Theoretical Study of Phase Transition in Type II Superconductors with Pauli Paramagnetic Effect in High Magnetic Field

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Abstract

High field phase diagram of type II superconductors with paramagnetic depairing effect is examined through a theoretical argument and a numerical simulation of a Ginzburg-Landau model with a negative quartic term. Our results strongly suggest, contrary to the argument based on magnetization data in $CeCoIn_5$, that the first order transition at $H_{c2}(T)$ in the mean field (MF) approximation is reflected in real systems merely as a crossover and that the thermal phase diagram is similar to that in the ordinary case where the MF transition is of second order.

Key words: vortex; paramagnetic effect; superconducting fluctuation

1. Introduction

Recently, several experiments in $CeCoIn_5$ [1–4] have suggested the presence of a first order phase transition (FOT) on the $H_{c2}(T)$-line at low temperatures where the Pauli paramagnetic pair breaking is no longer negligible. The experimental results are summarized as follows. First, the discontinuity in measured quantities suggestive of a FOT is quite large consistently with a high condensation energy in this material. Second, no feature is seen above the field at which the discontinuity occurs. Through these features, the discontinuity tends to be identified with a superconducting FOT in the mean field (MF) approximation. Further, except the ordinary magnetic hysteresis of a vortex pinning origin, no hysteresis is seen in experimental data.

However, the MF transition is not theoretically expected to occur in real systems with fluctuations, once extending theoretical knowledges on the vortex states [5] in the case with no paramagnetic pair breaking to the present case with a large paramagnetic effect. For instance, by considering elastic and phase fluctuations accompanying a melting of a vortex lattice, the resulting vortex liquid is found not to have any superconducting order. Namely, a MF transition at $H_{c2}(T)$ should not occur as far as the vortex lattice melts below $H_{c2}(T)$. This argument is valid irrespective of a form of nonlinear terms of a Ginzburg-Landau (GL) model, i.e., even when the MF transition is an FOT. If the fluctuation is so weak that the melting position may not be separable from H_{c2}, the amplitude fluctuation neglected above, in turn, plays essential roles: If, as usual, assuming the superconducting order parameter ψ near H_{c2} to be described within the lowest Landau level (LLL), we have [6]

$$\psi(\zeta, z) = \Phi(z) e^{-|\zeta|^2/4r_B^2} \prod_{i=0}^{Ns-1} (\zeta - \zeta_i(z)), \qquad (1)$$

where $\zeta = x + \mathrm{i}y$, $r_B = \sqrt{\phi_0/2\pi B}$ is the magnetic length, and $\{\zeta_i(z)\}$ denotes the position of each vortex. Although the MF approximation demands [7] an exact discontinuity in the amplitude $\Phi(z)$, Φ has one (zero) dimensional character in 3D (2D) systems, implying no transition at H_{c2} [8]. This fact is also valid irrespective of the details of a GL model. Therefore, except possible structural transitions between vortex lattices, the only transition occurring without a vortex pinning is a *weak* FOT implying the vortex lattice melting and

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associated with the freedom $\{\zeta_i(z)\}$ representing the positional order of vortices.

2. Monte Carlo analysis

To reinforce the above prediction, we have performed a Monte Carlo simulation based on the GL functional with a *negative* quartic term[7]

$$H_{\rm GL}^{(\rm LLL)} = \int d^3r \Big(\alpha|\psi|^2 + \gamma|\frac{\partial}{\partial z}\psi|^2 + |\frac{\partial^2}{\partial z^2}\psi|^2 - \frac{|\beta|}{2}|\psi|^4 + \frac{1}{3}|\psi|^6\Big), \quad (2)$$

where $\psi(r)$ is defined within LLL, and length scales and the pair-field are rescaled appropriately. At the MF level, the mean square average $\langle|\psi|^2\rangle$ corresponding to the transition entropy jumps from 0 to $3|\beta|/4$ at the transition. Due primarily to numerical difficulties, our analysis is restricted below to two dimensional (2D) case. We follow the simulational method of ref. [9] but use the different boundary condition $L_x/L_y = \sqrt{3}N_x/2N_y$ with $(N_x, N_y) = (6, 4)$.

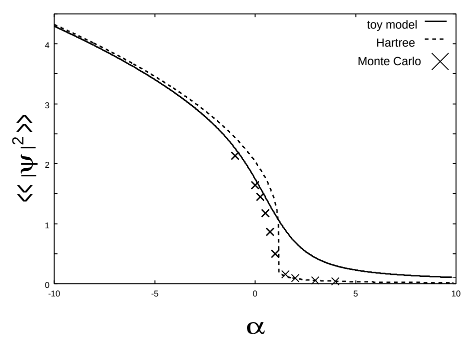

Fig. 1. $\langle|\psi|^2\rangle$ plotted against α for $|\beta| = 2.0$ case in the toy model (solid line), Hartree approximation (dotted line), and 2D Monte Carlo simulation (cross).

Fig. 1 shows α dependences of $\langle|\psi|^2\rangle$ for $|\beta| = 2.0$. For comparison, the results of a Hartree approximation and a zero dimensional toy model [10] are plotted. For small α (low temperature) values, three curves agree well with each other, while the discontinuous behavior near the MF transition point, seen in the Hartree approximation, is smeared and $\langle|\psi|^2\rangle$ seems to grow smoothly. Clearly, the MF-FOT is smeared out once the fluctuation is included. It is not surprising that the smooth $\langle|\psi|^2\rangle$-growth is seen, in a system with weak fluctuation [1–4] (i.e., a large $|\beta|$), as a discontinuous jump. Fig. 2 shows snapshots of the structure factor for $|\psi|^2$. We can see a positional ordering not at the MF transition point but only well below the MF transition point where most of the entropy seems to have already

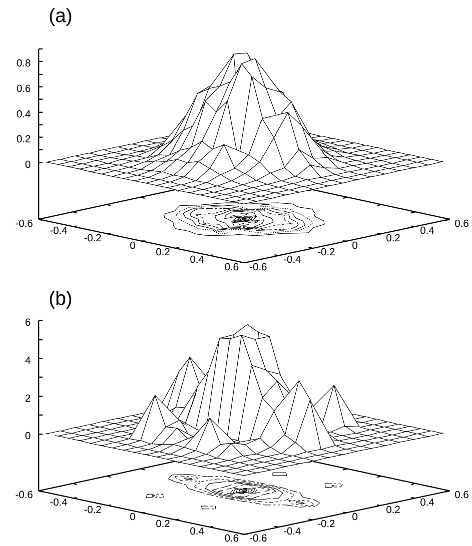

Fig. 2. Snapshot of the structure factor for different values of α. (a)α=0.75 (MF transition point), (b)α=-2.0.

been lost, and weak six-fold symmetric peaks appear. A separation of two temperature scales characterizing the smooth growth of $\langle|\psi|^2\rangle$ and a sudden growth of vortex positional ordering is clearly seen.

Even though our calculation is restricted to 2D case at the present stage, the separation of two temperature scales (i.e., the absence of the MF transition) mentioned above should hold in 3D case according to the argument in §1. Simulation for multi-layered case will be left for our future work.

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