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Anisotropic peak effect due to structural phase transition in the vortex lattice

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Abstract

The recently observed new peak effect in YBCO is explained by softening of the vortex lattice (VL) due to a structural phase transition in the VL. At this transition, square lattice transforms into a distorted hexagonal one. While conventional peak effect is associated with softening of shear modes at melting, in this case the relevant mode is the point. The squash mode is highly anisotropic and we point out some peculiar effects associated with this feature. © 2000 Published by Elsevier Science B.V. All rights reserved.

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Conventional peak effect, sudden increase of the critical current, has been observed in great variety of both low and high T_c superconductors. In conventional superconductors, the peak effect was theoretically explained a long time ago by Larkin and Ovchinnikov [1], while in high T_c superconductors like untwinned YBCO, it is generally believed that the peak is due to softening of the shear mode just before the first order melting transition of the vortex lattice (VL) takes place [2]. However, recently, another peak in critical current in YBCO has been discovered on a line almost parallel to the T -axis starting from the melting line at $H \sim 9$ T and continuing to lower temperatures. First it appeared only as a “fishtail” in magnetization hysteresis loops [3–5]; but recently, a direct measurement of the critical current [6] clearly established a line presumably cor-

responding to some transition in vortex matter. As a possible explanation, the transition (or crossover) from the topologically ordered (Bragg) glass to vortex glass (or pinned liquid) was proposed [7–10].

Independently from these findings, both experimental and theoretical advances indicated that in YBCO there is a structural phase transition in VL: “distorted” hexagonal lattice stable at lower magnetic fields transforms into the square lattice oriented at the angle of $\vartheta = 45^\circ$ with respect to the crystallographic [100] axis at higher fields. Experimental evidence for a significantly distorted hexagonal phase comes from scanning tunneling spectroscopy (STM) [11] and small angle neutron scattering (SANS) [12,13]. Theoretical evidence comes from the derivation of the d -wave Ginzburg–Landau (GL) equations from certain microscopic models [14–16]. The theory was simplified by Franz et al. [17,18] and by one of us [19,20]. Various properties of the VL solutions were also studied. In borocarbide superconductors, an analogous phase transition was firmly established by SANS and STM experiments [24]. This formalism

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had been proven adequate [21–23]. The location of the phase transition line in YBCO, inferred from the angle measured in SANS [19,20], roughly coincides with the line of “additional” peaks in critical current.

In this note we explain the second line of peaks by softening of the “squash” elastic mode of VL on the line of the structural phase transition. All the relevant elastic moduli of VL around the phase transition are calculated. We find that the characteristic width of vortex bundles depends on orientation. This leads to a prediction that the peak current for orientations along the crystallographic axes [100] and [010] is smaller than for orientations along [1,1,0] and [1,1,0] by a factor of $\sqrt{2}$.

We start with a description of the structural phase transition in VL and an estimate of its location on the phase diagram of untwinned YBCO. Qualitatively, anisotropy of the gap functions, in both the d -wave (the dominant component) and the s -wave channels, leads to asymmetric four-lobe shape of vortex cores [14–16]. This, in turn, causes VL to prefer the square arrangement. The asymmetric features are most prominent closer to H_{c2} where the core is more important, but even away from the H_{c2} line, the asymmetry of vortices still distorts the usual hexagonal VL as was clearly demonstrated in experiments [11–13].

We employ a simplified formulation of GL theory for four-fold symmetric superconductors using only one (d -wave) order parameter field ψ [17–20]. The free energy in addition to usual GL terms contains a term describing anisotropy:

$$F_{\text{anis}}[\psi] = \varepsilon |(\mathcal{D}_y^2 - \mathcal{D}_x^2)\psi|^2. \quad (1)$$

Here $\mathcal{D}_i \equiv \nabla_i - i(e^*/c)A_i$, $i = x, y$ is the covariant derivative and e^* is the charge of the Cooper pair. The material parameter ε quantifies the deviation from the exact rotational symmetry. The last term is the only four-derivative term, which is four-fold symmetric and violates rotational symmetry. We assume that magnetic field is in the c -direction and is constant (far enough from H_{c1} this is a good approximation since $\kappa \gg 1$). At certain value of ε there is a phase transition from distorted hexagonal to a more symmetric square lattice first noticed in simulations using the two-field (d and s) formula-

tion [25,26]. The present formulation was shown [19,20] to be essentially equivalent to the two-field one. However, it contains just one parameter ε characterizing the anisotropy and is simple enough to avoid numerical methods in the relevant regions of the phase diagram.

