Disorder Driven Destruction of a Phase Transition in the Vortex System of a Superconductor

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(Received 27 May 1997)

We investigate the effects of point disorder on the magnetically induced vortex system of a layered superconductor. The clean system is known to have a first order phase transition which is clearly identified by a sharp peak in the specific heat. The peak is lost abruptly as the strength of the disorder is increased. Hence, for strong disorder there is no phase transition (in the vortex degrees of freedom) as a function of temperature but merely a crossover which is still detectable in the *I-V* characteristic. [S0031-9007(97)04536-5]

PACS numbers: 74.60.Ge, 64.60.Cn

Disorder is known to play an important role in the phase diagram of even so-called *clean* superconductors at low temperatures and high magnetic fields. It has recently been shown that these clean systems have a first order transition. It is believed that this transition is associated with melting or decoupling of the vortex system. The thermodynamic signal of the transition is lost at a "critical point" below which pinning is thought to dominate the behavior [1,2].

Significant effort is currently being invested in attempting to understand theoretically the effect of disorder on the behavior of the magnetic flux system in superconductors [3–5]. In this Letter we discuss simulations of the phenomenological behavior and response to disorder of a layered vortex system. Our model is deliberately made sufficiently simple so that we are able to identify the mechanisms behind the effects we observe. We believe that our results demonstrate which degrees of freedom of the vortex system are necessary in order to interpret the real experimental data.

We present the results of a 3D layered simulation in the presence of point disorder. We have included *only* the degrees of freedom associated with vortex lines, an approximation we believe to be valid away from the vicinity of the zero field transition, T_c. The vortex lines consist of stacks of pancake vortices. These stacks are able to cross and to decouple when it becomes energetically favorable and this is an essential feature of the model. The clean system has a first order decoupling transition, with an entropy jump comparable to that seen experimentally away from T_c: namely, $\simeq 0.4 k_B$/vortex/layer. However, for strong disorder the first order transition is reduced to a gradual crossover. This can be seen in many aspects of the behavior. The pronounced peak in the specific heat that is a feature of the clean system is no longer present and the diffusion becomes thermally activated with an energy scale set by the strength of the interlayer coupling. Thus the decoupling transition is replaced by a depinning crossover whose underlying mechanism is plastic cutting of the vortex lines. This is confirmed by direct measurement of the cutting frequency. Hence a *vortex glass* phase [6] *cannot* occur in this system since the divergence of the elastic creep barriers at vanishing driving force [7] will be cut off by the finite activation energy barrier for plastic cutting of the flux lines. We analyze both thermodynamic and transport properties. The specific heat behavior demonstrates that above a threshold disorder destroys the phase transition of the clean system. However, the transport properties are relatively insensitive to the disorder. This stresses that one must be cautious when inferring the existence of phase transitions from transport data [8]. The manner in which the clean system phase transition is destroyed by the introduction of disorder has been investigated by Giamarchi *et al.* [4,9] and Kierfeld *et al.* [5,10]. The destruction of the thermodynamic phase transition may in fact take place via a phase transition as a function of disorder in our simulation.

The model is a layered pancake system which demonstrates quantitative features similar to those seen in the highly anisotropic Bi-2212 high temperature superconductor. The transition is studied as a function of fixed magnetic field, B (density of vortices), which is always perpendicular to the layers (along the c axis), and variable temperature. In order to be able to study the loss of the vortex lattice order the vortex position is varied continuously as an underlying discrete lattice can lead to spurious phases [11]. The disorder is the simplest possible—namely, random point pins.

The system is equilibrated via Langevin dynamics with periodic boundary conditions enforced in all directions. For simplicity all the temperature dependence of the model is introduced via a noise term [12]; additional temperature dependencies of the penetration depth and other length scales are neglected. We focus purely on the vortex lattice aspect of the melting—that is, only vortex loops representing fluctuations in the positions of the flux lines are included. To enable a sufficiently large simulation to study 3D effects Gaussian potentials are employed for all the interactions. In 2D the true in-plane interaction should be the K_0 Bessel function but it

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is only reasonable to use this numerically for very short penetration depths as otherwise the long range nature of the potential results in excessive relaxation times. For a layered superconductor the predicted potentials [13] are even longer. That the qualitative behavior is correctly simulated by the Gaussian potentials can be seen by comparing the 2D simulations of Jensen *et al.* [14] who used the Gaussian potential and Koshelev [15] who used the physical potentials.

