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Flux Flow, Pinning, and Resistive Behavior in Superconducting Networks

~~Final~~ Progress Report
FINAL

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Stephen Teitel

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

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Abstract

We have studied the behavior of fluctuation effects in superconducting systems using numerical simulations of *XY* and Coulomb gas models. Flux flow resistance in two dimensional Josephson junction arrays has been calculated, and related to correlations in vortex structure. Randomness has been introduced, and its effects on the superconducting transition, and vortex mobility, have been studied. We find that randomness destroys phase coherence, yet the randomness induced pinning reduces flux flow resistance at low temperatures. Vortex line fluctuations in high temperature superconductors have been studied using a three dimensional *XY* model. We have considered the melting of the vortex line lattice, and the entanglement and cutting of vortex lines in the vortex line liquid phase. Vortex line entangling and cutting appear to occur on the same length scales in the liquid phase. The vortex structure function has been calculated and from it, elastic properties of the vortex line liquid have been inferred. The two dimensional classical Coulomb gas, where charges map onto vortices in the superconducting system, has been simulated. The melting transitions of ordered charge (vortex) lattices have been studied, and we find evidence that these transitions do not have the critical behavior expected from standard symmetry analysis.

I. Summary of Progress for the Period 5/1/89-4/30/92

This project has concentrated on the modeling of fluctuation effects in superconducting systems, in terms of well defined statistical models which may be numerically simulated. These model fall into two categories: (1) "*XY*" models, in which the angle of planar spins located at the nodes of a network, model the phase of the superconducting wavefunction as it varies in space; and (2) "Coulomb gas" models, in which Coulomb interacting "charges" model the interaction between vortices in the phase of the superconducting wavefunction. A duality transformation establishes a rigorous mapping between the properties of the *XY* and Coulomb gas models. In particular applications, we have found it convenient to work in one or the other representation. We have applied numerical simulation of these models to the study of several problems of direct experimental interest, including flux flow in Josephson junction arrays, and vortex line fluctuations in high temperature superconductors. We have also made investigations into more theoretical aspects of these models, to enhance our understanding of them. In the following, I provide a detailed summary of the progress that has been made in each area.

A. Flux Flow Resistance in Two Dimensional Josephson Junction Arrays
(papers 5 and 8)

A two dimensional array of Josephson junctions, where all geometry and microscopic parameters are in principle known, serves as a useful model system for studying the response of highly correlated vortices to temperature, applied currents, and magnetic fields. It is the only system in which simulations have been able to directly compute flux flow resistivity. In collaboration with postdoctoral associate Dr. Ying-Hong Li, I have carried out equilibrium and non-equilibrium simulations of behavior in two dimensional square arrays of Josephson junctions in a uniform transverse magnetic field (modeled in terms of the uniformly frustrated *XY* model). This work follows an earlier collaboration with Prof. K.K. Mon (Phys. Rev. Letts. **62**, 1154 (1989)), which was the first to introduce dynamic simulations of Josephson arrays at finite temperatures. Our new work has concentrated on understanding the effect of vortex correlations, and localized vortex pinning sites, on flux flow resistance in response to an applied *dc* current.

We have considered two particular cases, where the applied magnetic field has the values of $f=1/5$ and 2/5 flux quantum per unit cell of the array. For the case of pure periodic arrays, we have found in both cases, that the ordered vortex lattice at low temperatures undergoes a first order melting at the superconducting phase transition temperature T_c. The flux flow resistivity R above T_c was found to display a short plateau, before rising to saturate at its high temperature limit. By a calculation of the vortex structure function, we have shown that this resistivity plateau is due to correlations in the disordered vortex liquid phase, which maintain ground state like order over finite but large regions. These correlations die out and the vortex liquid becomes isotropic at higher temperatures, leading to an increasing R. For the $f=2/5$ case, we have also considered non-linear current-voltage *(I-V)* characteristics below T_c. Here again, we find a plateau in the dV/dI vs. I curve which we have identified as an effect of local ground state order in the vortex correlations. Similar results have been observed experimentally, at other values of f, by Rzchowski *et al.* (Phys. Rev. B **42**, 2041 (1990)) At very small current, below the $T=0$ critical current, we see thermally activated vortex creep which involves domain like excitations of large numbers of correlated vortices, rather than single vortex motion. These results all indicate the importance of correlated vortex motion on dynamical behavior.

