DOE/ER/14017--2

DE91 002756

Flux Flow Pinning and Resistive Behavior in Superconducting Networks

Annual Progress Report, 2nd year

for the period May 1, 1990 to April 30, 1991

Stephen Teitel

Department of Physics and Astronomy
University of Rochester
Rochester, New York 14627

October 1990

Prepared for

THE U. S. DEPARTMENT OF ENERGY
GRANT NO. DE-FG02-89ER14017

Abstract

We have studied the behavior of superconducting networks in terms of XY and Coulomb gas models. The dynamics of frustrated Josephson junction arrays has been simulated, with a view towards understanding the effects of vortex correlations on flux flow resistance. Randomness has been introduced, and its effects on the superconducting transition, and vortex mobility, have been studied. A three dimensional network has been simulated to study the effects of vortex line entanglement in high temperature superconductors. Preliminary calculations are in progress. The two dimensional classical Coulomb gas, where charges map onto vortices in the superconducting network, has been simulated. The melting transitions of ordered charge (vortex) lattices have been studied, and we find clear evidence that these transitions do not have the critical behavior expected from standard symmetry analysis.

I. Progress Report for the Current Budget Period (5/1/90 - 4/30/91)

Research has focused on modeling behavior in superconducting networks in terms of well defined statistical models. One is the uniformly frustrated XY model, in which the angle of a two component classical spin is used to represent the phase of the superconducting wavefunction, and frustration models the effects of an applied magnetic field. The second is the classical Coulomb gas, in which the charges model vortices in the phase of the superconducting wavefunction. In terms of these statistical models, we carry out numerical simulations to determine equilibrium critical behavior, and non-equilibrium transport properties. We have applied these methods to investigating behavior in periodic arrays of Josephson junctions, and models of high temperature superconductors.

A. Flux Flow Resistance in Josephson Junction Arrays

I have continued, in collaboration with postdoctoral associate Dr. Ying-Hong Li, to carry out equilibrium and non-equilibrium simulations of the two dimensional uniformly frustrated XY model, as a model for the superconducting transition and flux flow resistance in a periodic Josephson junction array in a uniform transverse magnetic field. Within this model, we are able to explicitly compute flux flow resistivity and relate it to vortex correlations. My previous work concentrated on the "fully frustrated" case where the applied magnetic field is equal to one half flux quantum per unit cell of the array (f=1/2). This case is characterized by a particularly simple ground state. In the present work, we have extended our simulations to cases where the ground state vortex correlations are more complicated, to study the resulting effects on the resistive transition. We have investigated two new cases:

(i) f=2/5 periodic array: For the case f=2/5, the ground state vortex lattice consists of regions of f=1/2 like structure, separated by domain walls. Our goal was to investigate the effects of these domain walls on the behavior of the system. Our principal results are: (a) The equilibrium superconducting transition is now first order (discontinuous) in contrast to the previously studied cases which were second order (continuous). (b) The flux flow resistance above T_c was found to display a short plateau, before rising to saturate at its high temperature limit. We have shown that this plateau is due to short range correlations in the disordered vortex fluid, which die out as the vortex fluid becomes isotropic at higher temperatures. (c) The non-linear current-voltage (I-V) characteristics below T_c show two plateaus. We have shown that these are due to the onset of domain wall motion at the critical current I_c, followed by the breaking up of local f=1/2 like regions at higher current. (d) The thermally activated, non-linear, flux creep at low temperatures and current ($T<T_c$, $I<I_c$) consists of domain like excitations which significantly destroy the order of the ground state vortex lattice. Our results have been accepted for publication in Physical Review Letters (to appear Nov. 12), and a longer paper is in preparation.

