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LETTER TO THE EDITOR

Collapse of the vortex pinning force in LaSrCuO for *H* ∥ *a–b* planes

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Abstract. The irreversible magnetization and the associated critical current density of the high-temperature superconductor $La_{1.85}Sr_{0.15}CuO_4$ are investigated as a function of the orientation (θ, ϕ) of the applied field (H) with respect to the crystallographic axes. For small angles ($v = \pi/2 - \theta$) between vortex lines and *a–b* planes, we show for the first time that the decrease of the pinning force component parallel to these planes occurs in a narrow range $v \simeq 1°$ where it is of first order in $|v|$. This behaviour seems to be related to the existence of a 'staircase' (kinked) type of vortex lattice. Neither the usual anisotropic lattice (valid for a homogeneous superconductor), nor the more recently proposed combined lattice scheme, is compatible with our results in this range of field orientation.

It is well recognized now that the magnetic and transport properties of high-temperature superconductors (HTSs) differ considerably from those of more conventional materials in many fundamental aspects. Among these are a pronounced anisotropy and a very rapid decrease (exponential) with temperature [1, 2] of the critical current density J and the irreversible magnetization M. In classical models the vortex lines are assumed to have the well known Abrikosov structure. It is known that the critical current density is greatly influenced by (ξ dependent) 'core pinning' effects, and by (λ dependent) electromagnetic effects (λ and ξ are the penetration depth and the coherence length respectively). In anisotropic superconductors, λ and ξ take different values depending on the field orientation with respect to the crystallographic c axis. Thus, strong variations of J with angle $v = \pi/2 - \theta$ are already expected in this classical model. However, in HTSs, if the Lorentz force $F_L = J \times B$ is balanced by the c-axis component of the pinning force F_p ($F_p = -F_L$), intrinsic pinning effects may result due to the modulation of the core energy by the crystal lattice. These cannot be accounted for in the framework of the usual Abrikosov VL description which assumes a homogeneous medium.

Further, if the electronic coupling between CuO_2 layers is sufficiently low, it can be described by a Josephson-like interaction. Such a model was proposed by Lawrence and Doniach (LD) [3] for artificial superconducting multilayers, and seems now well fitted to HTS compounds such as Bi(2212), Bi(2223) and the equivalent

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superconductors obtained with Tl. The relevance of such a model to $La_{2-x}Sr_xCuO_4$ and Y(123), which exhibit less anisotropic properties, is not yet demonstrated convincingly even after the confirmation of intrinsic pinning effects in Y(123) [4]. One key point is that the modulation of the vortex core energy along the c axis which is revealed by these results does not automatically imply such a low coupling between layers as to allow a pure Josephson model to be valid. (In the Josephson limit, the modulus of the order parameter in the CuO_2 planes should not be depressed by the presence of the vortex between these planes.)

We show in the discussion below that experiments realized in the configuration $v \simeq 0$ and $F_p \parallel (a, b)$ provide additional information on the nature of the vortex lattice in HTSs. Results at a fixed value $v \simeq 0$ have been already obtained [5]. However, these data may lead to large underestimates of the anisotropy, since as shown below the minimum of F_p occurs in an extremely narrow range of v. Precise determination of $F_p \parallel ab$ thus requires a fine scanning of the pinning force variations around $v = 0$.

We have performed a detailed investigation of the irreversible magnetization M and the associated critical current density J as a function of field and temperature for about 40 orientations (θ, ϕ) of H in the crystallographic planes (100), (010), (001) and (110) of a single crystal of $La_{1.85}Sr_{0.15}CuO_4$. The measurements were made using a vibrating sample magnetometer in external magnetic fields up to 7 T and at temperatures ranging from 4.2 to about 30 K ($T_c \simeq 35$ K). All of the hysteresis cycles were measured at a sweep rate of 0.3 kG s^{-1}; however the qualitative form of the cycles was found not to change up to our maximum sweep rate of 1 kG s^{-1}. We also found that the relaxation in the a–b plane and along the c axis were comparable with $s = \mathrm{d}\ln M/\mathrm{d}\ln t \simeq 0.03$. Care was taken to reduce the time constants of the experiment to approximately 0.1 s.