For the $f=1/5$ case, we have also studied the effects of adding localized vortex pinning centers, by removing a dilute (2.5 – 10%) fraction of the junctions in the model. A missing junction models a normal metal inclusion, which acts as a vortex pinning site. These are the first simulations in which pinning has been added to a well specified model in a controlled way, and the resulting changes in equilibrium and flux flow behavior calculated. We find evidence that the dilute randomness drives the equilibrium superconducting transition temperature (where phase coherence across the system is established) to zero, and the ground state vortex configuration is disordered. Nevertheless the pinning sites, which decrease vortex mobility, result in a larger effective critical current, and smaller flux flow resistivity at low temperatures, compared to the pure periodic array.

In this project we have made significant use of DOE supercomputer time at the Florida State University Supercomputer Center.

B. Vortex Line Fluctuations in High Temperature Superconductors
(papers 7, 9, and 11)

One of the main areas of research in high temperature superconductors, has been the phenomenological treatment of fluctuations based on a Landau Ginzburg approach. Due to the increased critical temperature, large magnetic penetration length, small coherence length, and large anisotropies of these materials, fluctuation effects are dramatically enhanced in comparison to traditional superconductors. In the mixed phase, in the presence of an applied magnetic field, such fluctuations are believed to melt the low temperature vortex line lattice into an entangled vortex line liquid, at a temperature considerably below the onset of sizeable magnetization. The resistive behavior of the superconductor in this region therefore depends on the properties of this entangled vortex line phase. As direct measurement of vortex line positions threading through the sample is not possible (only surface imaging can be done), and transport measurements provide only indirect information, simulations are an important means of studying the behavior of vortex lines in this phase, and testing theoretical arguments.

In collaboration with postdoctoral associate Dr. Ying-Hong Li, I have carried out the first numerical simulations of vortex line lattice melting, and vortex line entangling, which include a realistic interaction between the vortex lines. Our model (the three dimensional XY model, with uniform frustration in planes perpendicular to one axis) applies in the strongly interacting limit where the magnetic penetration length is much greater than the average spacing between vortex lines, as is the case for a wide range of magnetic fields in the high T_c materials. Studying the special case of a magnetic field of $f=1/5$ flux quantum per unit cell, we have found clear evidence that at the superconducting transition (where phase coherence is lost), the vortex line lattice melts into an entangled vortex line liquid. In this liquid phase, transverse fluctuations of the lines were found to scale like a free random walk, and the length scale on which vortex lines entangle around each other is comparable to the length scale on which vortex lines cut through each other. The latter property is important for understanding flux flow resistivity in the vortex line liquid phase, as it would suggest that entanglement of vortex lines need not pose topological constraints against vortex line motion. We are in the process of investigating these behaviors in a model with $f=1/25$, where the vortex lines are more dilute compared to the spacing of our numerical mesh. Our preliminary results indicate the same qualitative behavior, particularly with respect to the entangling and cutting lengths.

We have also computed the vortex structure function within this model, which measures correlations between vortices in different planes transverse to the applied magnetic field. We have compared our results against the long wavelength hydrodynamic approximation and the "two dimensional boson" approximation. We find that the line tension in the vortex line liquid phase decreases as the correlation length along the field axis decreases, causing planes perpendicular to the field to decouple at some finite temperature above T_c. We have computed the decay of correlations between different planes, and found behavior qualitatively (though not quantitatively) consistent with the "2d boson" approximation. Our calculations confirm the importance of including the complete three dimensional interaction between vortex lines, in order to get the correct dependence of elastic properties of the vortex lines, at finite wavevectors. A long paper 11, describing the work in papers 7 and 9 in greater detail, as well as our work on the more dilute $f=1/25$ model, is in preparation.

In this project we have made significant use of DOE supercomputer time at the Florida State University Supercomputer Center.

C. Equilibrium Phase Transitions in the Two Dimensional Coulomb Gas
(papers 3, 6, and 10)

The problem of a Josephson junction array in a uniform transverse magnetic field, may be mapped onto that of a classical gas of Coulomb interacting vortices, which sit on the sites of the dual lattice of the Josephson array. There remain several incompletely understood questions concerning the nature of the equilibrium phase transitions in these systems, which have bearing on the nature of the loss of phase coherence, and vortex lattice melting in the Josephson array. For the case of zero applied magnetic field, where the ground state is empty of vortices and the transition occurs by the Kosterlitz Thouless (KT) mechanism of unbinding of thermally excited vortex pairs, Minnhagen has suggested that the transition may display non-universal features if the equilibrium density of vortices is sufficiently large. For the case of a magnetic field of $f=1/2$ flux quantum per unit cell of a square array, where the ground state has a vortex lattice, the temperature at which phase coherence is lost, appears to occur at the same temperature at which the vortex lattice melts in an Ising-like transition. The nature of this combined transition is poorly understood, as is also the case at other simple fractional values of f. It is not clear whether or not one may successfully predict the nature of the phase transition in such long range interacting systems by using familiar symmetry arguments.