The pancakes in the planes have an in-plane repulsive interaction between them, in our case modeled by a Gaussian potential $U^{ll}_{vv'} = A_v \exp(-r^2/\xi_v^2)$, where r is the in-plane distance between the vortices, ξ_v is the in-plane vortex range, and A_v is the (fixed) strength of the vortex potential.

Across the layers the interaction is more complicated as it must include a mechanism for cutting and reconnecting the vortices. This is known to be important near the melting temperature, in order to allow for the loss of long range phase coherence as seen, for example, in the pseudotransformer experiments [16]. It has been shown by Clem [17] that in order to model the electromagnetic interactions across the layers only pair-wise potentials are needed. However, Bulaevskii *et al.* [18] have shown that including the lowest order terms of the Josephson coupling makes three- and four-body terms equally necessary. For weak interlayer coupling we have found that the inclusion of the three-body term is sufficient. Hence the total interaction across the planes is composed of a two-body attractive interaction (where all r are in plane) $U^{ll'}_{vv'}(r_i^l, r_j^{l'}) = -A_l \exp[-(r_i^l - r_j^{l'})^2/\xi_{l^2}]$ and a three-body repulsive interaction.

$$U^{lll'}_{vv'v''}(r_i^l, r_j^l, r_k^{l'}) = A_{3b} e^{-[(r_i^l - r_j^l)^2 + (r_j^l - r_k^{l'})^2 + (r_k^{l'} - r_i^l)^2]/\xi_{3b}^2}. \quad (1)$$

A_l and ξ_l are the amplitude and range of the two-body interaction and similarly A_{3b} and ξ_{3b} are the amplitude and range of the three-body potential. The latter acts by excluding three or more pancakes (two in one layer and a third in an adjacent layer) from finding their equilibrium location to be within a coherence length in the x-y plane. The anisotropy is determined by the strength of the interlayer coupling parameter A_l, and is fixed to be 0.2, which corresponds to a highly anisotropic system; that is, the ratio between the tilt and shear moduli is $c_{44}/c_{66} \simeq 0.01$ for layer and vortex spacings pertinent to Bi-2212 in an external magnetic field of 1 T. This is similar to that estimated for Bi-2212 using the elastic moduli as defined in Blatter *et al.* [13]. The other parameters are $A_v = 1$ and $A_{3b} = A_l$, for the amplitudes of the potentials and $\xi_v = 0.6$, $\xi_l = 0.3$, $\xi_{3b} = \sqrt{2}\,\xi_l$ for the ranges in the Gaussians. Our unit of length is the average spacing between the pancakes.

For this choice of parameters the clean system loses order in both the a-b plane and the c direction over a very narrow temperature range which is comparable to the accuracy with which the temperature can be determined in the Langevin simulation. There is a pronounced peak in the specific heat at this temperature and a Lee-Kosterlitz [19] binning of the energies yields an associated entropy of $\simeq 0.4 k_B$/pancake. Furthermore the activation energy between the ordered and disordered states grows with system size, indicating a first order transition.

In two dimensions it has been shown by one of the authors [20] that weak disorder with amplitude in the range $0.01 \leq A_p \leq 0.05$ has a significant effect on the melting temperature (as defined by the onset of diffusion); see Fig. 1. T_{ab} initially decreases (to approximately half its clean value) but then increases as the pinning energy becomes dominant; see lower inset in Fig. 1. This is due to the weakening by disorder of the shear modulus of the system. In three dimensions this effect is still present but much weaker (of the order of a percent); see upper inset in Fig. 1. At these small values of A_p there is no difference in the results obtained for a broad range of vortex-to-pin ratios: $0.5 \leq N_v/N_p \leq 2$.

Experimentally the transition moves to lower temperatures as the magnetic field is increased [1]. At these lower temperatures less thermal energy is available and hence the pinning energies become more significant. To simulate this without changing the magnetic field a larger value of the pinning potential amplitude, $A_p = 0.5$, is used. The results are dramatically different from the clean system. First, the onset of the diffusion which in the clean system is very sharp becomes a gradual onset, and is in fact thermally activated. The activation energy is determined by the strength of the interlayer coupling: $E \simeq 1.5 A_l$ (from investigating $A_l = 0.2$, 0.3, and 0.5 with fixed $A_p = 0.5$ and varying numbers of pins). This suggests that the diffusion is occurring via *plastic* cutting of the vortex lines. The concept of "vortex lines"

