Nature of the vortex-glass order in the type-II limit

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Abstract

The stability and the critical properties of the three-dimensional vortex-glass order in random type-II superconductors with point disorder is investigated in the unscreened limit based on a lattice XY model with a uniform field. By performing equilibrium Monte Carlo simulations for the system with periodic boundary conditions, the existence of a stable vortex-glass order is established in the unscreened limit. Estimated critical exponents are compared with those of the same model with free boundary conditions and with those of the gauge-glass model.

Key words: vortex glass; flux lines; Monte Carlo simulation

In spite of extensive studies for a decade, the question of nature of the thermodynamic phase diagram of high-T_c superconductors has remained unsettled. For random superconductors with point disorder, possible existence of an equilibrium thermodynamic phase called the vortex-glass (VG) phase, where the vortex is pinned on long length scale by randomly distributed point-pinning centers, was proposed [1]. In such a VG state, the phase of the condensate wavefunction is frozen in time but randomly in space, with a vanishing linear resistivity ρ_L. It is a truly superconducting state separated from the vortex-liquid phase with a nonzero ρ_L via a continuous VG transition.

Since cuprate high-T_c superconductors are exremely type-II superconductors where the London penetration depth λ is much longer than the coherence length, it is important to clarify first whether the proposed VG state really exists in the type-II, unscreened limit $\lambda \to \infty$. Indeed, stability of the hypothetical VG state has been studied quite extensively by numerical model simulations [2–8]. Many have been based on a highly simplifed model called the the gauge-glass model. Previous simulations on the 3D gauge-glass model gave mutually consistent results that a continuous VG transition occured at a finite temperature characterized by the critical exponents, $\nu \simeq 1.3$, $\eta \simeq -0.5$, $z \simeq 4-5$, which was compared with experiments favorably[2–5].

Meanwhile, the gauge-glass model has some drawbacks [2]. It is a spatially isotropic model without a net field threading the system, in contrast to the reality. Furthermore, source of quenched randomness is artificial. The gauge-glass model is a random flux model where the qeunched randomness occurs in the phase factor assoicated with the flux. In reality, the quenched component of the flux is uniform, nothing but the external field, and the quenched randomness occurs in the superconducting coupling or the pinning energy. It remains unclear whether these simplifications underlying the gauge-glass model really unaffect the basic physics of the VG ordering in 3D.

Recently, several simulations were performed beyond the gauge-glass model[6–8]. The present author studied the type of the lattice XY model where the above limitations of the gauge-glass model were cured[6]. While the VG state was found to be stable, the estimated critical exponents, particularly $\nu \simeq 2.2$, differed significanly from those of the gauge-glass model, posing a possibility that the gauge-glass model lies in a different universality class. However, due to the effect of free boundary conditions employed in Ref.[6], the estimated critical exponents might possibly be subject to large surface effect. Vestergren *et al* studied a ran-

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dom pinning model which took care of the above limitations of the gauge-glass model in a different way, to obtain a finite-temperature VG transition characterized by the exponents, $\nu \simeq 0.7,\ z \simeq 1.5$[7], which differed significantly from either those of Ref.[6] or from those of the gauge-glass model[3–5]. Olsson and Teitel claimed on the basis of their simulations on the lattice XY model with weak disorder that the VG order was not stable even in the unscreened limit[8]. Thus, once one wishes to go beyond the gauge-glass model, the present theretical situation seems quite confused.

In the presnet paper, we study the lattice XY model of Ref.[6], but now with applying *periodic boundary conditions*, to overcome the type of the finite-size (surface) effect of Ref.[6]. We consider the Hamiltonian,

$$H = -\sum_{<ij>} J_{ij}\cos(\theta_i - \theta_j - A_{ij}), \tag{1}$$

where θ_i is the phase of the condensate at the i-th site of a simple cubic lattice with $N = L^3$ sites, and the sum is taken over all nearest-neighbor pairs. A_{ij} is the link variable associated with the vector potential due to uniform external magnetic field of intensity h applied in the z-direction. In the Landau gauge, it is given by $\mathbf{A}_i$=(A_i^x,A_i^y,A_i^z)=(0,hi_x,0), where $1 \leq i_x \leq L$ denotes the x-coordinate of the site i. Quenched rondomness occurs in the superconducting coupling J_{ij} which is assumed to be an independent random variable uniformly distributed between [0,2J], $J > 0$ being a typical coupling strength. Note that the present choice of J_{ij} corresponds to very strong randomness. In contrast to Ref.[6] where free boundary conditions were imposed in order to allow for the flux penetration into and out of the sample, I impose periodic boundary conditions in all directions in order to eliminate surface 'spins' which might contaminate the bulk critical behavior of present interest. The field intensity is chosen to be $h = 2\pi/4$ ($f = 1/4$), and the lattice sizes are taken to be multiples of four, *i.e.*, $L = 8, 12, 16$ and 20. Simulation is performed based on the exchange MC method. Sample average is taken over 100-980 independent realizations of J_{ij}.

In Fig.1, I show the Binder ratio (the definition given in Ref.[6]). As can be seen from the figure, $g(L)$ for different L cross at $T/J = 0.82(3)$, indicating that the VG transition occurs at a finite temperature. Note that the present data show a rather clear splay-out, in contrast to the near marginal merging behavior observed for the case of free boundary conditions[6]. Via a finite-size scaling analysis of $g(L)$, the correlation-legth exponent is estimated to be $\nu = 1.2(3)$. Then, from the finite-size scaling analysis of the VG order parameter and the VG autocorrelation function (not shown here), the critical-point-decay exponent and the dynamical exponent are determined to be $\eta = 0.1(3)$ and $z = 3.8(8)$, respectively. On comparing these exponents with the values obtained for the system with free boundary conditions, one sees that they differ considerably. Thus, in the range of lattice sizes studied here, the application of either periodic or free boundary significantly influences the estimates of critical exponents. If one compares the present estimates with those of the the gauge-glass model (with periodic boundary), the ν value comes rather close while the η value differs somewhat. Hence, the issue of whether one can safely regard the gauge-glass model as a true representive model of the universality class of real VG transitions still remains ambiguous.

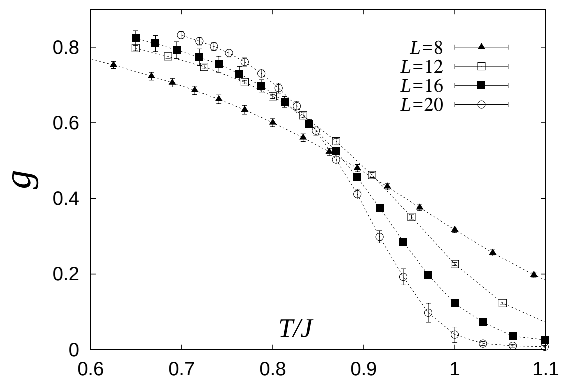

Fig. 1. Temperature and size dependence of the Binder ratio associated with the vortex-glass order parameter.

In view of the large deviations observed among the estimated critical exponents of different models and of different boundary conditions, further careful studies seem required to fully resolve the issue of the universality class of 3D VG transition. Meanwhile, in view of the clear crossing behavior observed in the Binder ratio, the existence of a finite-temperature VG transition in the unscreend limit $\lambda \to \infty$ seems well established.

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