The orientation of the single crystal along the desired direction was performed at room temperature using a home made orientable sample holder with a relative error in θ of the order of 0.2°. As we found that the results were independent of the azimuthal angle ϕ we shall only consider here the variation of M and J with the angle θ. The crystal dimensions are l_c, l_1, l_2 = 2, 1.4, 0.9 mm respectively (a and b axes have not been distinguished).

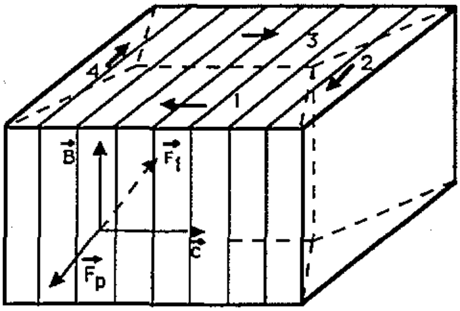

Figure 1. Quantitative distribution of currents within an anisotropic superconducting single crystal for H parallel to the ab conducting planes.

The application of the extended Bean model [2, 6] in the context $J_{c,ab} \ll J_{ab,c}$, shows that for $v = 0$, the irreversible magnetization signal M is essentially controlled by $J_{c,ab}$ as sketched in figure 1 (we recall that $J_{ab,c}$ is the in-plane critical current density for $B \parallel c$ while $J_{c,ab}$ is the inter-plane critical current density for $B \parallel ab$ planes).

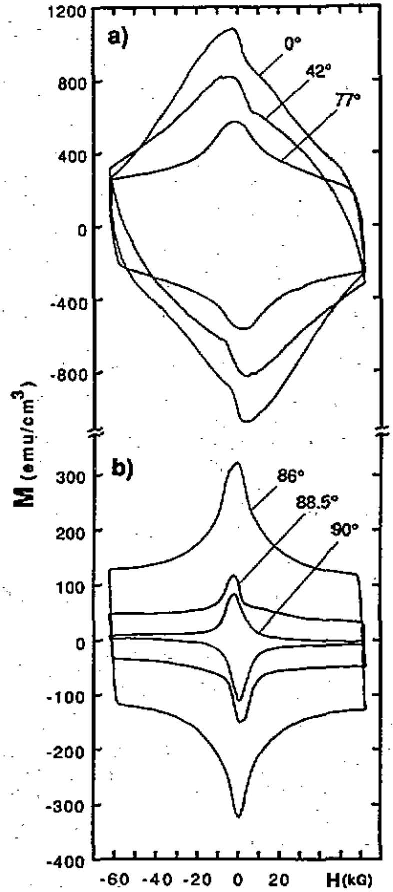

Figure 2. Evolution of the overall hysteresis cycle as a function of the tilt angle θ of H with the c axis at $T = 4.2$ K. As can be seen there are three qualitively different regimes. We find that up to $\theta \simeq 60°$ $M(H)$ varies rather regularly with H (except a very small anomaly near $H = 0$) but all of the cycles meet at about the same point $H = 45$ kG: this is seen in other cycles not shown here for the sake of clarity. Between about 65° and 89° the cycle exhibits a well defined but small peak followed by a field domain where $M(H)$ is almost constant. Very close to the a–b planes the high field magnetization tends to collapse rapidly leading to a very sharp peak in $M(H)$.

