Peak Effect and the Rhomb To Square Structural Transition In the Vortex Lattice

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Abstract. The theory of structural transformation of the vortex lattice in a fourfold symmetric type II superconductor in the presence of both thermal fluctuations and quenched disorder is constructed. We show that in the absence of pinning, the slope of the square to rhomb transition in the T-H plane is generally negative: thermal fluctuations favor a more symmetric square lattice. Disorder's influence on the slope is just the opposite- it favors a less symmetric rhombic phase in which the fourfold symmetry is spontaneously broken. The second magnetization peak line in LaSCO in a wide range of doping is well described as a result of the transition.

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It has been known for a long time that both in anisotropic low T_c and in the high T_c type-II superconductors, the vortex solid phase undergoes structural phase transformations (SPT). In particular, in the overdoped LaSCO at high magnetic fields and low temperature the square lattice was observed using SANS by Gilardi et al [1]. When the field is lowered, the rhombic vortex lattice appears. On the other hand, it was shown theoretically that the SPT leads to a peak effect due to softening of certain elastic modulus identified in the case of the square-to-rhomb transition as the "squash" modulus. It is natural to conjecture that the second magnetic peak clearly observed in tetragonal superconductor LaSCO marks SPT in the vortex lattice. The square-to-rhomb transition is by far the simplest possible structural phase transition. In the less symmetric phase there are two rhombic lattices differing by a 90° rotation, while in the more symmetric phase, i.e. the square lattice the vector between two closest vortices may be either parallel to the crystallographic axis a of the atomic lattice, or rotated by 45° with respect to it. Physically, the coupling between the crystal lattice and the vortex lattice in a fourfold symmetric superconductor such as LaSCO originates in two somewhat related anisotropies on a microscopic scale. The first is the Fermi velocity dependence on the angle θ. The second is the anisotropy of the gap function resulting in the anisotropy of the vortex-vortex interaction on the scale of the coherence length ξ. This anisotropy is obviously present and perhaps dominant in the d-wave superconductors due to the nodes in the order parameter. It is this asymmetry, which is effectively taken into account in the Ginzburg - Landau approach to the rhomb-to-square structural phase transition and it is taken into account within the non-local London approach as an asymmetric moment cutoff [2]. At the first glance, the structural phase transition in such a system, even at finite temperature (below the melting temperature of course), is driven by four-fold anisotropy of the inter-vortex interactions on scales smaller that the inter-vortex distances, and consequently have nothing to do with anisotropy of the vortex core. Thermal fluctuations generally prefer a more symmetric square lattice. The interplay between the four fold anisotropy and thermal fluctuations is extremely delicate, so the problem should be considered from a more fundamental stand point. A standard approach to the crystal structure of point-like (or rigid rods) objects at finite temperature requires a sufficiently sophisticated account of the lattice anharmonicity. The simplest version of such a theory takes into account interacting phonon excitations self-consistently (the self consistent harmonic approximation - SCHA).

We adapt in this contribution SCHA to consider structural transformations in tetragonal superconductor and apply the results to $La_{2-x}Sr_xCuO_4$ with different doping concentrations x.

We obtain a structural phase transition line with a negative slope in the B-T plane unlike other theories of thermal fluctuations. In our theory, unlike the preceding ones no ultraviolet cutoff is required. Using the intervortex interaction for a d-wave superconductor derived microscopically by Yang results compare well with experimental data in LaSCO in a wide range of doping.

The vortex-vortex potential at distances larger than the core size was derived from a microscopic model of the d-wave superconductor by Yang [3]

$$E = \frac{1}{2} W\left\{\vec{R}_a - \vec{R}_b + \vec{u}_a - \vec{u}_b\right\}; u_a^\alpha = \int_{BZ} u_q^\alpha \frac{d^2q}{(2\pi)^2}$$

$$W(q_x, q_y) = \left\{1 + \eta\left[2bh/(1+bg)\right]^2\right\} V(g), \qquad (1)$$

$$V(g) = \frac{L_z \Phi_0^2}{4\pi}\left[\frac{1}{1+bg^2} - \frac{1}{\kappa^2 + bg^2}\right]$$

