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Muon-spin rotation (μSR) measurements on $Bi_2Sr_2CaCu_2O_{8+\delta}$ in the presence of columnar defects

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Abstract

We present muon-spin rotation measurements on the cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$, in the presence of columnar defects. The results are compared to measurements on the pristine material, and indicate a strong suppression of thermal fluctuations of the vortex positions in the irradiated material.

Keywords: Superconductors – high-T_c; Muon-spin rotation; Flux-pinning; Fluctuations

The high-temperature superconductor (HTS) $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) provides an excellent system on which to study exotic vortex behaviour. The very high superconducting anisotropy makes the flux vortices particularly susceptible to fluctuations, which may be either dynamic (thermally-induced) or static (pinning-induced) [1]. Muon-spin rotation (μSR) is a very useful probe of the vortex state in superconducting materials, and over recent years has been used successfully to study static and dynamic vortex fluctuations in BSCCO [2–4]. The occurrence of dynamic fluctuations may be detrimental to successful application of HTS, since they result in increased vortex mobility. The passage of a transport current through a sample induces a Lorentz force on the vortices which can give rise to dissipation if the vortices are free to move. Vortex motion may be hindered by the presence of defects in the crystal which act as pinning sites. For a pinned vortex, however, dynamic fluctuations lead to an effective reduction of the pinning potential, so that the vortices may more easily break free. At higher temperatures, in the presence of weak pinning, the vortex fluctuations may even cause the vortex lattice to melt to a vortex liquid, leading to very large dissipation [1, 2, 5, 6].

In order to reduce the influence of dynamic fluctuations, ionising radiation has been used to induce defects in the material which can act as pinning sites. In particular, the use of heavy ions to produce extended tracks through the bulk of the material has attracted much attention. The magnetic phase diagram in the presence of these columnar defects has been studied theoretically by mapping the problem onto a system of 2D bosons subject to static disorder [7]. At low temperatures, and for a density of vortices less than the density of columnar defects ($B < B_\phi$), a Bose-glass (BG) phase is predicted, with strong localisation of the vortices on the tracks. In continuous anisotropic vortex systems such as $YBa_2Cu_3O_{7-\delta}$ (YBCO), this leads to an upward shift of the irreversibility line which marks the onset of strong disipative current flow [8]. More recently, the influence of columnar defects in more anisotropic systems such as BSCCO have been studied [9, 10]. In the pristine material the flux lines are best modelled as stacks of two-dimensional 'pancake' vortices, weakly coupled by Josephson or electromagnetic interactions [2]. Unlike in YBCO, in BSCCO the influence of columnar defects has been shown to completely alter the nature of the IL, from a melting transition [5, 6] to a pinning crossover [9, 10].

Here we present some recent μSR measurements which examine the influence of columnar defects on the dynamic fluctuations of vortices in BSCCO. In a μSR experiment the muons come to rest in the sample and precess at a rate determined by the local magnetic field.

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Since the muons implant randomly over the vortex lattice, the field probability distribution $p(B)$ of the vortex arrangement can be obtained from the frequency spectrum of the muon precession. The distribution $p(B)$ is intimately related to the spatial modulation of the field due to the vortex lattice, $B(r)$ [2–4, 6]. The width of the field distribution, given by the second moment of the μSR lineshape, $\langle \Delta B^2 \rangle \propto \lambda^{-4}$, where λ is the superconducting penetration depth in a plane perpendicular to the applied field direction. The temperature dependence of $\langle \Delta B^2 \rangle$ should thus ordinarily reflect that of λ, and should fall to zero as $\lambda(T)$ diverges at T_c. In pristine BSCCO we have previously shown that there is a strong field dependence of $\langle \Delta B^2 \rangle(T)$, which would not be expected for a conventional superconductor [4]. This has been explained in terms of a motional narrowing effect on the lineshape due to rapid thermal fluctuations of the vortices, the amplitude of which should be field depedent. An extremely good description can be obtained by inclusion of a Debye–Waller type correction of the form:

$$\langle \Delta B^2 \rangle(T, B) = \sum_{k \neq 0} \exp\left(-\tfrac{1}{2}\langle u^2 \rangle k^2\right)/(1 + \lambda^2 k^2)^2,$$

where $\langle u^2 \rangle(T, B)$ is the mean square thermal fluctuation, and k is a reciprocal vector of the vortex lattice [4]. The form of $\langle u^2 \rangle(T, B)$ which was found to best model that data was that which viewed the vortex lines as a stack of weakly-coupled pancakes. Recent measurements provide a very self-consistent picture in which features of both the melting line and $\langle \Delta B^2 \rangle(T, B)$ point towards a system controlled largely by electromagnetic interactions [2].

The sample used in this work is an aligned mosaic of high-quality single crystals of BSCCO irradiated with 17.7 GeV uranium ions at GSI, Darmstadt. The induced damage tracks lie parallel to the crystal c-axis, and have a density equal to the density of flux-lines at 100 mT (B_ϕ). Fig. 1 is a plot of the temperature dependence of the normalised μSR linewidth $\langle \Delta B^2 \rangle^{1/2}(T, B)/\langle \Delta B^2 \rangle^{1/2}(0, B)$. This is a useful way to present the data as it allows an easy comparison of the form of the temperature dependence of $\langle \Delta B^2 \rangle^{1/2}(T, B)$ for a range of applied fields. This normalisation is necessary since even for an ideal, conventional flux lattice, the low-temperature value $\langle \Delta B^2 \rangle^{1/2}(0, B)$ is expected to exhibit a slow variation with field, although the temperature dependence should remain unaltered. It is apparent from Fig. 1 that there is no change in the temperature dependence between 50 and 150 mT. This is in complete contrast to the pristine material, where over this field range the form of the temperature dependence varies dramatically [2, 4]. This is a strong indication that the thermal fluctuations of the vortex positions, which give rise to this dependence in the pristine material, are strongly suppressed in the presence of columnar defects. This is not an unexpected result, since extended defects are expected to act as extremely efficient pinning sites, with delocalisation of the vortices from the pinning sites pushed to much higher temperatures than for isotropic pinning [1, 7].

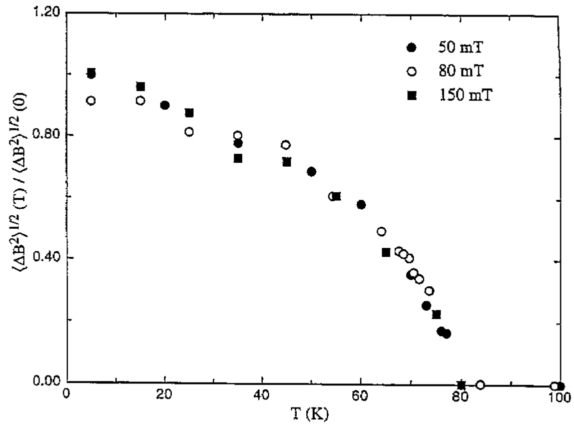

Fig. 1. The temperature dependence of the normalised second moment of the μSR lineshapes for BSCCO containing columnar defects. The equivalent flux-density of the defects is $B_\phi =$ 100 mT. There is no significant difference between the data measured at 50 mT (filled circles), 80 mT (open circles) and 150 mT (filled squares). This is in stark contrast to the pristine material [2, 4], and indicates the supression of strong thermal fluctuations of the vortices.

In conclusion, we have used μSR to detect substantial differences between the amplitude of vortex fluctuations in pristine BSCCO samples and in those containing columnar defects. In the latter there is no significant evidence for the influence of fluctuations on the μSR linewidth, indicating a suppression of the fluctuations by the anisotropic pinning sites.

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