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ANL/MSD/CP--79555
Conf-930801--11

DIMENSIONAL CROSSOVER IN THE TORQUE IN A LAYERED SUPERCONDUCTOR*

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APRIL 1993

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Submitted to International Conference LT XX on Low Temperature Physics, Eugene, OR,
August 4-11, 1993.

* Work Supported by the U.S. Department of Energy, BES-Materials Sciences, under Contract #W-31-109-ENG-38.

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Dimensional crossover in the torque in a layered superconductor

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The procedure of Bulaevskii, Ledvij, and Kogan for evaluating the line energy of a single, straight vortex in the Lawrence-Doniach model in the linearized phase-only approximation is modified to take accurate account of the vortex core cross-sections. Dimensional crossover effects are found to be pronounced, with oscillations in the angular dependence of the torque for $\theta \simeq \pi/2$ and $T \approx T^* < T_c$.

1. INTRODUCTION

The Lawrence-Doniach (LD) model has been used extensively in treating the superconducting properties of layered superconductors [1,2]. Recently, Bulaevskii, Ledvij, and Kogan (BLK) [3] showed that the line energy of a single vortex in the LD model could be calculated by assuming the amplitude of the order parameter was a constant outside of the vortex core, and by neglecting non-linearities in the order parameter phase ϕ . BLK assumed the vortex to form a straight line at an angle θ with respect to the c -axis, with a periodic set of topological defects in ϕ at the intersections of the vortex line with the superconducting layers. In the absence of Josephson coupling between the layers, the vortices are pancakes [4], with circular core cross-sections at the superconducting layers, as assumed by BLK. Such a situation is applicable in the 2D regime $T \ll T^* < T_c$, where T^* is the dimensional crossover temperature given by $\xi_{\perp}(T^*) = s/\sqrt{2}$ [2].

However, it is not correct in the (3D) London regime $T^* < T < T_c$, and cannot therefore properly address the question of dimensional crossover effects in the vortex line energy $\epsilon(\theta, T)$ and in the magnetic torque $\tau(\theta, T) = \partial\epsilon/\partial\theta$. In general, the vortex core cross-section is given by the lines of constant order parameter amplitude [5], which vanishes at the core centers. To investigate the role of dimen-

sional crossover on $\tau(\theta, T)$, we have therefore modified the BLK core cutoff to account for finite Josephson coupling. As shown below, such a treatment reduces to the correct London limit [5,6] for $T^* < T \simeq T_c$, and to the 2D limit of BLK for $T \ll T^*$. In addition, it gives striking oscillations in $\tau(\theta)$ for fixed $T \approx T^*$, which may serve as a fingerprint for the intrinsic superconducting parameters of the material under study.

2. VORTEX LINE ENERGY

Using the linearized phase-only LD model, BLK found the line energy of a single vortex to be given by [3,5]

$$\epsilon = \frac{\Phi_0^2 |\cos \theta|}{32\pi^3} \int d^2\mathbf{k} \frac{k_x^2 G_{\perp} + Q^2 G_{\parallel}}{k_x^2 G_3 G_{\parallel}}, \quad (1)$$

where $G_{\parallel,\perp}(k_x, k_y) = 1 + \lambda_{\parallel,\perp}^2(k^2 + Q^2)$, $G_3(k_x, k_y) = 1 + \lambda_{\parallel}^2 Q^2 + \lambda_{\perp}^2 k^2$, $Q^2 = (2/s^2)[1 - \cos(k_x s \tan \theta)]$, $\lambda_{\parallel}$ is the penetration depth for $\mathbf{H} \parallel \hat{c}$, s is the c -axis repeat distance, $\lambda_{\perp} = \gamma \lambda_{\parallel}$, $\gamma = (M/m)^{1/2} \geq 1$ is the anisotropy factor, Φ_0 is the flux quantum, and $k^2 = k_x^2 + k_y^2$. The integration over $\mathbf{k}$ is restricted to the regions outside the cores. As shown elsewhere [5], this restriction can be accurately obtained from the linearized order parameter amplitude equation below T_c ,