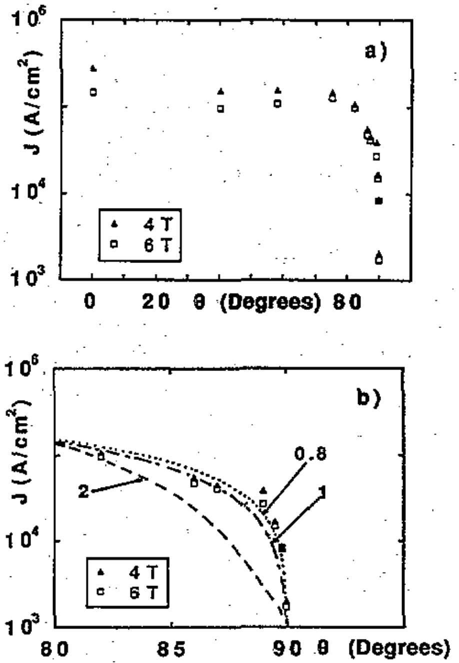

Figure 3. Angular dependence of the critical current density deduced from the hysteresis cycle at 4.2 K for three different field values, using the standard Bean formula: $J-15\Delta M/R$ where ΔM is the width of the hysteresis cycle expressed in emu cm^{-3} and R is the radius of the specimen averaged along the directions perpendicular to H. (*b*) is an enlargement of the data close to the a–b plane. The curves represent the variation of J as a function of θ for equations (1)–(3) and for the indicated values of the exponent n entering those equations.

For $v \neq 0$, the interpretation of the signals is rather delicate. This is particularly true at very low applied field when the self-field ceases to be negligible: $H \ll H_{\mathrm{sf}} \simeq N_{\mathrm{eff}}|M|$ where N_{eff} is the effective demagnetizing factor.

We first focus on high-field results, $B > 3$ T, for which we assume that the field orientation inside the sample is parallel to the externally applied field. (Vortex rotation during its penetration inside the sample is negligible at $B \gg \mu_0 H_{\mathrm{C1}}$ since in this range, the energy of the system is dominated by its isotropic part.) In this case, $J \perp B$ is verified. For small v, the shape of the domains 1–3 shown in figure 1 is not expected to be strongly modified, although for $v \neq 0$, B and J are no longer strictly aligned with the crystal axes. We thus interpret our results as controlled by the pinning force $F_{\rm p} = -F_{\rm L} = -J \times B$, which is parallel to the (a, b) plane in domains 1–3.

Figures 2 and 3 show the evolution of the overall hysteresis cycle $M(H)$ and the associated critical current density respectively as a function of the angle. We note the presence of a broad peak (figure 2(*a*)) which becomes anomalously sharp as H approaches the a–b planes (figure 2(*b*)). To our knowledge this is the sharpest peak ever seen in the T–H domain far from both $T_{\rm c}$ and $H_{\rm C2}$. A second very unusual feature of this figure is the sudden drop of M as v tends to 0, especially at high fields. This is better illustrated in figure 3 where it is seen that $J(v)$ varies rather slowly and regularly with v up to very close to $v = 0$ and then drops abruptly towards zero (in a logarithmic scale). The effect of temperature on M and J is displayed in figures 4 and 5 respectively. At first we note the dramatic fall of J with T for $\theta \simeq 0$ (or $v \simeq \pi/2$). This behaviour is fairly normal for HTS single crystals. What is not usual and is rather puzzling is the J versus T curve for $v \simeq 0$ which increases slightly with T in some T–H domain (see the curve for $H = 60$ kG). This would be very hard to understand in the framework of a usual Abrikosov VL which should provide at least a linear drop of J with T. Similarly, theoretical models for homogeneous superconductors predict a rather smooth variation of J with v around $v = 0$ ($\theta \simeq \pi/2$) [7, 8]. Therefore the very sharp collapse of J occuring in the hysteresis cycle for v close to 0 would be hard to account for in these theories.