It is important for calculation of elastic moduli to consider the energy of VL of most general form. It is characterized by the lattice vectors \mathbf{a} and \mathbf{b} (with an angle ϑ between them) and by an angle φ specifying the orientation of VL with respect to the crystallographic [1,0,0] axis. One solves the linearized GL equation perturbatively in dimensionless anisotropy parameter $\eta \equiv \varepsilon m_{ab} e^* H$. Finally, we minimize the free energy analytically with respect to φ (clearly $\varphi = \pi/4$ is one of the minima) and numerically over ρ and σ to find the lattice structure.

It was found [19–23] that the transition occurs at $\eta_c = 0.00238$. For every $\eta < \eta_c$, there are two degenerate minima. One is at $\rho = 1/2$, $\sigma = \bar{\sigma}$ and, correspondingly, $\vartheta = \arctan(2\bar{\sigma})$. The other minima correspond to the lattice rotated by $\pi/2$. On the mean field level the phase transition is a second order phase transition with mean field critical exponents. For example, we calculated the dependence of the angle ϑ on η close to the transition point and found that $\vartheta = 3.3(\eta_c - \eta)^{1/2}$. At lower fields and temperatures, one can use the London approximation [17,18] to study the triangular lattice. However, the peak effect is prominent at fields sufficiently close to H_{c2} .

The line of the structural phase transition in VL is parallel to the T axis and goes at certain $H_{\text{str}} = \eta_c / (\varepsilon m_{ab} e^*)$. We estimate this field using input of $\vartheta = 53.5 \pm 0.5^\circ$ for $H = 2T$ [12,13] that for the sample of $6H_{\text{str}} \cong 6T$.

Using thermodynamic arguments, we calculate all the relevant non-dispersive elastic moduli. The only modulus that has a dispersion [27,30], the tilt modulus c_{44} , is not changed significantly compared to the usual case without the asymmetry term. In order to obtain all the 2D elastic moduli of the flux line lattice, we first choose a particular form of distortion and then express the excess free energy corresponding to this distortion in terms of elastic moduli. We obtain following two useful combinations of the four elastic moduli: the shear c_{66} and the “squash” $c_{\text{sq}} \equiv c_{11} + c_{22} - 2c_{12}$.

The dependence of the shear modulus on anisotropy is weak. On the other hand, the squash modulus vanishes on the transition line linearly in $|\eta - \eta_c|$. It is noteworthy that above and below the point $\eta = \eta_c$ the coefficients are different:

$$c_{sq} = \begin{cases} 8.7|1 - \frac{\eta}{\eta_c}|[H - H_{c2}(T)]^2, & \eta_c < \eta \\ 5.5|1 - \frac{\eta}{\eta_c}|[H - H_{c2}(T)]^2, & \eta_c > \eta. \end{cases} \quad (2)$$

This is similar to the behavior of the soft moduli at structural phase transitions in solids.

Because of vanishing of squash elastic modulus of VL we expect some anomalies in physical properties of the superconductor. For example, vanishing of an elastic modulus in the ferroelastic phase transitions in usual crystals manifests itself via softening of the speed of corresponding branch of the sound. Below we argue that in our case, a peak in critical current should appear once one crosses the transition line.

To determine critical current j_c we use the ‘‘dynamical approach’’ [28–30]. The VL equation of motion:

$$\frac{\sigma B^2}{c^2} \frac{\partial \mathbf{u}}{\partial t} = - \frac{\delta F_{\text{elast}}}{\delta \mathbf{u}} - \frac{\delta F_{\text{pin}}}{\delta \mathbf{u}} - \frac{1}{c} \mathbf{j} \times \mathbf{B} \quad (3)$$

is solved perturbatively in the disorder energy $F_{\text{pin}} = \int d^3r \mathcal{E}(\mathbf{r}), \int d^3r \langle \mathcal{E}(\mathbf{r}) \mathcal{E}(0) \rangle e^{i\mathbf{K}r} = (2\pi\Phi_0/B)W(\mathbf{K})$. Here σ is the normal state conductivity, c is the speed of light and \mathbf{K} is the reciprocal lattice vector. The critical current is found to be:

$$j_c(\theta) = \frac{4cW^2(2\pi B/\Phi_0)^{7/2}}{Bc_{44}c_{66}c_{sq}} f(\theta)^2 \quad (4)$$

where $f(\theta) = |\cos(\theta + \pi/4)|^{3/2} + |\cos(\theta - \pi/4)|^{3/2}$. Therefore, the critical current along the crystalline axes a or b is smaller by factor of $\sqrt[4]{2} = \sqrt{2}$ compared to the one along $[110]$ or $[\bar{1}\bar{1}0]$. For untwinned YBCO, one estimates [2] $W = U_0^2 B \xi^2 n_p$, where n_p is point pinning centers density and U_0 is the depth of an individual pinning potential. As in the melting peak effect [28,29], the effect of thermal depinning is taken into account by an additional factor $(1 + T/T_{dp})^{-11/2}$ where T_{dp} is the

depinning temperature. The case of ‘‘small bundles’’ where dispersion of c_{44} is important can be treated analogously [2,30].

