INTRINSIC PINNING OF VORTICES IN LAYERED SUPERCONDUCTORS.

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Most high-Tc superconductors possess striking anisotropy properties, due to their quasi-bidimensional lattice structure. Nevertheless, the anisotropic London theory[1-3] is valid only if the coherence length ξ is much larger than any atomic distance. Recent low temperature estimates for $\xi_\perp$ (perpendicular to the layers) rather give $\xi_\perp \approx$ 3-5 Å in $YBa_2Cu_3O_7$ [4,5], while the largest distance between Cu-O planes is $d \approx 8$ Å. The situation is even more striking in the Bi-Sr-Ca-Cu-O family where values as low as $\xi_\perp \approx$ 1-3 Å have been suggested[6], while $d \approx 10$ Å. This naturally leads to a model of Josephson-coupled superconducting planes[7]. In that case the cores of flux lines are drastically affected by the lattice discreteness, for they can fit between the layers[8]. Such flux lines are actually similar to those penetrating Josephson junctions. Obviously such vortices encounter a lattice barrier, similar to Peierls-Nabarro barriers for dislocations, as they move perpendicularly to the planes. This is a cause of strong intrinsic pinning and thus responsible for intrinsic critical currents $J_{c//}$ if the field is parallel to the layers. The free energy of an undulated line can be written easily for small curvature: the kinetic part is given by the orientation-dependant line energy [1-3] and the z-dependant core contribution can simply be added phenomenologically[9]. One can thus write the free energy of an element of line $\mathbf{ds}=(dx,dz)$ making an angle θ_B with the z-axis as

$$\frac{d\varepsilon}{ds} = \left(\frac{\phi_0}{4\pi\lambda}\right)^2 \gamma^{-\frac{1}{3}}\,\Gamma(\theta_B)\left[\mathrm{Ln}\frac{\kappa_{//}}{\Gamma(\theta_B)} + \alpha(z)\right] \quad , \qquad \alpha(z) = \alpha_0 - \alpha_1 \sin^2\left(\frac{\pi z}{d}\right) \qquad (1)$$

where $\tan\theta_B = dx/dz$ (see Fig. 1). γ is the anisotropy ratio defined by $\gamma = (m_\perp/m_{//})^{1/2}$, $\lambda = (\lambda_{//}^2\lambda_\perp)^{1/3}$ and $\xi = (\xi_{//}^2\xi_\perp)^{1/3}$ are averaged penetration and coherence lengths and $\kappa_{//} = (\lambda/\xi)\gamma^{-1/3}$, $\Gamma(\theta_B) = (\sin^2\theta_B+\gamma^2\cos^2\theta_B)^{1/2}$; $\alpha_1 < \alpha_0$ represents the reduction of the core energy when lying between layers. The value of α_0 is close to 0.5 , thus the core energy is roughly ten per cent of the total line energy if $\kappa \approx 10^2$. With the layer separation given by d, the critical current parallel to the layers and perpendicular to the field is easily obtained from the barrier, equal to the modulation of the core energy, given by (1), i. e. $J_c=\alpha_1\phi_0\gamma^{-1/3} / (4\pi\lambda)^2 d$. Taking for instance for Y-Ba-Cu-O the values $\lambda = 2500$ Å ,

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d=8Å, $\gamma = 5$ and $\alpha_1 = 0.5$ leads to **Jc = 6.5. 10^7 A.cm^{-2}.** On the other hand Jc should depend very sensitively on a small desorientation of flux lines with respect to the layers, for the flux line would then take the shape of a soliton (kink) lattice (Fig. 1) and the kinks can move very easily parallel to the layers[9]. With the same numerical values as above, the energy and length of a single Sine-Gordon soliton (kink) are easily calculated, using (1) for $\theta_B \approx 90^o$ and minimizing the line free energy, and are respectively given by $E_k = 0.07$ eV and $L_k = 60$Å for YBaCuO ($\gamma = 5$) and $E_k = 0.62$ eV and $L_k = 825$ Å for BiSrCaCuO, taking $\gamma = 55$ as proposed by some authors[10].