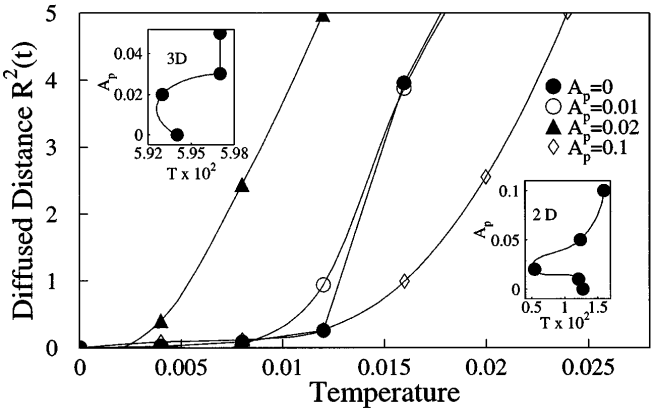

FIG. 1. Main figure: Diffused square distance after $t =$ 75 000 time steps as a function of temperature for the two dimensional system with $N_v = 1024$ for different pinning strengths, A_p. The insets are the 2D and 3D behaviors of the melting temperature (as defined by diffusion) as a function of pinning strength. It is clear that the effect is much more significant in the 2D case.

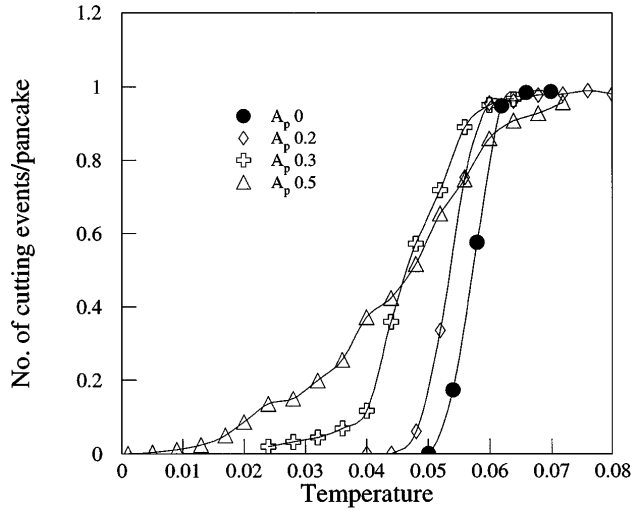

FIG. 2. Number of cutting events/pancake as a function of the strength of the disorder.

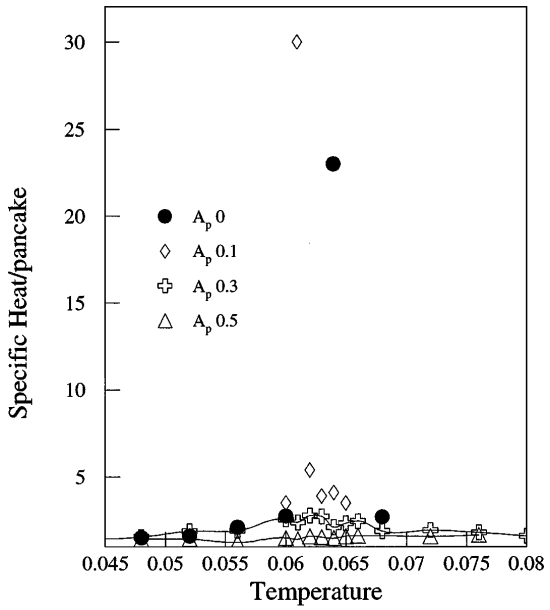

FIG. 3. Specific heat as a function of temperature for the clean system and with 144 pins of amplitude $A_p = 0.5$ and range $R_p = 0.125$. Both systems consist of 144 pancakes in each of eight layers.

is a matter of convention in our layered system. However, the obvious way of identifying them is in terms of stacks of pancakes—where nearest neighbor pancakes in adjacent layers are said to belong to the same stack. The cutting rate can now also be measured directly. We define the rate to be the number of times a pancake changes its nearest neighbor assignment to pancakes in adjacent layers, in a given time interval. There is a plateau in the rate above the pure system decoupling temperature; see Fig. 2 for all pinning strengths. However, the onset temperature for cutting decreases as the pinning strength increases, in agreement with the diffusion results.

In the clean system there is a peak in the specific heat, which is a thermodynamic indicator of the transition and can be compared with the experimental results of Zeldov *et al.* [1] and Schilling *et al.* [21]. In the presence of weak disorder ($A_p \lesssim 0.1$) the peak is essentially unaffected but the peak vanishes rapidly with increasing disorder when $A_p \simeq 0.2$ and drops away into the background; see Fig. 3. It should be emphasized that when a peak is present, it is as sharp as our temperature resolution. The height of the peak is difficult to determine due to the strong fluctuations in the vicinity of the transition. Our results are fully consistent with the idea that there may be a phase transition as a function of disorder.

