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Muon-spin rotation studies of the flux lattice in κ-(BEDT-TTF)$_2$Cu(SCN)$_2$

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Abstract

Muon spin rotation (μSR) studies of the vortex lattice in the superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$ have revealed a crossover from a quasi-$2d$ to a vortex-line lattice structure for fields below a characteristic field B_{cr}. The μSR-lineshapes measured from the vortex-line lattice have allowed a re-evaluation of the in-plane penetration depth.

Keywords: Organic superconductors, Superconducting phase transitions, Magnetic measurements

The superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$ (ET-SCN) has recently attracted much interest [1, 2, 3, 4, 5]. This is due largely to its two-dimensional ($2d$) Fermi surface which has led to claims of unusual superconducting pairing [5] and unconventional vortex structure [3, 4]. In this respect they have much in common with the high-T_c superconductors, where the quasi-$2d$ Fermi surface topography also leads to exotic vortex behaviour [6, 7, 8, 9]. The muon-spin rotation (μSR) method is extremely useful for investigating the microscopic flux-vortex behaviour in the bulk of a superconductor and has been particularly successful when applied to studies of the similarly anisotropic high-T_c material $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (BSCCO) [6, 8, 9]. Here we discuss some recent μSR results which have given new insight into the magnetic phase diagram of ET-SCN, with emphasis on the consequences for the determination of the in-plane penetration depth $\lambda_{||}$.

The superconducting anisotropy of a uniaxial superconductor may be quantified as the ratio $\gamma = \lambda_\perp/\lambda_{||}$, where $\lambda_\perp$, $\lambda_{||}$ are the superconducting penetration depths for currents flowing perpendicular and parallel to the superconducting planes. Recent *ac*-susceptibility measurements have allowed estimates of $\gamma \sim 150 - 350$ [3], which is similar to extremely anisotropic high-T_c materials such as BSCCO [9, 8]. For such systems it is useful to model the flux vortices as being essentially $2d$ objects confined to the conduction planes. These 'pancake' vortices interact with vortices in neighbouring planes via electromagnetic coupling and Josephson tunnelling currents, and may thus form strings of pancakes which resemble vortex lines. The degree of rigidity of these line-like vortices depends on the strength of the coupling, and in highly anisotropic materials such as ET-SCN and BSSCO is expected to lead to fairly flexible objects. If the energetic cost of in-plane shear deformations of the lattice outweighs that for inter-layer tilt deformations of the lattice, then the system will tend to adopt a quasi-$2d$ character. Such a system might comprise a stack of $2d$-lattices , well-ordered in each layer but only weakly correlated along the direction of the applied field. For a strongly Josephson-coupled superconductor this is expected to occur above a characteristic field $B_{2D} = \phi_o/(\gamma s)^2$, where s is the separation of the superconducting layers and ϕ_o is the flux quantum. A similar crossover behaviour has been observed in BSSCO using μSR [6, 10], and should also be expected to occur in ET-SCN.

The sample consisted of a $10 \times 20\text{mm}^2$ mosaic of crystals, grown by an electrochemical oxidation method. Each crystal measures typically $1.0 \times 1.5 \times 0.5\text{mm}^2$ with the largest face parallel to the superconducting planes. The experiments were performed on the MUSR spectrometer at ISIS, UK and on the πM3 beamline at PSI, Switzerland as described in refs. [2, 6, 11].

In a μSR experiment the muons come to rest in the sample and precess at a rate determined by the local internal fields of the mixed state of the superconductor. By sampling the real space field distribution $B(r)$ the muons thus give information on the closely

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related probability distribution of the internal field values, $p(B)$. The μSR-lineshapes, which are a good measure of $p(B)$, contain information on the local field distribution and also on the magnitude of the penetration depth $\lambda_{\|}$ and the coherence length $\xi_{\|}$. For instance, for a vortex lattice composed of rigid, static vortex lines, $p(B)$ has a well-defined and easily identifiable shape [12]. Moreover, for B perpendicular to the planes the width of the distribution $\langle \Delta B^2 \rangle^{1/2} \propto \lambda_{\|}^{-2}$.

