

Physics 880.06, Spring, 2003: Term Project

The term project assignment is to write a paper or give a short talk on a subject of current interest related to superconductivity. If you do a paper, it should be from 10 to a maximum of 15 pages (preferably typewritten, double-spaced), including figures and references. If a talk, it should be around twenty minutes, with five more minutes for questions. You can also do a computer project; a couple of suggestions are given below.

If you give a paper, it is due Friday, June 6 by 5PM. The talks will be scheduled during the last week of classes, probably during class time Tuesday and Thursday, June 3 and 5. You should turn in a proposed topic by Thursday, May 9, along with one or two references and a sentence or two describing what you plan to do. You can choose a topic from the list below or you can propose your own. Your paper or its substantial equivalent should not have been previously submitted to another course. However, it can be related to your planned research area.

In the next few days, I will try to supply a couple of references for each of the projects below, to get you started.

1. Melting of the Abrikosov Vortex Lattice.

As will be mentioned in class, the Abrikosov vortex lattice of a Type-II superconductor is not rigid in the high- T_c cuprate materials, but is quite flexible. In fact, it can undergo a melting transition into a kind of vortex liquid. This transition, in a sufficiently clean material (i. e., one without defects), is first-order, i. e. there is a nonzero latent heat. In this project, you would could discuss theories underlying this melting, or experiments which demonstrate it in some of the cuprate superconductors.

2. The Vortex Glass and Bose Glass Transition.

Most superconductors (including the high- T_c cuprates) are not perfect crystals, but have lots of defects. This means that the vortex lattice feels all kinds of “pinning” from defects in the crystal. As a result, the vortex lattice is not a perfect lattice, but more like a glass, with no long-range translational order as in a perfect crystal. This vortex glass can melt into a liquid, but it is thought that this transition is continuous rather than first-order. The Bose glass transition is a special kind of glass transition thought to occur in some superconductors with a special kind of disorder. In this project, you could discuss the theory of one or more of these transitions, or experiments which might observe it, and what the observable properties would be.

3. The Superconductor/Insulator Transition in Two-Dimensional Superconductors

In thin superconducting films which have a sufficiently high resistivity in their normal state, there is experimental evidence that one can never produce a perfect superconducting state even at very low temperatures. Instead, the material seems to become insulating, not superconducting, at low temperatures. Some of the behavior may be “universal” in that it depends only on one or two properties of the films, not other details. In this project, you could discuss experiments which show this behavior, and some theories which might explain it.

4. Rabi Oscillations in Small Josephson Junctions

In certain systems of very small Josephson junctions, the behavior of the junctions is described by a purely quantum-mechanical Hamilto-

nian (that is, the phase difference across the junction cannot be known exactly, but has quantum fluctuation). One can then see certain phenomena familiar from other quantum systems, such as Rabi oscillations between two different quantum-mechanical states. In this paper, you could discuss the meaning of these Rabi oscillations, and how they might be observed.

5. **Superconductivity in Quasi-1D Organic Metals**

There are by now many materials which are composed of long, nearly one-dimensional organic molecules. Some of these are metallic under certain conditions, and a few have been observed to be superconducting. In this paper, you might discuss the properties of some of these quasi-one-dimensional organic superconductors - e. g., nature of the order parameter (s wave, p wave, or what?), whether they are type I or type II, etc.

6. **Superconductivity in MgB₂**

MgB₂ has the highest T_c (around 40K) of those superconductors which are more or less conventional metals in their normal state. In this paper, you could discuss the observed properties of this superconductor, what is known about the order parameter, whether it is an isotropic or anisotropic material, the nature of the vortex lattice, if known, what happens when it is doped with impurities, and what kinds of models have been proposed to describe its behavior.

7. **Systems with a p-wave Superconducting Order Parameter**

(This project may overlap with some other projects on this list.) There are some superconductors which are believed to have p-wave rather than s-wave order parameters. In this case, the order parameter is not just a single complex number, but may be a group of two or more complex numbers. You could discuss how one generalizes the BCS theory to describe systems of this type, and perhaps some experimental realizations.

8. **Dynamics of Josephson Junction Arrays**

In class, we will discuss the RSJ and RCSJ model (resistively shunted and resistively and capacitively shunted junction model) for the behav-

ior of single junctions. In this project, you would consider how this model has been extended to groups of many junctions, what new and interesting predictions come out of these models, what experiments have been done on arrays, and what possible applications these arrays might have. (You don't need to do all of these in a single project.)

9. Superfluidity in ^3He : A Fermi Liquid with a non-s-wave Order Parameter

^3He is, above a few millikelvin, a Fermi liquid - that is, it is made up of uncharged Fermions (the ^3He atoms). But at low enough temperatures, it becomes a superfluid. This superfluidity is achieved by formation of Cooper pairs, analogous to what is seen in ordinary superconductors, except that the mechanism of attraction is somewhat different. Also, there are more than one superfluid phase, depending on external conditions. In this project, you would describe some of the properties of superfluid ^3He , and some of the models used to describe it.

10. Bose-Einstein Condensation in Atomic Gases

Within the last few years, experimentalists have succeeded in cooling gases of Bose atoms to a sufficiently low temperature to cause the gas to undergo Bose-Einstein condensation. In this paper, you could discuss how these experiments are done, the theory underlying Bose-Einstein condensation, and some of the properties of the condensate. You could also (but do not need to) discuss similarities and differences between this condensation and the BCS superconducting state.

11. Finite-Size Effects in Small Superconducting Particles

Very small superconducting particles do not behave exactly like bulk superconductors. Instead, the superconducting transitions are typically rounded by thermodynamic fluctuations. In this paper, you could discuss what one might expect of small superconducting particles, what is meant by "small," and how this compares with experiments.