To investigate these issues, I have carried out, in collaboration with my graduate student Jong-Rim Lee, simulations of the neutral integer Coulomb gas on a two dimensional lattice, mapping out the phase diagram as a function of temperature and vortex chemical potential. By varying the chemical potential we can arbitrarily control the equilibrium vortex density. We have treated both the square and triangular lattices (dual to the square and honeycomb Josephson arrays respectively). When the chemical potential is below a critical value, we find that the ground state of the system is empty of vortices, and the transition at finite temperature occurs by a pair unbinding mechanism. In this case, we have found that the transition follows the universal behavior of the KT transition, no matter what the vortex density. For a chemical potential above the critical value, the ground state of the system consists of an ordered vortex structure, similar to that obtained in Josephson arrays at $f \neq 0$. For the case of a square lattice, the ground state has the structure of the $f = 1/2$ Josephson array, with positive and negative vortices on alternating sites. However we find a clear separation between an Ising transition temperature at which the vortex structure melts, and a (lower) KT temperature at which vortices first become mobile. At the critical chemical potential, we find evidence for a tricritical point in the phase diagram, however the critical exponents at this point do not appear to be those of the Ising tricritical point, as would be expected from a symmetry analysis.

On a triangular lattice, we find at intermediate chemical potentials, ground state ordering into a vortex structure with 2/3 occupancy (1/3 positive vortices , 1/3 negative vortices, 1/3 vacancy). Symmetry analysis would predict the vortex structure to melt with a transition of the universality class of the six state clock model. In contrast, our finite size scaling analysis suggests a different scaling behavior. At higher chemical potential, the ground state has a vortex structure as in the $f = 1/2$ Josephson array (positive and negative vortices on each alternating site). This structure has similarities with the short ranged Ising antiferromagnet on a triangular lattice. We have clarified the role of the long range interactions in reducing the ground state degeneracy as compared to the short ranged model. We identify a critical excitation that disorders the ground state vortex structure at any finite temperature, driving the critical temperature to zero.

We have also carried out simulations of "fractional" Coulomb gases, where a fraction f of positive unit charges are placed on a uniform compensating negative background. These systems more directly model the Josephson array at values of $f \neq 0$. On the triangular lattice, we have studied the $f = 1/2$ case and find behavior similar to that described above in the dense integer Coulomb gas. We have also studied the $f = 1/3$ case, which by symmetry analysis would be expected to have a transition in the universality class of the three state Potts model. However our finite size scaling analysis again suggests a different critical behavior. A long paper 10, describing the details of papers 3 and 6, as well as this latter work on the fractional Coulomb gas, is in preparation. We are currently investigating the use of new Monte Carlo acceleration methods to improve the accuracy of our simulations, and test the universality of these transitions.

D. Theoretical Studies of the *XY* Model in Two and Three Dimensions

(papers 1, 2, and 4)

In preparation for the work described in section B above, I have carried out, in collaboration with postdoctoral associate Dr. Ying-Hong Li, the first finite size scaling analysis of the critical exponents of the isotropic three dimensional *XY* model. Our results agreed well with previous results from series expansion. Motivated by recent experiments observing new critical exponents describing the behavior of the superfluid transition of ^4He in a three dimensional porous material, we extended the above work to study an *XY* model with an algebraic distribution of random bond strengths. While we found some evidence for a shift in critical exponents, dependent on the parameters of the random bond distribution, our results remained inconclusive due to the small size systems we were able to study, and large statistical fluctuations.

The equilibrium phase transition of the two dimensional *XY* model has long been understood in terms of the Kosterlitz Thouless vortex pair unbinding mechanism. Recent dynamic "damage spreading" simulations by Golinelli and Derrida however, in which different initial configurations are evolved subject to the same thermal noise and the overlap between these configurations measured, suggested the possibility that the *2d XY* model might have two separate transitions. In collaboration with my senior thesis student John Chiu, I demonstrated that these new results were strictly a dynamical effect, produced by a dynamics which broke the rotational symmetry of the XY Hamiltonian. When we chose instead a rotationally invariant dynamics, we found only one transition consistent with the usual Kosterlitz Thouless transition.

