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FLUX MOTION AND DISSIPATION IN HIGH-TEMPERATURE SUPERCONDUCTORS*

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The effects on flux motion and dissipation of interlayer coupling of the Cu-O planes along the c-axis are considered for the high-temperature superconductors (HTS). It is argued that for the *highly-anisotropic* HTS, the weak interlayer coupling plays a dominant role that can be described by *incoherent* Josephson tunneling between superconducting Cu-O bi- or tri-layers. In $YBa_2Cu_3O_7$, the layers are strongly coupled, presumably because the conducting Cu-O chains short circuit the Josephson tunneling, so that these effects are weak or missing.

Recently[1], the effects of anisotropy and fluctuations on critical current densities, $J_c(T,H)$ and the field-induced broadening of resistivity transitions, $\rho(T,H)$, have been studied in high-temperature superconductors (HTS). Although the broadening looks similar for the applied field, H, oriented either parallel to the superconducting Cu-O layers (H∥*ab*) or parallel to the *c*-axis (H∥c), its width and the detailed shape of $\rho(T,H)$ are different. The explanations given below for the *highly-anisotropic* HTS differ in detail for the two cases, but have a crucial feature in common: they result from fluctuations affecting the Josephson coupling across the interlayer junctions[2,3].

For H∥*ab*, the broadening is smaller: the absence of any measurable Lorentz-force dependence[1,3-5] in the highly-anisotropic HTS together with the anticipated intrinsic pinning of the insulating region between layers, questions explanations involving motion of vortices from the external field[1,4]. Various mechanisms can explain the weak or missing Lorentz-force dependence of $\rho(T,H)$ and $J_c(T,H)$ for H∥*ab*. Some relate to sample perfection: (a) meandering current paths in the *ab* plane due to poorly-coupled grains or other defects; fluctuation of the Josephson coupling, either (b) between Cu-O bi- or tri-layers when meandering current paths include a *c*-axis component[3], or (c) between grains[6]; (d) misalignment of the sample, or (e) misorientation of individual grains with respect to the field[7]; and (f) field-induced granularity[8]. Another is intrinsic: (g) *field-induced* thermal excitation of vortex/anti-vortex pairs in the Cu-O planes[9]. The results on single crystals[5] and epitaxial films[3] of $Tl_2Ba_2CaCu_2O_x$ seem to adequately rule out explanations (a) and (c). The measured distributions of c-axis misorientations[1,3] are <0.3°, which rules out (e), while the need of a 3.8° sample misalignment[1] for (d) likewise precludes it. Recently, the degree of Lorentz-force dependence of $\rho(T,H)$ and $J_c(T,H)$ in HTS has been shown to depend on the interlayer spacing[3], suggesting that the interlayer coupling, predominated by Josephson tunneling between neighboring Cu-O bi- and tri-layers, may be important for (b) or (g).

In the case of (b), these tunnel junctions would occur between isolated finite-area plates of neighboring Cu-O bi- or tri-layers, with defects in these layers causing a meandering of the current path between such plates[3]. Fluctuations of the relative phase across these junctions occur when kT exceeds $E_{cj}(T,H)$, the Josephson coupling energy between adjacent Cu-O multilayers, and this would result in a crossover to finite resistance and a reduction in the low-temperature $J_c(T,H)$, both of which effects are known to occur in thin-film Josephson tunnel junctions. For (g), we note that as kT exceeds $E_{cj}(T,H)$, there would be a crossover to isolated 2D superconducting layers, such that the thermal activation of vortex/anti-vortex pairs is greatly enhanced over the well-coupled, 3D system.

Josephson fluctuations were used to explain the observed Lorentz-force independence of the broadened $\rho(T,H)$ in *granular* NbN films[6] and of $J_c(T,H)$ in *granular* multilayers[10] of NbN with AlN. Motion of the external flux was suppressed by the relatively strong pinning, e.g., the insulating AlN layers, and a distinct crossover in $J_c(H)$ was observed between depinning of the *external* flux and Josephson fluctuations between grains[10]. Recent experiments[11] on discreet Josephson junctions, made with high-quality Nb films, confirm this conclusion. A broadened resistive transition, very similar to that of HTS materials, was observed in such junctions in fields, perpendicular to the film plane, up to 0.03 T. These measurements used a current density of 0.1 A/cm^2, for which the resistive transitions of the films were very sharp, indicating that the external flux was completely pinned in the electrodes. The dissipation was caused by self-field, Josephson vortices which are perpendicular to the applied field direction.

In zero field, E_{cj} is proportional[12] to the product of the superconducting order parameters on each side of the junction, ψ_a and ψ_b, divided by the normal-state resistance, R_N. For HTS interlayer junctions with an area A, $R_N=\rho_c s/A$, where ρ_c is the c-axis resistivity and s with cell size along the c-axis, so that $E_{cj}\sim FA$. This relation reflects the fact that fluctuations must produce self-field, Josephson vortex loops which cover the total junction area, while F accounts for the energy required per unit area. The activation energy measured on discreet Nb junctions[11] indicate that $A=\Phi_o/H$ at high fields, where Φ_o is the flux quantum. In zero field, A will be limited either by the sample dimensions or the inevitable presence of defects, even in single crystals and epitaxial films, to a value A_o. For the Nb junctions, A_o was found to be ~1 μm^2, while the physical junction area is ~8x12 μm^2. We suggest that the effect of H may be to further limit the minimum size of the fluctuation-induced vortex loops to Φ_o/H, since they can then connect with the pinned, external-field vortices in the electrodes. This is analagous to dislocation-mediated shearing (melting) of crystal lattices[13].