We have shown that the thermodynamic phase transition is destroyed by directly investigating a thermodynamic property (the specific heat). We now demonstrate that the existence of the transition can be falsely assumed by indirect measurements, such as *I-V* characteristics if they are not correctly analyzed.

For $A_p \gtrsim 0.2$ there is no longer a true phase transition but this is not apparent if a diffused distance criterion, say $R^2(t = t_s) = 1$, is used to determine melting. From this criterion one finds that disorder merely shifts the melting temperature and one would misleadingly conclude that the melting transition survives the presence of disorder. It is, however, clear from the form of the diffusion curves that the diffusion mechanism has changed; see Fig. 4. Measuring the onset of diffusion is a close analog of an experimental *I-V* characteristic. This is demonstrated in

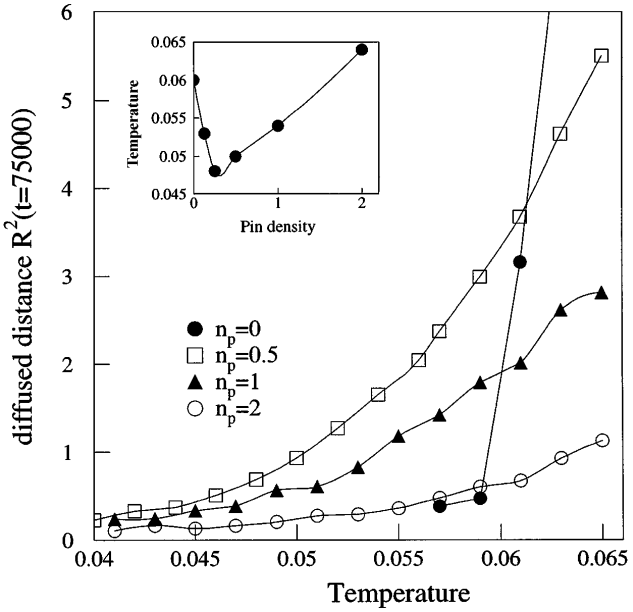

FIG. 4. Average of square of moved distance over a fixed number of time steps for a different number of pins N_p. The amplitude is $A_p = 0.5$ and range is $R_p = 0.125$ in all cases. The system consists of 144 pancakes in each of eight layers. The inset shows the temperature at which $R^2 = 1$ for different pin densities.

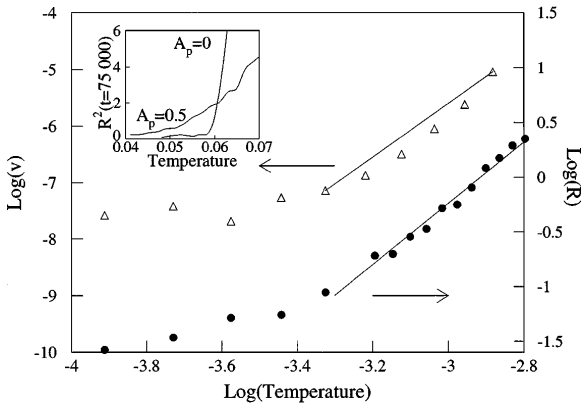

FIG. 5. Plots of the log(voltage) and log(diffused distance) versus log(temperature) for $A_l = 0.2$ and $A_p = 0.5$ indicating an onset temperature for both $\sim$0.04. The inset shows the change in the behavior of the diffusion curve between the clean and strongly pinned systems.

Fig. 5 with log-log plots for both the diffused distance as a function of temperature (at fixed time) and the voltage as a function of temperature (at fixed driving force). Within the numerical accuracy the *I-V* characteristic is linear as a function of current at small current. The *I-V* characteristics correspond to thermally assisted flux flow [13]. By assuming that the induced voltage has an Arrhenius form we find that the activation energy is of the same order of magnitude as that deduced from the onset of the diffusion data. Hence our system does not have a vortex glass phase [6].

To summarize we have presented a simple model which demonstrates that the thermodynamic decoupling transition is abruptly destroyed by a finite amount of disorder. We believe that this is the explanation for the critical point in the Bi-2212 phase diagram of Zeldov *et al.* Furthermore, our study shows that transport data can suggest the existence of a transition even when it is known that disorder has destroyed the thermodynamic phase transition.

N. K. W. thanks the School of Physics, Birmingham University for hospitality while some of this work was carried out. N. K. W. and H. J. J. were supported by EPSRC Grants No. Gr/J 36952 and No. GR/L28784.

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