Let us now study the first flux penetration as a function of the field orientation. The problem has been studied in the past, in the anisotropic London theory. The flux lines prefer to be oriented close to the easy directions (here the layer directions), thus the induction **B** is not parallel to the field **H**. Let us now include the core trapping and calculate in low fields the Gibbs potential of a single line, given on an unit length along **x'** by

$$G = \int ds\, \varepsilon(\theta_B) \; - \int dx' \left(H\phi_0 / 4\pi\right) \cos\left(\theta - \theta_B\right) \qquad (2)$$

with $\varepsilon(\theta_B)$ defined by (1). All angles θ_B (but not θ) are supposed to be close to 90° thus $dz/dx = 90 - \theta_B \ll 1$. G can then be rewritten as

$$G = \varepsilon_{0//} - \frac{H\phi_0}{4\pi}\sin\theta - \frac{1}{2}Kq^2 + \int dx\left[\frac{1}{2}K\left(\frac{dz}{dx} - q\right)^2 + \frac{\delta}{2}\cos\frac{2\pi z}{d}\right] \qquad (3)$$

with $K = (\phi_0/4\pi\lambda)^2 \gamma^{5/3} (\mathrm{Ln}\kappa_{//}+\alpha_0)$, $\delta = (\phi_0/4\pi\lambda)^2 \gamma^{-1/3} \alpha_1$. The core term acts like a commensurate potential, the field imposing to the line angle a "misfit" q, given by $q = \phi_0 H\cos\theta/4\pi K$. The minimization of the integral term with respect to z(x) gives rise to the well-known Sine-Gordon soliton lattice. It shows a lock-in transition at a critical value of the misfit $q_c = (4/\pi)\ (\delta/2K)^{1/2}$. For $q<q_c$ the lines enter parallel to the layers. The critical angle for lock-in of vortices at H_{c1} results from setting $H=H_{c1//}$ and $q=q_c$, i.e.

$$\tan\theta_c = \frac{\pi}{4\gamma}\left(\frac{\mathrm{Ln}\,\kappa_{//} + \alpha_0}{\alpha_1}\right)^{\frac{1}{2}} \qquad (4)$$

With the previous numerical values, this yields $\theta_c = 26^o$. On the other hand, the calculation of the equilibrium properties in higher fields $H_{c1} \ll H \ll H_{c2}$ can be performed by a generalization of the usual vortex lattice calculation. The result is [9]

$$\cos\theta_c = \frac{2}{\pi}\left[\alpha_1\frac{H^*}{H}\left(1 + \gamma^2\frac{H^*}{H}\right)\right]^{1/2} \qquad (5)$$

where H* is of the order of H_{c1}. This result, together with the low field result, can be represented on a phase diagram (H, θ_H) (Fig. 2). The region of field orientations for which the flux lines are trapped parallelely to the layers increases with the barrier height (measured by α_1) and with the anisotropy factor γ, and decreases with the field intensity. Typically, for fields of the order of 10^2 H_{c1} and $\alpha_1 = 0.5$ the lock-in transition (dotted line on Fig. 2) occurs at θ_c=87° if γ=5 (YBaCuO) and θ_c=75° if γ=55 (BiSrCaCuO).

On the other hand, for **H** parallel but **J** perpendicular to the layers, i.e. for flux line motion parallel to the layers, the quasi-absence of normal cores make the vortices glide easily, being hardly pinned by defects. This could explain why the critical currents for **H** parallel and **J** perpendicular are so low, even in single crystals[6]. The anisotropy of the critical current for parallel fields is thus a very crucial question and has not been paid much attention up to now.

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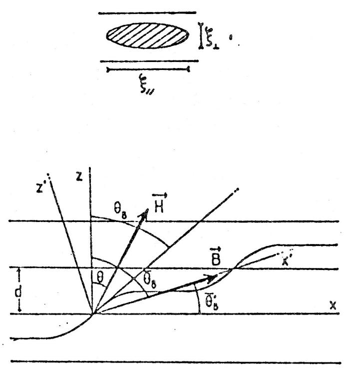

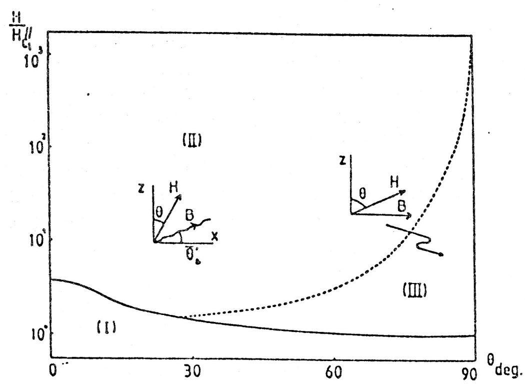

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