The specific contribution of the previous results rely on the fact that they reflect the pinning force $F_{\rm L}$ in a configuration $F_{\rm L} \parallel ab$ for small angle v. Unlike intrinsic pinning experiments, this allows a measurement of the smallest pinning force of the superconductor. We first show from figure 2 that high-field results are fitted reasonably well by the expression $J \simeq J_n(v^n + \delta v_n)$ where the parameter n is taken in the range 0.8–1. The term δv_n reflects either the accuracy limit of our angle measurement or the residual J for $B \parallel ab$. We believe however that the first possibility is much more likely because of the quasi-impossibility of aligning H along the a–b planes with an angular precision better than 0.1°; i.e. better than δv_n for n in the range 0.8–1. Of course this implies that the critical current density $J_{c,ab}$ is much lower than the effective value deduced from figure 2. Attempts to fit these results with $n = 2$ were definitely unsuccessful. Some examples are shown in figure 2 with

$$J_{(0.8)} = 22.400(v^{0.8} + 0.08) \qquad (n = 0.8)$$

$$J_{(1)-} = 14.250(v + 0.124) \qquad (n = 1)$$

$$J_{(2)} = 1.420(v^2 + 1.24) \qquad (n = 2)$$

where J is given in A cm^{-2} and v and δv in degrees.

Homogeneous anisotropic superconductors present a second-order variation of all the VL parameters around $v = 0$ (free energy, elastic constants and characteristics lengths) with none of them going to zero in this limit. Thus, a first- (or lower-) order variation of the pinning force in v, which reflects complex combinations of these parameters, cannot be explained in such a framework. As recalled in the introduction, HTSs are expected to present a modulation of the core energy along the c axis which may lead to the occurrence of kinked vortices [9–11]. A characteristic feature of this type of VL is its first-order energy variation around $v = 0$ because the

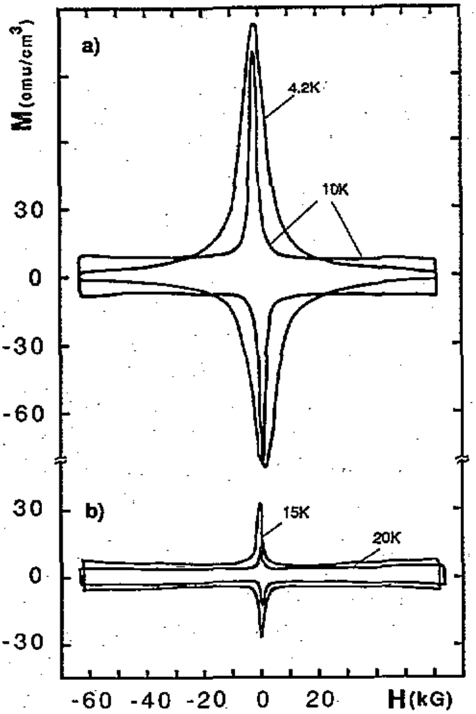

Figure 4. Evolution of the hysteresis cycle with temperature for H parallel to the a–b planes within the experimental uncertainties of about 0.2°. In (*a*) we see that the high-field irreversible magnetization increases weakly with T and with H at intermediate T.

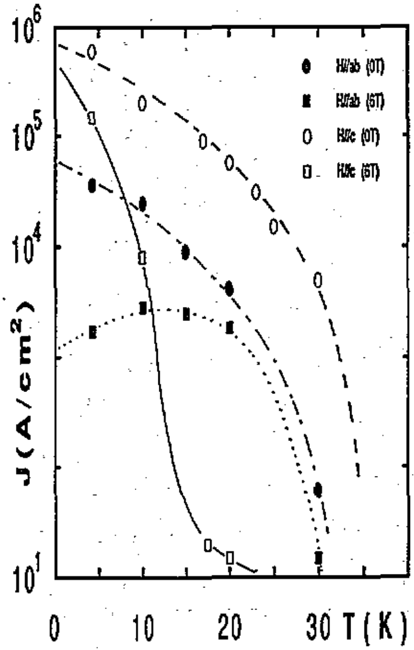

Figure 5. Variation of the apparent critical current density with temperature in semi-logarithmic scales for H parallel and perpendicular to the a–b planes respectively. The curves are to guide the eye.

number of kinks is proportional to $|\sin v|$. Thus, our results give a strong support to the idea of a modulated core energy along c in $La_{2-x}Sr_xCuO_4$.