(ii) <u>f=1/5 bond diluted array</u>: For the case f=1/5, the ground state consists of a square lattice of vortices. Our goal was to study the effects of randomness on the behavior of the system, by removing a dilute (2%-10%) fraction of the junctions. Each missing junction serves as a local pinning site, due to the reduced core energy to place the vortex in this cell. Our principal results are: (a) The randomness reduces the equilibrium transition temperature T_c compared to the pure case. The sharp specific heat peak of the pure case disappears, and the superconducting state may be described as a vortex glass. (b) The flux flow resistance of the random case is reduced compared to the pure case, due to the reduction in vortex mobility arising from trapping at the pinning sites. These results indicate that in this case, the lowering of T_c with the loss of long range correlations among the vortices, has a less important effect on the flux flow resistance than the reduction in single vortex mobility due to the randomness. Work in this area is still in progress. For both (i) and (ii) we have made extensive use of the DOE supercomputer facilities at Florida State University.

B. Flux Line Entanglement in High T_c Superconductors

Recent experimental and theoretical works have indicated that one aspect in which the high temperature superconductors differ from the conventional ones, is the presence of very strong fluctuations, due to the increased transition temperature and relatively large ratio of penetration length to correlation length. Mean field theories can thus no longer be employed, and statistical methods must be used. With this motivation we have carried out simulations on three dimensional XY models, a well prescribed microscopic model for superconductivity in which fluctuation effects can be taken into account. My previous work, in collaboration with Dr. Ying-Hong Li, was to model the pure 3D XY model, and a 3D model with random bonds (see Appendix A).

Presently we are simulating a uniformly frustrated 3D XY model, to model the behavior of a bulk high T_c superconductor in a uniform magnetic field parallel to the *c* axis. Much theoretical work, originating with Nelson, has suggested that for some finite temperature range above T_c, the system may be described as an entangled vortex line fluid. If so, one would expect the effects of pinning sites on flux flow resistance to be greatly enhanced, as a single pinned vortex line may effectively trap all other vortex lines it is entangled with. A key assumption of this idea is that vortex lines are unable to cross each other, cut, and reconnect; this would give a mechanism allowing vortex lines to pass through the entanglement. By studying the vortex lines in the uniformly frustrated 3D XY model we are able to test this assumption. Our preliminary results indicate that substantial cutting and reconnection does in fact take place for a wide range of the ratio of in-plane (perpendicular to magnetic field) to out-of-plane Josephson couplings. Work is still in progress

C. The Two Dimensional Coulomb Gas

For a superconducting network in a transverse magnetic field, the superconducting transition, and resistance due to flux flow, are most conveniently described in terms of the correlations among vortices in the phase of the superconducting wavefunction. These vortices and their interactions may be mapped onto "charges" in an equivalent statistical problem, the classical Coulomb gas. It is often advantageous to work in this Coulomb gas model directly, rather than in terms of the original superconducting wavefunction.

I have continued work with my graduate student, Mr. Jong-Rim Lee, carrying out Monte Carlo simulations of the dense Coulomb gas. As the charge density is increased, the ground state of the system becomes an ordered charge lattice, analogous to the vortex lattice induced in a superconducting network by a transverse magnetic field. The resistive transition of the network may be described in terms of the melting of this charge lattice, with the creation of freely moving charges (vortices). It is thus of fundamental importance to understand such melting transitions, and in particular see if they may be classified according to the symmetry of the charge lattice, as is the case in many other statistical systems.

We have extended our previous work on the integer Coulomb gas on a square lattice (see Appendix B), in which an anomalous tricritical point was found, to the case of a triangular lattice. Here we find anomalous charge lattice melting transitions, where the critical behavior is strikingly different from what one expects based on standard symmetry analysis. One of the transitions we find is analogous to that in the fully frustrated (1/2 flux quantum per cell) Josephson junction array on a honeycomb lattice. More direct connections to the case of the network in a magnetic field, which may be described in terms of a fractional Coulomb gas, are currently being explored. Our new results have been submitted for publication to Physical Review Letters, and a longer paper is in preparation.

D. Dynamic Transitions in the Two Dimensional XY Model

As the XY model is the fundamental model I have been using in the study of superconducting networks, it is important to keep abreast of any new theoretical developments in the study of this model. Recently, a paper by Golinelli and Derrida, based on a dynamical approach, suggested that the two dimensional XY model might have three distinct phases, as opposed to the two phases predicted by the Kosterlitz-Thouless (KT) theory. To check this surprising result, I gave this problem to John Chiu, then an undergraduate student (presently doing graduate work at Caltech), to work on as a senior thesis. Together we showed that the three phases found by Golinelli and Derrida resulted from their using a dynamical rule which violated the rotational symmetry of the Hamiltonian. When a dynamical rule preserving this symmetry was used, we found only the two phases expected from the KT theory. This work was published in the Journal of Physics A (see Appendix C).