$$b = \frac{4\pi^2\lambda^2 B}{\Phi_0}; g = q_x^2 + q_y^2; h = q_x^2 - q_y^2.$$

Here B is the magnetic induction, Φ_0 is the unit flux, $\kappa = \lambda/\xi$, R_a is the vortex coordinate in the vortex lattice, while u_a notes vortex displacement. To develop a SCHA one has to take into account in the statistical sum the interaction between phonons to the third and fourth orders in vortex displacement. Performing gaussian integration over u_q and taking into account the long range order fluctuations of the displacement correlator $\Delta_{\alpha\beta}(q) = L_z T^{-1}\left\langle u_q^\alpha u_{-q}^\beta \right\rangle$ for tetragonal lattice in the form $\Phi_{\alpha\beta} = \left(\Delta_{\alpha\beta}\right)^{-1}$

$$\Phi_{xx} = c_{11}q_x^2 + c_{66}q_y^2; \Phi_{xy} = cq_xq_y;$$
$$\Phi_{yy} = c_{11}q_y^2 + c_{66}q_x^2; c = c_{11} - \frac{c_{sq}}{2} + c_{66}; \qquad (2)$$

where c_{11}, c_{66}, c_{sq} are the variation parameters related with elastic moduli in the crystallographic axes $c_{11} = C_{11} + C_{66} - C_{sq}/4; c_{66} = C_{sq}/4; c_{sq} = 4C_{66}$. one obtains the variational free energy for the square lattice. In order to find the line of SPT one has to find the minimum of this energy with respect to the variational parameters. It was found for the SPT line

$$b = (1-t^4) f\left(\frac{at}{1-t^4}\right) \simeq \frac{\left(1-t^4\right)^\nu}{t^{\nu-1}}\left[s_1\frac{\left(1-t^4\right)}{t} - s_2\right], \qquad (3)$$

here $t = T/T_c$, $a = \left(4\pi^3\lambda_0^2 T_c/\Phi_0^2 L_z\right)$; $s_1, s_2 \sim 1$ while s_1 and s_2 are the fitting parameters. Three $La_{2-x}Sr_xCuO_4$ single crystals, with different amount of Sr, were grown by the traveling-solvent floating-zone method: underdoped with doping concentration: $x = 0.126, T_c = 32K, \lambda \approx 2 \cdot 10^{-5} cm$ optimally doped $x = 0.154, T_c = 37K, \lambda \approx 10^{-5} cm$, and overdoped $x = 0.194, T_c = 30K, \lambda \approx 10^{-5} cm$. Samples of these crystals, were cut into parallelepiped shape with dimensions (c×a×b) 1.05×1.7×2.3 mm , 1.08×0.7×1.17 mm, 2.08×0.83×0.96 mm, respectively. Measurements were performed using a commercial superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS-XL) utilizing the RSO technique with 1-cm scans. Magnetization was measured at constant temperature as a function of the external field applied parallel to c axis and being swept up to 5 T and down to zero in steps of 200 Oe. The structural reconstruction of the vortex lattice leads to softening of the squash elastic modulus and thus to peak effect [4]. The position of the second peak magnetization versus temperature presented in Fig.1 is in a good agreement with theoretical prediction (solid lines).

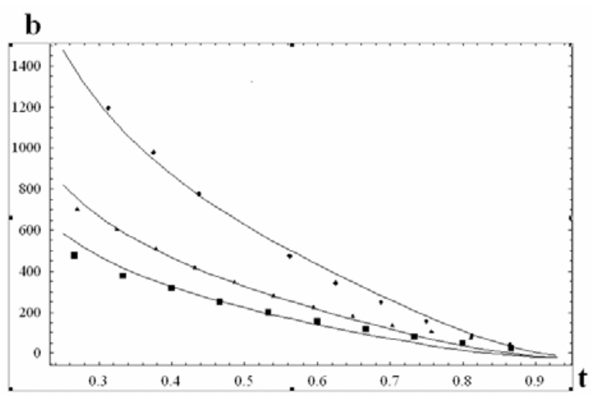

FIGURE 1. Comparison of the experimental second magnetization peak line of $La_{2-x}Sr_xCuO_4$ with the theoretical square-to-rhomb transition line. The rhombs, stars squares, and represent the underdoped, optimally doped and overdoped samples ($\eta = 0.03; 0.02; 0.01$) respectively. The theoretical curves (solid lines) are all for κ=75 .

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