The next question is related to the possibility of a complete core localization between CuO_2 layers for vortex sections parallel to a–b planes which connect the kinks. We remark that the characteristic perturbation range of the order parameter in the directions a or b, which would define the core extension and the pinning range of an uncompletely localized vortex, is still ξ_{ab}. The elementary core pinning energy is expected to be only reduced by a factor $\Gamma = \xi_{ab}/\xi_c$ as compared to the case $B \parallel c$. In the strong pinning limit, for which the macroscopic force is roughly proportional to the elementary one, one could expect that $J_{ab,c} \simeq \Gamma J_{c,ab}$. However, Γ for $La_{2-x}Sr_xCuO_4$ is only in the range 15–20, which has to be compared to the lower limit of the ratio $J_{ab,c}/J_{c,ab} > 200$ obtained from our results. This indicates either that the strong pinning scheme does not hold (at least for the orientation $B \parallel ab$), or that vortex sections parallel to a–b planes have practically no core energy (or that both assessments are verified). Nevertheless the very large critical current anisotropy seems to favour the second possibility. As stressed before, the vary unusual dependence of $J_{c,ab}$ on T could also be interpreted as an indication of the occurrence of such a VL structure in our sample. It might be due to a gradual evolution of the in-plane Josephson vortices into Abrikosov vortices as a function of T since the crossover between the two would occur at $\xi_c \simeq \xi_\infty(1 - T/T_c)^{-m} \simeq d/2$

where ξ_{c0} is the coherence length in the c direction at $T \simeq 0$, $m \simeq 1/2$, $\xi_{c0} \simeq 3$–5 Å and $d \simeq 6$ Å is the crystalline lattice parameter in the same direction.

Assuming the presence of Josephson vortices localized between CuO_2 planes, one should remark that our results at low v are not compatible with the recently proposed combined lattice model [12], at least if the two components of this lattice (Josephson and two point-like vortices) do not interact significantly as assumed in this model. Indeed, this model should lead to a magnetization M_{ab} along a (or b) independent of the c component of the induction B_c. We find the opposite result, with an M_{ab} signal essentially controlled by B_c ($J_{c,ab} \simeq B_c^n$ at low v). The possibility that we detect the M_c component in our experiment is ruled out because it can be shown that this should provide a signal $\simeq Bv^2$ for low Hv values, i.e. for $Bv \ll B_{c,p} \simeq JR \simeq 3$ T (here) where $B_{c,p}$ is the field of complete flux penetration for an applied field parallel to the c axis and for a sample of effective radius R (see for instance equations (85*b*) and (83*b*) of [2] for more details). This could reflect the fact that the VL structure is of a 'staircase' type [8], with Josephson sections connected by 2D point-like vortices crossing the CuO_2 layers. The 2D point vortices would bring the essential contribution to the pinning force as soon as $v \neq 0$.

Our low-field results are more difficult to interpret since in this range the applied field is small compared to the self-field of the sample. This makes the resultant field orientation poorly defined especially around $v = 0$ where a high precision is required. The absence of a visible lock-in transition for $v \neq 0$ in our results is probably related to this experimental limitation (in high fields the c component of the applied field is too large for the lock-in transition to occur at sizeable v).

In conclusion we have shown that the critical current density of $La_{1.85}Sr_{0.15}CuO_4$ exhibits a very large anisotropy occurring predominantly in a narrow angle around the ab planes. Moreover, this angular region is marked by a sharp peak in $M(H)$ as well as by a slight (but unusual) increase of J with T up to ~12 K. All of these results are rather new and suggest that the behaviour of J and M is controlled by in-plane segments of Josephson vortices connected by 2D point-like vortices crossing the ab planes.

More experimental and theoretical studies are needed to clarify the situation completely.

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