Critical-current anisotropy in single crystals of the organic superconductor κ-(BEDT–TTF)$_2$Cu(NCS)$_2$

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The anisotropy of the critical currents has been determined in single crystals of the organic superconductor κ-(BEDT–TTF)$_2$Cu(NCS)$_2$. The result is ≈ 160 at $T = 4.2$ K with $B \to 0$. With increasing field, the anisotropy of J_c falls off rapidly. The activation energy U_0 has been determined. It cannot be the reason for the anisotropy of J_c.

The magnetic properties—the Meissner effect, the first critical field H_{c1}, the anisotropy of H_{c2}, and magnetization curves—of the organic superconductor κ-(BEDT–TTF)$_2$Cu(NCS)$_2$, which has the highest transition temperature,[1] $T_c \approx 10.4$ K, have been studied previously.[2–5] On the other hand, there has been no previous study of the field dependence of the critical current density J_c for the orientations $B \perp bc$ and $B \| bc$, where bc is the conducting plane of the crystal (Ref. 2, for example). Our purpose in the present work was thus twofold: to study the field dependence of the anisotropy $J_c^{B\perp bc}/J_c^{B\| bc}$ of κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ (we used two single crystals) and to determine the anisotropy of the activation energy U_0 of the vortex lattice as a possible reason for this behavior.

The single crystals of κ-(BEDT–TTF)$_2$Cu(NCS)$_2$, with typical dimensions of $2.3 \times 0.76 \times 0.05$ mm (sample 1) and $1.5 \times 0.55 \times 0.05$ mm (sample 2), were synthesized by the procedure described in Ref. 1.

Under the assumption that the distribution of the screening currents in the sample can be described by Bean's critical-state model,[7] that the anisotropy of J_c in the bc basal plane is slight, and that the value of J_c in the basal plane of the quasi-2D superconductors does not depend on the orientation of the magnetic field,[8] the field dependence of J_c was derived for both orientations from the equations of an anisotropic version of Bean's model.[9] We have shown previously[10] that in the orientation $B \perp bc$ the temperature dependence of the critical current density, $J_c(B \to 0,\ T)$, can be written in the form $J_c(T) = J_c(0)e^{-T/T_0}$ with $J_c(0,\ 0) \approx 6.5 \times 10^4$ A/cm^2. The value of $J_c(0,\ 0)$ is the same, in order of magnitude, as the value found for $J_c(0,\ 0)$ in Ref. 2. The difference between the value of $J_c(B \to 0,\ 4.2\ \text{K})$ in our study and that in Ref. 2

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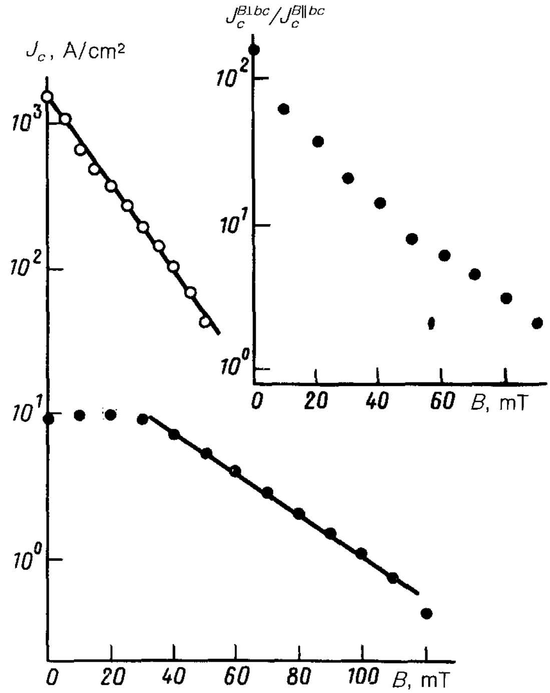

FIG. 1. Field dependence of the critical current density J_c of a κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ single crystal at $T = 4.2$ K. ○—$B \perp bc$; ●—$B \parallel bc$. The inset shows the field dependence of the anisotropy of the critical current density at $T = 4.2$ K.

can be attributed to a time dependence of P_M, and thus $\Delta P_M \propto J_c$ (ΔP_M is the width of the hysteresis loop) as a result of flux creep. It has been shown[11] previously for high-T_c superconducting single crystals that $\Delta P_M / P_{M0}$ can amount to $\approx 60\%$ in the initial time interval, $t \leqslant 1$ min. Accordingly, when we take into account the difference between the measurement time scales τ (in the measurements by the SQUID magnetometer in our apparatus the time scale was $\tau \approx 10^{-2}$ s), we find quite different values of J_c. Figure 1 shows a plot of $J_c^{B\perp bc}(B)$ (line 1) and a plot of $J_c^{B\parallel bc}(B)$ (line 2). For the orientation $B \perp bc$ the functional dependence $J_c(B)$ can be described by

$$J_c(B,T) = J_c(0,T)\exp(-B/B_0) \tag{1}$$

over the entire field range with $\Delta P_M \neq 0$ (ΔP_M is again the width of the hysteresis loop), while $J_c(B)$ for $B \parallel bc$ is independent of the field B at fields $\leqslant 30$ mT. Only at $B > 30$ mT can $J_c(B)$ be described by Eq. (1). The inset in Fig. 1 shows the field dependence of the anisotropy of J_c, i.e., $K = J_c^{B\perp bc}/J_c^{B\parallel bc}$, at $T = 4.2$ K, for crystal 1. While K reaches 160 as $B \to 0$, the anisotropy falls off rapidly with increasing B, and at $B \approx 120$ mT we find K = 1.