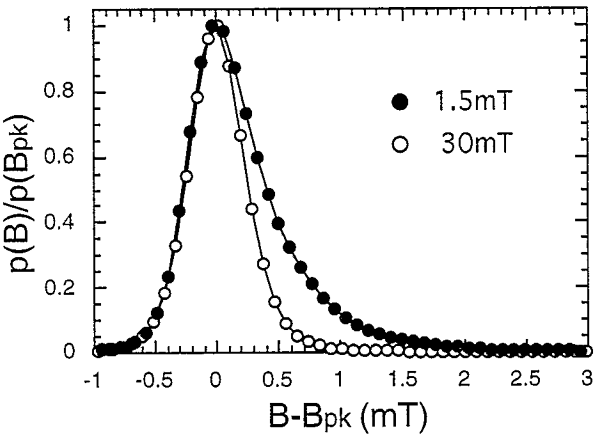

Figure 1: The μSR normalised lineshapes $p(B)$ taken after cooling from above T_c in fields applied perpendicular to the superconducting planes at a) 1.5mT, 3K b) 3mT, 3K. B_{pk} is the the mode of each distribution.

We have recently used μSR to observe a dimensional crossover in ET-SCN [2]. These experiments were performed at ISIS with B directed at 45° to the conduction planes. The essential features may be observed in the data of Figure 1, measured at PSI with B perpendicular to the conduction planes. The solid points of Figure 1 represent a lineshape measured at 1.5mT and 3K, the lowest temperature obtainable on the πM3 spectrometer. This has all of the features to be expected from a vortex-line lattice: a low field cut-off; a peak just below the average field; and a low probability tail running to fields much higher than the average, which arises from the fields close to the vortex cores [12]. The second lineshape in Figure 1, taken at 30mT and 3K, has quite a different shape. Most notably the long high-field tail is much reduced, so that the overall shape is much more symmetric. This is the type of lineshape which has been reported in previous μSR studies [4, 5]. Similar lineshapes have also been reported in BSCCO above a characteristic crossover field B_{cr}, and can be easily understood as arising from a quasi-2d flux lattice. At fields above B_{cr} the vortex lines become more flexible and the pancake vortices in each layer are subject to fluctuations of position which tend to smear out the high-field values arising from the vortex cores. These fluctuations may arise from the effects of random point pinning on the pancakes, thus inducing a static disorder along the direction of the field [6, 7]. At higher temperatures thermally-induced disorder can also occur [8]. The onset of this quasi-2d behaviour has been determined to be $B_{cr,45}$ ~5mT for B at 45° to the planes [2], corresponding to B_{cr} ~$5.0/\sqrt{2}$ =3.5mT for B perpendicular to the planes.

While for an ideal vortex-line lattice $\langle \Delta B^2 \rangle^{1/2} \propto \lambda_{\|}^{-2}$, this is no longer valid for narrowed lineshapes such as those for $B > B_{cr}$. Since previous μSR studies have concentrated on analysing these high-field lineshapes, they have tended to systematically overestimate the value of $\lambda_{\|}$. Some attempts have previously been made to correct for dynamic disorder [4], but here we present the first analysis on the lineshapes arising from line-like vortices in ET-SCN. While $\langle \Delta B^2 \rangle^{1/2}$ is a useful measure of $\lambda_{\|}$, it too involves systematic errors. For lineshapes having long high-field tails with low probability $p(B)$, the width of the lineshape is underestimated as the signal becomes comparable to the experimental noise for field values having low $p(B)$. It is much better to estimate $\lambda_{\|}$ from the separation of the peak in $p(B)$, B_{pk}, from the average field value $\langle B \rangle$, where the systematic errors are much reduced. This is given by:

$$\langle B \rangle - B_{pk} = \frac{\phi_o \sqrt{3}}{d^2 2} \sum_{m,n} \frac{(-1)^m}{1 + \lambda_{\|}^2 \left(\frac{2\pi}{d}\right)^2 (n^2 - mn + m^2)}$$

where d is the flux-lattice plane spacing and m, n are integers obeying m. NOR $.n = 0$. The 1.5mT data of Figure 1 yields a value of $\lambda_{\|} = 6500$Å. A recent analysis of the low field phase diagram of highly anisotropic superconductors suggests that for a material having $\lambda_{\|} \lesssim \gamma s$ the system is controlled at low temperatures by electromagnetic coupling [13, 9]. We have recently demonstrated that in this case a more reasonable estimate of B_{cr} is given by $B_{cr} \sim B_{\lambda} = \phi_o/\lambda_{\|}^2$ [10]. For ET-SCN this would yield $B_{\lambda} \sim$ 5mT, in reasonable agreement with the estimated values of B_{cr} ~3.5–5mT[2]. Thus like BSCCO, ET-SCN may be a system controlled largely by electromagnetic interactions [10, 9, 2, 13].

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