using transformation procedures [5,6],

$$k^2 + Q^2/\gamma^2 \leq 2\xi_{||}^{-2}, \quad (2)$$

where $\xi_{||} = \gamma\xi_{\perp}$ is the Ginzburg-Landau coherence length parallel to the layers. It is straightforward to evaluate the integral over k_y analytically. In evaluating the integral over k_x , we let $k_x = \gamma^2 z/s \tan \theta$. In the limit $\kappa_{\perp} \equiv \lambda_{||}/\xi_{||} \gg 1$, we find $\epsilon = (\bar{\epsilon}_1 + \bar{\epsilon}_2)\Phi_0^2/(16\pi^2\lambda_{||}^2)$, where

$$\bar{\epsilon}_1 = |\cos \theta| \ln \left(\frac{1 + |\cos \theta|}{\gamma[A(\theta) + |\cos \theta|]} \right), \quad (3)$$

$$\bar{\epsilon}_2 = \int_{1/\kappa'}^{\infty} \frac{2dz A(\theta) \Theta(h) \sqrt{f} \tan^{-1} \sqrt{h/f}}{\pi z^2}, \quad (4)$$

$A^2(\theta) = \cos^2 \theta + \gamma^{-2} \sin^2 \theta$, $1/\delta(\theta) = 1 + \gamma^2 \cot^2 \theta$, $f(z) = z^2[1 - \delta(\theta)g(z)]$, $g(z) = 1 - 2z^{-2}(1 - \cos z)$, $\kappa' = 2\delta^{1/2}(\theta)\lambda_{||}/s$, $h(z, \theta) = 2(s/\xi_{\perp})^2 \delta(\theta) - f(z)$, and $\Theta(x)$ is the Heaviside step function. The main contribution to $\bar{\epsilon}_2$ arises from the region $1/\kappa' \leq z \leq z_0 \equiv \min f^{-1}[2(s/\xi_{\perp})^2 \delta(\theta)]$. The torque $\tau(\theta) = \partial\epsilon/\partial\theta$ can then be found in closed (integral) form.

We have evaluated the line energy and the torque numerically, keeping only the region $1/\kappa' \leq z \leq z_0$ for simplicity. In Fig. 1, we have plotted the (dimensionless) torque $\bar{\tau}(\theta) = \partial(\bar{\epsilon}_1 + \bar{\epsilon}_2)/\partial\theta$ versus $2\theta/\pi$ for $\gamma = 100$, $\kappa_{\perp} = 1000$, and various values of $r' = \sqrt{2}s/\xi_{\perp}(T)$. For $r' \leq 2.0$, $\bar{\tau}(\theta)$ closely approximates the anisotropic London result [5-7]. In these cases, $z_0 \leq \pi$. Dimensional crossover occurs precisely at $r' = 2.0$. For $r' = 2.1$, however, $z_0(\theta) \geq \pi$ for θ sufficiently close to $\pi/2$, leading to divergences in the torque, arising from step discontinuities in $\bar{\epsilon}(\theta)$. With increasing r' (or decreasing T), fewer divergences are apparent, but remnants of them persist as oscillations. Well below T^* , the $r' = 20.0$ curve shows that the oscillations are still present, but

very small. Although we expect thermal fluctuations and finite sample mosaics to smear out the extremely narrow divergences, these oscillations should be observable, and could serve as a fingerprint for the particular material parameters of the layered superconductor under study.

Fig. 1. Plot of $\bar{\tau}(\theta)$ for $\gamma = 100$, $\kappa_{\perp} = 1000$, and $r' = \sqrt{2}s/\xi_{\perp}$ values 1.0, 2.0, 2.1, 5.0, and 20.0, for $0.99 \leq 2\theta/\pi \leq 1$. Inset: Same parameter plots of $\bar{\epsilon}(\theta)$ and $\bar{\tau}(\theta)$ for $0 \leq 2\theta/\pi \leq 1$.

This work was supported by the US-DOE under contract W-31-109-ENG-38.

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