It was shown in Refs. 12 and 13 that

$$J_c = J_{c0}\left[1 - \frac{kT}{U_0} \cdot \ln(Bd\Omega/E_c)\right], \tag{2}$$

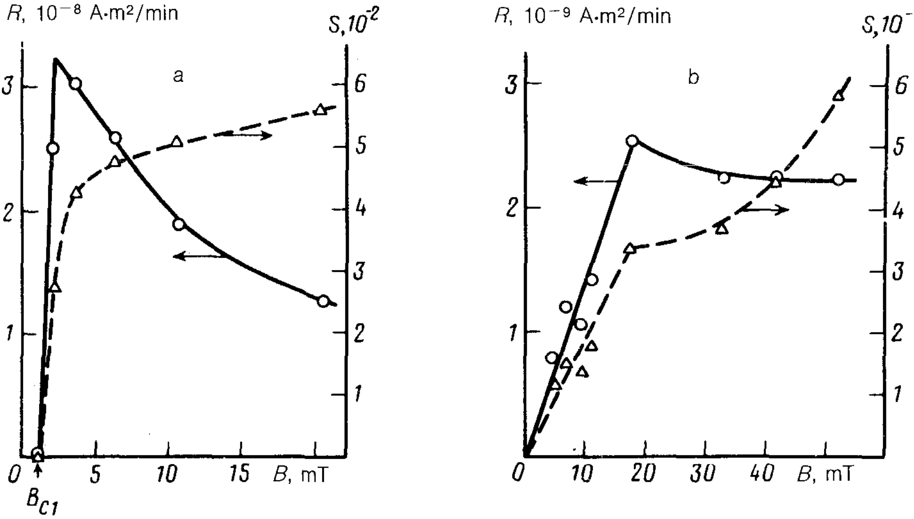

FIG. 2. Field dependence of the logarithmic relaxation rate (R) and the reduced value of this rate (S) for the relaxation of the magnetic moment of a κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ single crystal at $T = 4.2$ K. a—$B \perp bc$; b—$B \| bc$.

where J_{c0} is the critical current density in the absence of thermally activated creep, B is the magnetic induction, Ω is the oscillation frequency of a vortex at a pinning center, d is the distance between such centers, and E_c is the lowest voltage measurable. Since B and E_c are the same in the two orientations, and Ω is inside a logarithm, one might suggest that the change in the anisotropy of J_c is caused by an anisotropy of U_0.

Since the time evolution of the magnetic moment, $P_M(t)$, of κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ single crystals can be described well by $P_M(t) \propto \ln t$, we can determine U_0 from measurements of the magnetization relaxation.[14] Figure 2 shows the relaxation rate R and the reduced logarithmic relaxation rate S in various magnetic fields at $T = 4.2$ K for the orientations $B \perp bc$ (Fig. 2a) and $B \| bc$ (Fig. 2b).

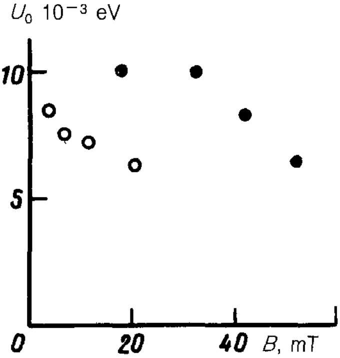

FIG. 3. Field dependence of the activation energy U_0 for a κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ single crystal at $T = 4.2$ K. ○—$B \perp bc$; ●—$B \| bc$.

Since we have

$$S = kT/U_0{}^{9} \quad \text{for} \quad B > B^{*}, \qquad (3)$$

where B^* is the field at which the screening currents penetrate all the way to the center of the sample, we can work from (3) to find $U_0(B)$ for the two orientations. Support for the validity of expression (3) comes from the circumstance that the temperature dependence $S(B = \text{const}, T) = kT/U_0$ can be described quite accurately at $B > B^*$ by the linear function $S = \alpha T$ in the coordinates T, S, as in the case of high-T_c superconducting single crystals.[9] The anisotropy turns out to be $U_0^{B\perp bc}/U_0^{B\parallel bc} \approx 1 - 0.5$ at $T = 4.2$ K (Fig. 3) and cannot explain the observed anisotropy of J_c.

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