For HTS, the lack of intrinsic pinning for H∥c implies that the broadening is due to thermally-activated flux motion. This broadening is fairly independent of sample quality, but depends strongly on the spacing between Cu-O bi- or tri-layers[2]. Thus, we suggest that for H∥c, thermally-activated decoupling of the Josephson-coupled superconducting phases causes the broadening by decoupling the magnetic-field-induced pancake-like[14] vortices in adjacent Cu-O layers. The resulting independent motion of vortices in adjacent layers, i.e., 2D behavior, greatly reduces the effectiveness of pinning compared to extended, 3D vortex *lines*. For the *highly-anisotropic* HTS, such a crossover from 3D to 2D vortices was found[2,3] for $kT \sim E_{cj}(H,T)$. In addition, at sufficiently low temperatures, the finite pinning strength, $E_p(H,T)$, of individual Cu-O multilayers was found[2] to be effective even in the 2D regime.

A finite dc resistance requires that the vortices are excited out of their potential wells of *both* energy barriers, so $k_BT=E_p(H^*,T)+2E_{cj}(H^*,T)$ was solved[2] for the crossover field, H^*. For H∥c, this model gives convincing fits[2] to measurements of resistive transitions for the Bi- and Tl-cuprates with realistic values for the parameters ρ_c, B_c and H_{c2}, providing that $E_{cj} \sim 1/H$, in agreement with the above Josephson-junction model. Mechanical oscillator experiments can also probe E_p and E_{cj} individually, since dissipation can also occur *without* vortices being excited out of their potential wells (i.e., when $kT>E_p$ and $2E_{cj}$, but $kT<E_p+2E_{cj}$). The two loss peaks found in such experiments[15] on $Bi_2Sr_2CaCu_2O_x$ single crystals agree[3] surprisingly well with the Josephson model with substantially the same parameters as found resistively[2].

Returning to the case of H‖ab, Josephson vortex cores divide the interlayer junctions into areas given by $\sqrt{A_o\Phi_o\lambda_c/\lambda_{ab}H}$, providing $A_o>\Phi_o\lambda_c/\lambda_{ab}H$, where λ_c and λ_{ab} are the c-axis and in-plane magnetic penetration depths, respectively, and thus $E_{cj}\sim 1/\sqrt{H}$. Experimentally, the activation energy which best fits[3] the resistive transitions in epitaxial $Tl_2Ba_2CaCu_2O_x$ films is (4800 [$KT^{0.54}$]) $k_B(1\text{-}t)/H^{0.54}$. This dependence is valid for H≥0.25 T, which, together with a lower limit of $\lambda_c/\lambda_{ab}\sim 350$ from torque magnetrometry[16], implies that $\sqrt{A_o}$ must be ≥1.5 µm. One can also obtain $\sqrt{A_o}$ from the saturation of the 1/H dependence in the same filmsat low fields with H‖c: although this occurs very near T_c and there is no independent measure of T_c, a lower limit of $\sqrt{A_o}\sim 1.5$ µm is found. An important difficulty arises when fitting $\sqrt{A_o}$ to the experimental prefactor, 4800 [$KT^{0.54}$], with the other parameters of the Josephson model. Using $\lambda_c/\lambda_{ab}\sim 350$, we find $\sqrt{A_o}\sim 0.3$ µm, in disagreement with the above estimates. Although this is ~800 unit cells and may be reasonable even for epitaxial films, a five-times-larger value of λ_c/λ_{ab} would be necessary to make the model quantatively compatible.

We note that the predicted vortex/anti-vortex pair creation energy[9] is $E_{cv}=\Phi_o^2 d_s/8\pi^2\lambda_{ab}^2$ ~(1400 [K]) $k_B(1\text{-}t)$ for $Tl_2Ba_2CaCu_2O_x$, where d_s is the Cu-O bilayer thickness and λ_{ab} is the in-plane magnetic penetration depth. For presently attainable H, E_{cv} is less than experiment, so we cannot choose between mechanisms (b) and (g). For larger H, (g) would predict a field-independent activation energy.

Although there is a quantatitive inconsistency in the detailed Josephson-coupling model for H‖ab, the correlation of the degree of Lorentz-force dependence on interlayer spacing/coupling suggests that it is important in this case. Thus, for the highly-anisotropic HTS, the dissipation may be described by thermal fluctuations of the interlayer coupling, resulting in dissipation by Josephson vortices crossing interlayer junctions, rather than motion of the external field vortices. For H‖c, thermal fluctuations of the interlayer Josephson coupling decouples the pancake vortices of the external field, leading to significantly greater dissipation than the well-coupled case at low fields and temperatures.

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