II. Publications Acknowledging DOE Support

1. *A Finite Size Scaling Study of the Three Dimensional Classical XY Model*, Ying-Hong Li and S. Teitel, Phys. Rev. B **40**, 9122 (1989)

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

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

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

5. *Flux Flow Resistance in Frustrated Josephson Junction Arrays*, Ying-Hong Li and S. Teitel, Phys. Rev. Letts. **65**, 2595 (1990)

6. *The Dense Two Dimensional Classical Coulomb Gas on a Triangular Lattice*, Jong-Rim Lee and S. Teitel, Phys. Rev. Letts. **66**, 2100 (1991)

7. *Vortex-Line Lattice Melting, Vortex-Line Cutting and Entanglement, in Model High T_c Superconductors*, Ying-Hong Li and S. Teitel, Phys. Rev. Letts. **66**, 3301 (1991)

8. *The Effect of Random Pinning Sites on Behavior in Josephson Junction Arrays*, Ying-Hong Li and S. Teitel, Phys. Rev. Letts., to appear Nov. 11 1991 issue

9. *The Structure of a Dense Vortex Line Liquid in a Model High T_c Superconductor*, Ying-Hong Li and S. Teitel, Phys. Rev. B, Rapid Communications, submitted

10. *Phase Transitions in Classicol Two Dimensional Lattice Coulomb Gases*, Jong-Rim Lee and S. Teitel, in preparation

11. *Vortex-Line Fluctuations in Model High T_c Superconductors*, Ying-Hong Li and S. Teitel, in preparation

III. Seminar and Conference Presentations

Flux Creep in the Fully Frustrated Josephson Array (poster), Gordon Conference on the Phenomenology of High Temperature Superconductors, Wolfeboro NH 6/26/89

Phase Coherence and Non-Equilibrium Behavior in Josephson Junction Arrays, Condensed Matter Seminar, University of Neuchatel, Switzerland, 10/22/89

New Critical Behavior in the Classical two Dimensional Coulomb Gas, Condensed Matter Seminar, Los Alamos Scientific Laboratory, 1/20/90

Flux Creep and Flow in Frustrated Josephson Junction Arrays, Condensed Matter Seminar, The Ohio State University, 6/11/90

Flux Flow Resistance in Josephson Junction Arrays, Statistical Mechanics at the 45th Parallel, Montreal, 10/20/90

Flux-Line Lattice Melting, Flux-Line Cutting and Entanglement in Model Anisotropic Type II Superconductors, Meeting of the American Physical Society, Cincinnati OH 3/19/91 (with Y.-H. Li)

Theory of Flux Flow Resistance in Josephson Junction Arrays (invited), Meeting of the American Physical Society, Cincinnati OH 3/21/91

The Dense Two Dimensional Classical Coulomb Gas on a Triangular Lattice, Meeting of the American Physical Society, Cincinnati OH 3/21/91 (with J.-R. Lee)

Structure of a Dense Vortex Line Liquid in a Model High T_c Superconductor, Statistical Mechanics at the 45th Parallel, Ottawa, 10/5/91

Vortex-Line Fluctuations in High Temperature Superconductors, Physics Department Colloquium, Syracuse University, 11/7/91 (to be presented)

IV. Personnel Involved With The Project

Dr. Stephen Teitel, Assistant Professor (PI)

50% of my effort during the academic year, 100% effort during the summer, has been devoted to this project during the entire period of the grant.

Dr. Ying-Hong Li, postdoctoral associate

Dr. Li arrived in Rochester on an IBM postdoctoral fellowship in 9/88, and was supported 50% by this grant from 5/89 to 9/91, with 50% support coming from the the Department of Physics and Astronomy of the University of Rochester. During his three years at Rochester, Dr. Li devoted 100% of his effort to this project, working primarily on the topics described above in sections A, B, and D. As of 9/91, Dr. Li is a research associate at the Institute for Theoretical Physics in Utrecht, The Netherlands.

Jong-Rim Lee, 5th year graduate student

Mr. Lee has been a graduate student with me for the last three years. During this time he has been supported by this grant, devoting 100% of his effort to this project, primarily on the topics described in section C above. It is anticipated that Mr. Lee will complete his Ph.D. work this summer.

Tao Chen, 3rd year graduate student

Mr. Chen has been a graduate student with me for the last year. During this time he has been supported by the Department of Physics and Astronomy of the University of Rochester, and has devoted approximately 50% of his effort to this project. This current year, he has started to extend some of the projects begun by Dr. Li concerning vortex line fluctuations, and will be devoting 100% of his effort to this work. It is expected that Mr. Chen will continue to complete his Ph.D. thesis working on topics related to this project.

John Chiu, undergraduate student

Mr. Chiu completed his B.S. senior thesis with me in 6/90 working on the topic described in the second half of section D. He won the Department of Physics and Astronomy award for best senior thesis of that year. Mr. Chiu is presently a graduate student at the California Institute of Technology.

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Appendix A

Flux Flow Resistance in Frustrated Josephson Junction Arrays

Reprints removed and cycled separately

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Appendix C

Vortex-Line Lattice Melting, Vortex-Line Cutting and Entanglement, in Model High T_c Superconductors

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Appendix B

The Dense Two Dimensional Classical Coulomb Gas on a Triangular Lattice

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