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Flux Pinning and Forced Entanglement by Splayed Columnar Defects

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Flux Pinning and Forced Entanglement by Splayed Columnar Defects

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We propose controlled splay of artificial columnar defects in cuprate superconductors as a strategy to enhance transport properties in a field compared to parallel columns. The theory predicts a new "splayed glass" phase with a greatly reduced flux creep, an entangled ground state, and very slow response to a transverse field.

A remarkable enhancement of the critical current J_c was observed recently using heavy ion irradiation [?]. These irradiations produce long and almost *parallel* columns of damaged material. The theory of flux pinning by straight parallel columns of [?] shows that the low temperature physics is that of the Bose glass.

We have investigated the effect of a splay, i.e., a dispersion in the orientation of the columnar defects. We find [?] that flux lines now form a new thermodynamic phase, the "splayed glass", at low temperatures. The splay glass has some similarities with the Bose glass: The physics is dominated by localization along columnar defects, and low energy excitations can be constructed by adapting variable range hopping ideas. Also, the dramatic increase in the magnitude of $H_{irr}(T)$ observed in [?] should be reduced only slightly by a small splay. The splay glass differs from the Bose glass, however, in at least two important respects, both of which should *enhance* transport properties. First, random misorientations of columns strongly inhibit large scale, low energy excitations, which implies a much reduced dissipation rate for low-current transport at finite temperatures. Second, flux lines in the splayed glass ground state are entangled, in sharp contrast to the unentangled Bose glass ground state. Because of flux cutting barrier U_X , entanglement

can strongly enhance pinning and improve transport at all currents.

It may be thus be possible to produce the strongest flux pinning hitherto known by deliberately *splaying* the columnar defects. This can be achieved by rocking the sample during irradiation or decollimating the beam. Other methods worth exploring to engineer splayed columnar defects include inducing fission of nuclei inside the superconductor to produce heavy ions, needle-like inclusions, directional solidification, extrusion, etc.

We consider flux lines of trajectories $r_i(z)$ traversing a sample with magnetic field aligned with $\hat{c}||\hat{z}$. $\epsilon_0 = (\phi_0/4\pi\lambda)^2$ is the magnetic interaction energy scale between flux lines, $\tilde{\epsilon}_1 \approx \epsilon_0 M_\perp/M_z$ is the local tilt energy, and λ is the in-plane London length. Columnar pins are randomly positioned with average spacing d and modeled [?] by a potential V_1 of depth U_0 and spatial extent b , of the order of the vortex core size, so that $U_0 \approx \epsilon_0$. The total disorder potential is $\sum_i V_1[r - R_i(z)]$, where $R_i(z) = R_i(0) + v_i z$ denotes the position of the center of the i th columnar pin. The tilt v_i describes the misalignment between the direction of the pin and the z -axis. We first consider a gaussian distribution of the v_i 's with small width v_D .

The Bose glass transition is unstable to small random splay which acts like a random transverse field. Splay should degrade the glass transition temperature $T_g(v_D)$, but only when v_D exceeds the average thermal tilt v_0 in the flux liquid. At low field $B \leq \phi_0/\lambda^2$ we estimated $T_g(v_D) \approx T_{BG}$

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for $v_D \ll v_0$, and $v_0 \approx n_0^{1/2} T / \bar{\epsilon}_1$. An estimate valid at all fields is $v_0 \approx a_0 / l_z$, where a_0 is the vortex spacing and l_z is the entanglement length [?]. Since $a_0 / l_z \sim 0.3$ with $T = 77^\circ K$ when $B \sim 2$ Tesla in YBCO, the splay variance can be of order 10° without significantly changing the location of the transition. Such a small splay nevertheless greatly enhances transport at low temperature. In highly anisotropic materials such as BSCCO our theory still applies, but the angles are rescaled to large values $\tan \theta \propto M_z / M_\perp$.