Due to different slopes of the moduli c_{sq} as function of $\eta - \eta_c$ (see Eq. (2)) the peak shape is asymmetric provided the general $1/B$ trend is eliminated:

$$j_c B \sim \begin{cases} \frac{1}{8.7(B - B_{\text{str}})}, & B < B_{\text{str}} \\ \frac{1}{5.5(B_{\text{str}} - B)}, & B > B_{\text{str}}. \end{cases} \quad (5)$$

Of course cutoff is understood when the size of the Larkin domain is no longer large compared to the distance between vortices. In this case, the elasticity theory becomes inapplicable.

To determine the applicability region of the elasticity theory, we calculate the correlation length which is the most important characteristics of the mixed state in the collective pinning theory. It is deduced from the displacement correlator $\langle u^2(\mathbf{r}) \rangle$ [30] is given by:

$$2W \int \frac{d^3k}{(2\pi)^3} [1 - \cos(\mathbf{k} \cdot \mathbf{r})] G_{ij}(\mathbf{k}) G_{ij}(-\mathbf{k})$$

where $G_{ij}(\mathbf{k})$ is the elastic Green’s function. To determine the correlation length in certain direction \hat{n} within the collective pinning theory (size and shape of the Larkin domain) one writes $\langle u^2(R\hat{n}\hat{n}) \rangle = \xi^2$ [30]. The correlator in the c -direction does not change compared to the case of hexagonal lattice, $\langle u^2(R_c) \rangle = 2WR_c/(\pi^{3/2}c_{66}c_{44})$, while in the ab plane it depends on the angle ϕ that \hat{n} makes with the crystallographic direction $[100]$:

$$\langle u^2(R_\phi) \rangle = \frac{WR_\phi}{\pi^2 c_{sq} c_{66}^{1/2} c_{44}^{1/2}} f(\phi). \quad (6)$$

The results are significantly different compared to the case of peak effect associated with the VL melting where c_{66} vanishes and $\langle u^2(R_{ab}) \rangle = WR_{ab}/(2\pi^2 c_{66}^{3/2} c_{44}^{1/2})$. We see that $1/c_{sq}$ replaces $1/c_{66}$. In the present situation, Larkin domain is not only asymmetric with respect to a, b vs. c directions. Due to particular orientation of the soft mode

destroying the square lattice the correlation length becomes asymmetric within the ab plane as well:

$$R_c = \frac{\pi^{3/2} c_{66} c_{44} \xi^2}{2W}, \quad R_\phi = \frac{c_{sq} c_{66}^{1/2} c_{44}^{1/2} \xi^2}{Wf(\phi)}. \quad (7)$$

The dynamical approach calculation of j_c can be supplemented by a simpler and more intuitive derivation from the correlation volume. The critical current in certain direction ϕ with respect to the crystal is determined by equating the Lorentz force to the pinning force. The pinning energy for the relaxed lattice is linked to the in plane elastic energy due to the displacement of order ξ in the direction $\theta + \pi/2$ caused by the Lorentz force [30]. The elastic energy is $U_c(\theta) \sim c_{sq}(\xi/R_{\theta+\pi/2})^2 V_c$, where V_c is the correlation volume. Therefore, the critical current obtained from the balance of the Lorentz force and the pinning force is:

$$j_c(\theta) = \frac{c}{B} \frac{U_c(\theta)}{\xi V_c} \sim c_{sq} j_0 \left(\frac{\xi}{R_a} \right)^2 f(\theta + \pi/2)^2 \quad (8)$$

where $j_0 = cH_c/(3\sqrt{6}\pi\lambda)$ is the depairing current. This agrees with the dynamical approach result and shows in addition its range of applicability. Obviously too close to the transition, the calculation is invalid.

To summarize the structural phase transition in the VL of YBCO leads to the anisotropic peak effect via vanishing of the ‘‘squash’’ elastic modulus. We calculated the value of the peak in critical current and its shape.

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