12. Effects of Nodal Quasiparticles in Cuprate Superconductors

As will soon be mentioned in class, the order parameter of the cuprate superconductors is believed to be of the $d_{x^2-y^2}$ kind. In this case, the order parameter is a single complex number, but the quasiparticle

excitations do not have a gap at all possible values of k . Instead, there are certain values of k where there is no gap. In this project, you could discuss the experimental consequences of this kind of order parameter, and perhaps why such an order parameter is reasonable for the cuprate superconductors.

13. **The Hubbard Hamiltonian as a Possible Model for Superconductivity in the Cuprates**

The Hubbard Hamiltonian has two terms: one which describes a band of tight-binding electrons, and another term involving a repulsive electron-electron interaction. It is thought that this Hamiltonian may have some states which are superconducting, and some people believe that this model could describe superconductivity in the cuprates. In this project, you could describe the Hubbard Hamiltonian, and explain why it might give rise to superconductivity (or why you think it wouldn't work in the cuprates).

14. **Possible Realizations of Superconducting Qubits**

In recent years, many people have become interested in a novel kind of possible computer known as a "quantum computer." (So far, this is only a dream, not reality.) A quantum computer has a basic element called a quantum bit, or qubit, which is a special kind of controllable two-level system. Several realizations of qubits have been proposed which are made up of superconducting elements - generally involving small Josephson junctions. In this project, you could discuss one of these realizations, and also briefly explain what a qubit is, or should be.

15. **The Kosterlitz-Thouless Transition in Two-Dimensional Superconductors**

In some superconducting films, it is believed that superconductivity disappears, not via a first-order phase transition, but rather via a continuous phase transition first proposed by Kosterlitz and Thouless. In this transition, there are thermally excited vortices and antivortices which unbind at a critical temperature T_{KT} . In this paper, you would discuss some of the theory underlying this transition, and/or some of the possible (and observed) experimental consequences.

16. **Systems with Non-Triangular Abrikosov Vortex Lattices**

Recently, some superconductors have been found to have a square, or rectangular, rather than triangular, Abrikosov vortex lattice. In this paper, you could discuss some of the materials where this may have been observed, and some of the models which have been proposed to explain it.

17. **Phase-Sensitive Measurements to Determine the d-Wave Character of the Superconducting Order Parameter in the Cuprates**

As mentioned above, the most widely accepted theory of the cuprate superconductors proposes that they have a $d_{x^2-y^2}$ order parameter. To observe this order parameter, one must do certain types of phase-sensitive experiments. These have, indeed, been carried out. In this paper, you could describe one or more of these experiments, and explain how their results imply that there is a non-s-wave order parameter.

18. **Anisotropic Ginzburg-Landau Hamiltonians**

The Ginzburg-Landau hamiltonian to be presented in class is appropriate for *isotropic* superconductors. But many superconductors are anisotropic. In this project, you could describe how one develops an anisotropic Ginzburg-Landau theory. You might also describe how one can produce a Ginzburg-Landau theory for a superconducting order parameter comprised of more than one complex wave function.

19. **Properties of Layered Superconductors**

The high- T_c cuprates are all layered superconductors. A common model to describe these was first proposed by Lawrence and Doniach, in a short conference paper, around 30 years ago (obviously it was intended for other kinds of layered superconductors). In this project, you could describe some of the properties expected of layered superconductors, and how these are treated by the Lawrence-Doniach model and its more modern generalizations.

20. **Superconductivity in C_{60} and Related Materials**

C_{60} is known as a buckyball, because the sixty carbon atoms are arranged in the form of the geodesic dome first proposed by Buckminster

Fuller. (“Buckyball” is a familiar term for “Buckminsterfullerene.”) Some of the buckyball-based materials are actually superconducting. In this paper, you could discuss the properties of these materials, and the theory used to describe those properties.

21. Possible Superconductivity in Metallic Hydrogen: Implications for the Giant Planets

It is thought that the cores of the giant planets (Jupiter and Saturn) are enormously compressed hydrogen. At such pressures, hydrogen is undoubtedly metallic, and at low enough temperatures, the metal may become superconducting. Some believe that the transition temperature could be close to room temperature. In this project, you could discuss the properties of metallic hydrogen, when and why it might become superconducting, experiments which cast light on this speculation, and theories which try to explain them, and the relevance of all this to the giant planets. A variant of this project could be to discuss possible BCS pairing in neutron stars and related materials.

22. Methods for Producing Enhanced Critical Currents in Superconductors: Natural and Artificial Flux Pinning Centers

One of the problems of the high- T_c superconductors is that, in a magnetic field, the flux lattice is hard to “pin down.” Instead, it tends to move when a current is introduced, and a moving flux lattice gives rise to dissipation (i. e. resistance). In this project, you could discuss why moving flux lines produce dissipation, and various methods which have been proposed to pin these flux lines and hence to eliminate dissipation.

23. Anderson-Kim Theory of Flux Creep

Flux creep is one of the mechanisms whereby flux lines can move in superconductors. One of the basic theories describing this flux motion was proposed by Anderson and Kim almost forty years ago. In this paper, you could describe how this theory works, and how it applies to various materials. YOU could also discuss some generalizations intended for the high- T_c materials, such as the Malozemoff-Yeshurun theory of “giant flux creep”.

24. Specific Experimental Probes of Superconductivity.

In this project, you could carefully analyze one of the experiments used to probe superconductivity. There are a host of such experiments, each of which would easily be worth a term project or more. These include nuclear magnetic resonance probes (NMR), muon spin resonance (μ SR), neutron diffraction studies of superconductivity, etc. If you have a specific experiment you would like to describe, please check with me first so I can approve your project.