We now consider low temperatures $T \leq T^* \leq T_g$, where $T^* = \sqrt{U_0 \bar{\epsilon}_1} b \approx 0.9 T_c$. Below T^* a flux line is tightly bound to a single pin, with localization length $l_\perp(T) \approx b$ [?]. We account for interactions by excluding multiple occupancy of pins. The pins have different U_i 's, with dispersion $\Delta \gg \frac{1}{2} \bar{\epsilon}_1 v_D^2$ resulting from interactions and from the intrinsic dispersion in the irradiation process [?]. The ground state is constructed by first filling up the pins in the order of increasing pinning energies. Then one allows for exchanges of two localized flux lines which approach each other, along z with probability $\exp(-2\rho/l_\perp(T))$, where ρ is the distance of closest approach of two columnar pins. Although they are rare at low T exchanges must take place for sample thickness $L > L_0 = a_0^2 / (l_\perp v_D)$, estimated to be $\sim 5 \mu m$ for a field of several Teslas, $l_\perp \approx 40 \text{ \AA}$ and $v_D \approx 0.1$. For $L \gg L_0$, each flux line thus performs a random walk along z , leading to heavily entangled ground state configurations. The effective "diffusion constant" $D_{\text{eff}} \approx 500 \text{ \AA}$ is comparable to the diffusion constant in the liquid!

Low energy excitations are constructed by considering a flux line localized on the weakest occupied pin. A pair of superkinks must be created as a segment of length l attempts to hop to a vacant pin. As in [?], it is advantageous to seek out far away pins with similar tilts and binding energies. This leads to an estimate of the lowest excitation energy $E_{sk}^* \sim \epsilon_k v_D l_c (l/l_c)^{3/5}$, where $l_c \sim (d/v_D) \sqrt{\Delta/\epsilon_k v_D}$ is a crossover length below which the superkink is of the Bose glass type $E_{sk}^{\text{BG}} \propto l^{1/3}$. For $l > l_c$ angular selection leads to a higher energy scale since it is necessary to hop further away to find matching directions within

angle $v^* = v_D (l/l_c)^{-2/5}$. Standard arguments then give a nonlinear dependence of the electric field $\mathcal{E}$ on the applied current J as $J \rightarrow 0$,

$$\mathcal{E} = \mathcal{E}_0 \exp[-(\epsilon_k d/T)(J_0/J)^{3/5}], \quad (1)$$

$J_0 = (v_D l_c/d)^{-4/3} J_1$, $J_1 = \epsilon_0 c / (\phi_0 d)$. Comparing to the Bose glass, $\mathcal{E}_{\text{BG}} \sim e^{-(\epsilon_k d/T)(J_1/J)^{1/3}}$ [2], we find that the more nonlinear splayed glass behavior takes over for $J \leq (v_D l_c/d)^{-3} J_1$. Flux line entanglement should lead to an activated prefactor $\mathcal{E}_0 \approx \rho_0 J e^{-U_x/T}$ where ρ_0 is the flux flow resistivity well above T_g . $U_x/T \approx 5 - 15$ in pure systems and should be larger with splay disorder. Thus we gain an extra $\sim 10^2 - 10^6$ reduction in $\mathcal{E}$ at low currents. J_c itself should be enhanced when $U_x \gg T$. The lines are "ballistically entangled" for $L_0 \geq L \geq a_0/v_D \approx 3000 \text{ \AA}$. Deliberately enhancing Δ or freezing-in high temperature entanglements by field cooling rapidly from a flux liquid will improve transport.

Other distributions of v_i lead to interesting physics: If the orientations of the pins lie within a fixed vertical plane, barriers to flux crossing should reduce flux motion parallel to the vertical plane more than the perpendicular one. Global relaxation however should be unaffected since flux can escape through the easy direction. Irradiations producing a discrete set of orientations, such as $\pm\theta$ around c , could lead to additional effects of (spontaneous) symmetry breaking. Whenever there is a continuum of tilt angles the equilibrium tilt modulus c_{44} will be finite, while $c_{44} = \infty$ for the Bose glass. However, the response to a small transverse field will be dynamically frozen in thick samples. Research supported in part by NSF Grants No. DMR-91-15491, 06237, 07752.

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