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Angular-dependent muon-spin rotation on the mixed state of the organic superconductor K-(BEDT-TTF)$_2$CU(SCN)$_2$

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Abstract

We have performed muon-spin rotation (μSR) measurements on the organic superconductor K-(BEDT-TTF)$_2$CU(SCN)$_2$ as a function of the angle between the applied field and the superconducting planes. The measurements are found to have much in common with those on the anisotropic cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$.

Keywords: Superconductors; Muon-spin rotation; Organic compounds; Flux distribution

The organic superconductor K-(BEDT-TTF)$_2$ CU(SCN)$_2$ (ET) (T_c = 10.4 K) has much in common with the very anisotropic high-T_c superconductors (HTS) such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). As with the cuprate systems, ET has a highly layered crystal structure, with superconducting charge carriers confined largely within the conduction planes. The plane separation $s = 16$ Å of ET is comparable to that of BSCCO, and like BSCCO it has a superconducting anisotropy $\gamma = \lambda_\perp/\lambda_\parallel > \sim 100$, where $\lambda_\perp$, $\lambda_\parallel$ are the superconducting penetration depths perpendicular and parallel to the planes, respectively [1]. BSCCO is a very typical example of a highly anisotropic HTS, and has been the subject of intense study concerning the exotic flux vortex arrangements which it exhibits. Muon-spin rotation (μSR) has made significant contributions to the study of this and other materials, due to its ability to microscopically probe the local distribution of the magnetic fields inside the bulk of the material [2–5]. Here we present angular-dependent μSR data on ET, which we compare to similar measurements on BSCCO.

Until recently μSR investigations on ET had been confined largely to high fields, typically ~ 100 mT [4, 5]. The line shapes obtained in those experiments were reminiscent of those observed at high fields in BSCCO, which result from disorder in the vortex lattice along the length of the vortex lines. This occurs in BSCCO above a characteristic crossover field B_{cr}, where a field-induced softening of the vortex line rigidity renders it more susceptible to the influence of random point pinning sites [3]. Thus, the vortex lines are better described as a weakly coupled *disordered* stack of 2D 'pancake' vortices. In BSCCO the μSR line shapes below B_{cr} are as expected for a conventional lattice of rigid vortex lines, and B_{cr} has thus been described as a dimensional crossover field. Similar changes have recently been found in samples of ET [6, 7], indicating that this material also undergoes a crossover to a more conventional vortex-line lattice as the field is reduced below $B_{cr} \sim 7$ mT. For a strongly Josephson-coupled layered superconductor the theoretical expression for the crossover field is given by $B_{cr} \sim \phi_0/(\gamma s)^2$, where ϕ_0 is the flux quantum. This expression may need modification for highly anisotropic systems [3, 6].

The experiments were performed on mosaics of high-quality single crystals of ET. The crystals were aligned so

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that their conduction planes were parallel, although unaligned within the plane. The experiments were carried out mainly on a deuterated sample, ET-D8, although some results on undeuterated material ET-H8 have also been included. The reason for using deuterated samples was to reduce the contribution to the μSR line shapes due to nuclear depolarisation, which in undeuterated samples is comparable to the superconducting contribution to the linewidth in ET due to the long pentration depth ($\lambda_{\parallel} \sim 5000$ Å [6, 7]).

The experiments were carried out on the MUSR spectrometer at the ISIS facility, UK, and on the πM3 spectrometer at the Paul Scherrer Institute, Switzerland. These two facilities have different beamline geometries, with the muon spin polarised parallel or perpendicular to their momentum direction, respectively. Since for a μSR experiment the field is always perpendicular to the muon spin, these two complementary geometries allow experiments to be performed on the plate-like crystals for the whole range of angles between the applied field and the planes. In a μSR experiment the muons come to rest in the sample and precess at a rate determined by the local magnetic field. 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 width of the field distribution, given by the second moment of the μSR line shape, $\langle \Delta B^2 \rangle \propto \lambda^{-4}$, where λ is the penetration depth in a plane perpendicular to the applied field. For an anisotropic superconductor this will vary with the angle ϑ between the applied field and the normal to the superconducting planes, reflecting the superconducting anisotropy. For a continuous anisotropic vortex lattice, such as the HTS $YBa_2Cu_3O_{7-\delta}$ (YBCO), the angular variation $\langle \Delta B^2 \rangle(\vartheta)$ has been calculated in Refs. [7–9]. This should take the form

$$\langle \Delta B^2 \rangle(\vartheta) = \langle \Delta B^2 \rangle(0)(\cos^2 \vartheta + (1/\gamma^2) \sin^2 \vartheta). \qquad (1)$$

This was indeed found to be the case for YBCO, which has only moderate anisotropy [9]. However, in the high-field region of BSCCO, $B > B_{cr} \sim 65$ mT, a very much weaker depedence was found [9], which was inconsistent with its high anisotropy parameter $\gamma > \sim 100$. This is attributed to the pinning-induced disorder discussed above. Recent measurements in BSCCO at lower fields indicate a move towards the expected behaviour of Eq. (1) as the field falls below B_{cr} [10].

Fig. 1 contains the normalised angular dependence $\langle \Delta B^2 \rangle^{1/2}(\vartheta)/\langle \Delta B^2 \rangle^{1/2}(0)$ for ET-D8 and ET-H8 samples at fields above and below B_{cr}. According to Eq. (1), for large values of γ this should reduce to a $\cos(\vartheta)$ dependence except for values of $\vartheta \approx 90°$. The data taken at high fields is very reminiscent of measurements taken on BSCCO for $B > B_{cr}$ [9], with very little change in the linewidth between $\vartheta \approx 0°$ and $\vartheta \approx 45°$. For comparison a $\cos(\vartheta)$ dependence is also included in the plot. Referring now to the data taken below B_{cr}, the angular dependence falls off more rapidly than the high-field data, although it still does not follow the $\cos(\vartheta)$ curve. We contrast this with BSCCO, where for fields well below the crossover field the $\cos(\vartheta)$ dependence is recovered. It is possible that in ET the vortex lattice never fully develops an ideal 3D structure.

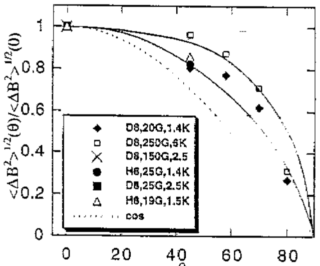

Fig. 1. The angular dependence of the normalised μSR linewidth for ET, where $\vartheta = 0°$ corresponds to the field directed perpendicular to the superconducting planes. Samples are either deuterated (ET-D8) or undeuterated (ET-H8), and measured at either PSI or ISIS (see text). The field and temperature values are indicated in the legend, the dashed line is $\cos(\vartheta)$, and the remaining lines are guides to the eye. The data have been corrected for nuclear dipolar broadening. The data divide broadly into those taken above and below B_{cr} (see text).

In conclusion, we have shown that like BSCCO, ET has an angular dependence of the μSR linewidth, which becomes increasingly anomalous with increasing field. This provides further evidence in ET for increasing disorder of the vortex lines along their length at high fields.

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