II. Research Plans for the Next Budget Period (5/1/91-4/30/92)

Research for the remainder of the current budget period, and next budget period, will continue the projects outlined above.

A. Flux Flow Resistance in Josephson Junction Arrays

Following the work described in I.A.ii above, we will continue studies of two dimensional arrays with randomness, to clarify the nature of the ground state and the superconducting transition. We will look at different types of randomness in addition to junction dilution, such as taking a continuous distribution of junction couplings, and taking random fluxes.

B. Flux Line Entanglement in High T_c Superconductors

We will continue our preliminary investigations of flux line entanglement described in I.B above. We will investigate the effects of random impurities on entanglement, and attempt dynamic simulations to directly study the effects of entanglement on flux flow resistance.

C. Dynamics in The Two Dimensional Coulomb Gas

Our dynamic simulations of the uniformly frustrated XY model have the advantage of being a microscopically correct model for the Josephson junction array. Hence are results may be directly compared to experiments on real arrays. However the array structure of the junctions creates a periodic one-body potential in which vortices have to move. For a vortex to hop from one cell to its neighbor involves a mobility which is determined in part by thermal activation over the energy barrier of this periodic potential. This makes it difficult to obtain good numerical results in the limit of low temperature and applied current, as well as being an artifact of the array model which may not be appropriate when applied to behavior in more uniform films.

To circumvent this problem we will extend our simulations of the Coulomb gas to the non-equilibrium case, modeling flux flow resistance directly in terms of the vortex variables. We will take a dynamics which directly hops vortices from one cell to its neighbor in one discrete time step. While having the disadvantage that it is no longer a precise microscopic model of the superconducting dynamics, it will remove the effects of the periodic energy barriers discussed above. This should improve numerical accuracy and allow a better determination of the characteristic form (ie. power law? exponential? etc.) of the non-linear I-V curves at low current. As such form should be dependent more on the nature of the critical excitations than on the details of the microscopic dynamics, our results on the Coulomb gas will give insight into the behavior of superconducting systems.

III. Publications for the Current Budget Period (5/1/90 - 4/30/91)

1. Ying-Hong Li and S. Teitel, "Three-Dimensional Random XY Model: Application to the Superfluid Transition of ^{4}He in Porous Media," Phys. Rev. B **41**, 11388 (1990)

2. Jong-Rim Lee and S. Teitel, "New Critical Behavior in the Dense Two-Dimensional Classical Coulomb Gas," Phys. Rev. Letts. **64**, 1483 (1990)

3. John Chiu and S. Teitel, "The Effect of Dynamics on Damage Spreading in the Two Dimensional Classical XY Model," J. Phys. A **23**, L891 (1990)

4. Ying-Hong Li and S. Teitel, "Flux Flow Resistance in Frustrated Josephson Junction Arrays," Phys. Rev. Letts., accepted for publication (to appear Nov. 12 1990)

5. Jong-Rim Lee and S. Teitel, "The Dense Two-Dimensional Classical Coulomb Gas on a Triangular Lattice," Phys. Rev. Letts., submitted

IV. Technical Personnel Supported

1. Stephen Teitel, Assistant Professor (PI)
   50% effort during academic year, 100% effort during summer, devoted to project for present budget period, and expected for next budget period.

2. Ying-Hong Li, postdoctoral associate
   100% effort for present, and 50% next budget period.

3. Jong-Rim Lee, 4th year graduate student
   100% effort for present, and next budget period.

4. Tao Chen, 2nd year graduate student
   50% effort expected for next budget period.

5. John Chiu, undergraduate student
   Completed senior thesis under this project, graduated 6/90.

V. Budgetary Information for Current Period (5/1/90 - 4/30/91)

No unexpended balance is anticipated at the end of the current funding period.

END

DATE FILMED

11 / 29 / 90