for an ideal vortex lattice with that for a random distribution of rigid vortex lines. The simulations were performed in real space using the London model description of the field variation around a single vortex line. We also include an intermediate case, where we have taken the spatial distribution of vortices found in Monte Carlo simulations of an irradiated system [5], where vortex correlations have been allowed to develop for reasons discussed above. It can be seen that this latter case is much closer to that of an ideal lattice than the purely random case, although there are significant qualitative differences in the line shape. μSR is sensitive to local order, and it can be shown that even a liquid-like structure factor will have a width close to that of the ideal case. The presence of a truly random arrangement of vortices would give rise to a μSR signature which is thus clearly distinguishable.

In Fig. 1b we present a measured line shape from a BSCCO sample which has been irradiated

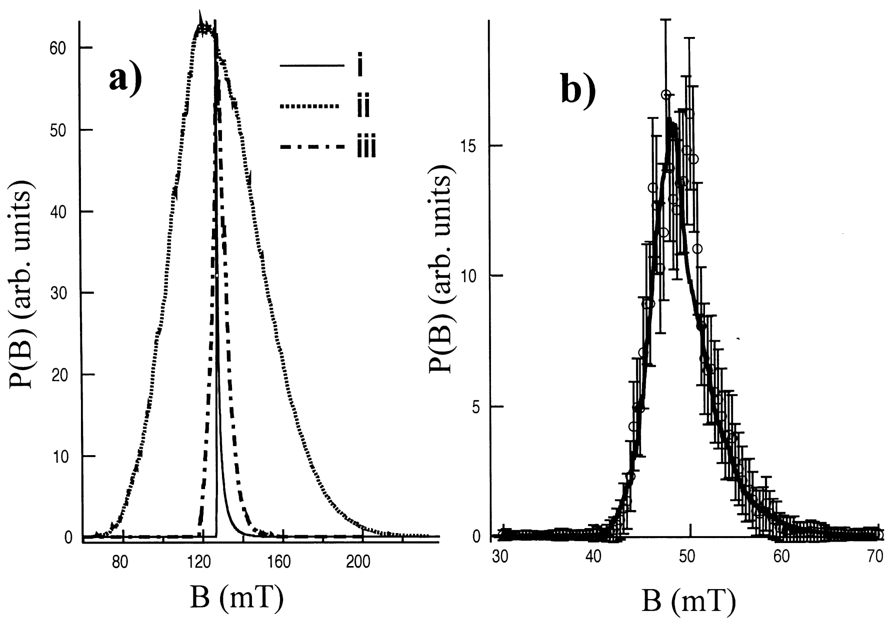

Fig. 1. (a) Numerical simulations of the μSR line shape for (i) an ideal triangular vortex lattice of lattice parameter $a = 0.67\lambda$, (ii) a random arrangement of vortices with the same average density as in (1), and (iii) a vortex arrangement for a Monte Carlo simulation of rigid vortices in a CD matrix with $B \sim B_{\Phi}/2$. (b) A measured μSR line shape for an irradiated BSCCO sample with a matching field of 100 mT, after cooling in a field of 50 mT to a temperature of 5 K. The solid line is the result of a numerical simulation of the line shape using the results of Monte Carlo simulations for similar conditions taken from Ref. [5], using a penetration depth of 2000 Å.

parallel to the c-direction to produce a matching field $B_{\Phi} = 100$ mT. The line shape is compared with that from the simulations of Täuber and Nelson [5] in which vortex–vortex spatial correlations exist. There is clearly a fair correspondence between the two curves, indicating that the latter is a reasonable representation of the positional correlations in this system at low temperature, which are clearly not random. This indicates that caution must be exercised when trying to relate the predictions of Bose-glass theory to the behaviour of vortices in irradiated samples.

It is reasonable to question the validity of the above type of modelling in BSCCO, since it is well known that the vortex lines in the pristine system are extremely flexible, as has indeed been shown by a number of μSR experiments [10,16–18]. For this geometry with the field $B < B_{\Phi}$ directed parallel to the tracks, the pancake vortices will tend to form stacks aligned with defects due to their strong pinning influence. At low temperature where thermal disruption is small, the system will be one of rigid line-like objects which are spatially disordered in a plane perpendicular to the field, as in the above models. At higher temperatures the vortex arrangement will thus be more complicated. Magnetisation and muon measurements suggest that excitations in this field range may consist of short strings of pancake vortices [19,8].

4. Comparison with SANS measurements

For something approaching an ideal vortex line lattice, SANS experiments give rise to a Bragg diffraction pattern, as measured for BSCCO in Ref. [20]. In a highly disordered system of vortices the scattered neutron intensity is given by a convolution of the pair correlation function $S(q)$ of the vortex positions and the square of the form factor of a single flux line $f(q) = B(1 + \lambda^2(T)q^2)^{-1}$ [12]. If the positions of the vortices are truly random, then the scattered neutron intensity $I(q) \propto f^2(q)$ will not contain any structure. If there exist some residual vortex–vortex correlations, these will give a small contribution to $I(q)$ from an $S(q)$ peaked at $q \sim 2\pi\sqrt{B/\Phi_0}$. In Fig. 2 we plot a quantity derived by dividing $I(q)$ by q^5, which is related to $S(q)$. Here we see that $S(q)$ is indeed peaked, and analysis shows that this occurs at the q expected for a triangular vortex lattice at the same field. The total $I(q)$ is dominated, however, by the form factor contribution $f(q)$, and should be contrasted with the

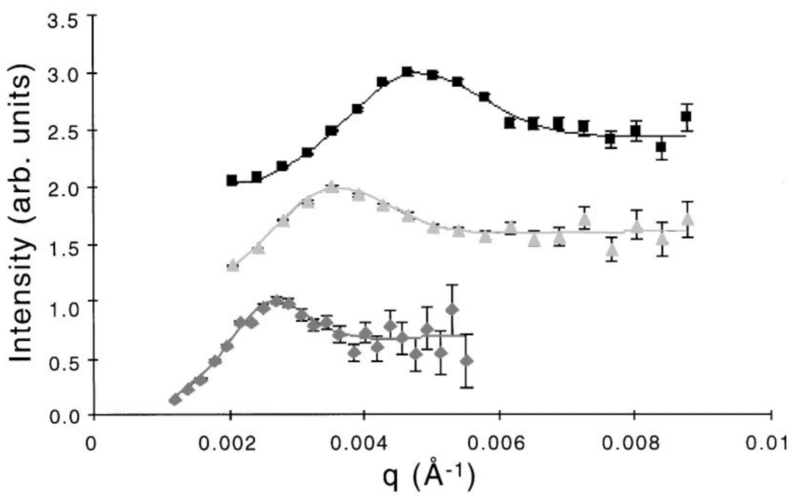

Fig. 2. $S(q)$ versus q for three different fields in a BSCCO sample with $B_{\Phi} = 100$ mT, with both tracks and field parallel to c. The data were obtained by dividing the SANS intensity $I(q)$ by q^5 to account for both London form factor and an additional $1/q$ term in the scattering function [20]. For clarity the three curves have been plotted with an arbitrary vertical offset.

well-defined Bragg peaks measured for the pristine material at similar fields [20]. Thus as with the μSR results there is good evidence for a highly disordered lattice which nonetheless retains considerable correlations between flux line positions. Further details of the temperature dependence of the neutron intensity and the μSR line width are given in Ref. [8].

Acknowledgements

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