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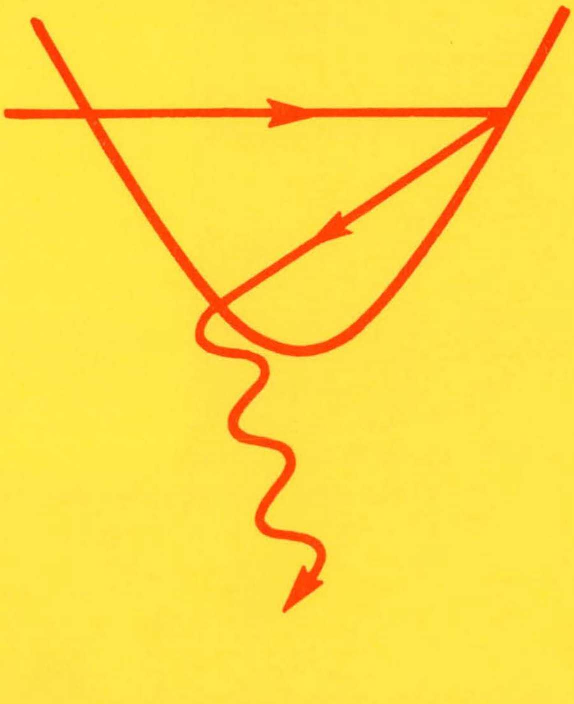
Scientific Affairs Division of
NATO Advanced Study Institute

Abstracts for NONEQUILIBRIUM SUPERCONDUCTIVITY, PHONONS AND KAPITZA BOUNDARIES

at

Acquafredda di Maratea, Italy
25 August to 5 September 1980



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Co-chairmen

Kenneth E. Gray* and Donald N. Langenberg**

May 1980

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FOREWORD

This volume is a compendium of abstracts for lectures presented at the NATO Advanced Study Institute (ASI) on "Nonequilibrium Superconductivity, Phonons and Kapitza Boundaries." This ASI held in Acquafredda di Maratea, Italy from August 25 to September 5, 1980 is supported by the Scientific Affairs Division of NATO, and the U.S. Department of Energy. Despite the strong interconnection of these topics, both conceptually and experimentally, there have been as yet no conferences or study institutes treating them on an equal basis. The lecturers are internationally recognized experts who will provide an authoritative, definitive review of the current status of each subtopic.

In addition to the scientifically interesting aspects of the topics covered they are important to relevant applications of superconductivity and other low temperature phenomena specifically focussing on energy related problems. These include large scale superconducting magnets for MHD and magnetically confined fusion. They also include sensitive superconducting electronics for geophysical exploration, fault current limiters in electrical power systems, and superconducting transformers and transmission lines.

The abstracts in this volume present an overview of work in this area, including references to more detailed publications. They provide an extended table of contents for the full text of the published lectures of the the ASI. Hopefully, they will also provide an opportunity to increase awareness among basic and applied scientists.

Mark C. Wittels

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INTRODUCTION

The importance of phonons has long been recognized by researchers in nonequilibrium superconductivity. Similarly, experimentalists studying phonons at low temperatures have relied heavily on superconductors as sources and detectors. To a large extent this symbiotic relationship has developed with a general mutual awareness; however, to our knowledge these subjects have never been treated together in conferences or study institutes. It is with the hope of further contributing to the awareness and communication between workers in these areas that this NATO Advanced Study Institute (ASI) has been conceived. A second, but equally important, reason for holding this ASI is to fill a void by providing the first general textbook in this important area of physics. Therefore, there will be an emphasis on the tutorial nature of the lectures and written contributions to the published proceedings.

One purpose of this collection of summaries is to provide the authors with cross reference information about the other lectures, thus enabling a more uniform and complete coverage of the subject This should avoid needless duplication by allowing the authors to refer to the text of others. In addition, the use of standard notation (symbols) should make the relationship of the chapters more easily transparent to the readers. This compendium also provides the participants with a general overview of the subject material to be covered in the lectures, so that they may better prepare themselves to take full advantage of the ASI and participate fully in the discussion sessions. General references are given with the summaries.

The areas of research covered by this ASI can certainly be considered mature, however there still exist many unresolved problems. It is hoped that through the lectures and discussion sessions, these problems will be adequately clarified and understood, and that the ASI will provide stimulation for further work aimed at resolving these issues.

The study of the Kapitza boundaries resistance provides an excellent example. The first measurements by Kapitza are almost 40 years old. Although the solid-solid boundary is quantatively described by the accoustic mismatch theory, the solid-liquid helium boundary still has mysteries which are only begining to be understood. The importance of the Kapitza resistance is readily seen in measurements of the lifetime of quasiparticle excitations in superconductors. In many experimental situations, what is actually measured is the phonon escape time through the superconductor-substrate boundary.

Superconducting tunneling has been extremely important for the creation and detection of nonequilibrium states as well as phonons. Tunneling techniques are useful for measuring the microscopic properties of energy gaps and distribution functions in superconductors driven away from equilibrium by phonons, microwaves, quasiparticle injection, temperature gradients, transport current, etc.

A particularly exciting result has been the observations of energy gap enhancement in superconductors which have been induced by a perturbation such as tunneling or microwave irradiation. Although this effect seems to defy intuition, it is understood within the framework of theoretical models.

Instabilities can occur in nonequilibrium superconducting states. These include multigap states and first order transitions into the normal state as a result of perturbations which drive the superconductor out of thermal equilibrium. Both the theoretical and experimental situation seems somewhat unclear at this time.

The concept of charge imbalance, that is an exchange of charge between the superconducting pairs and quasiparticles, has received considerable attention recently. Many nonequilibrium states exhibit a charge imbalance, and its relaxation rate back to equilibrium determines the properties of such states. This concept is required to properly describe normal-superconductor boundaries, thermoelectric effects, phase slip centers, collective modes and tunnel junction asymmetries. There has been tremendous progress in the theoretical formulation of charge imbalance and its relationship to the various nonequilibrium states of superconductors.

The motion of magnetic flux (flux flow) was one of the first studied, but remains perhaps one of the poorest understood nonequilibrium states. There is a severe lack of microscopic experimental information to compare with theory. On the other hand the phenomenological macroscopic picture is reasonably well understood.

In summary, there are sufficient new and unresolved issues to make this ASI an interesting and stimulating event, in addition to its purpose to provide a tutorial overview of the fields.

THE KAPITZA THERMAL BOUNDARY RESISTANCE BETWEEN TWO SOLIDS

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When a heat flux $\dot{Q}$ flows across the interface between two different materials, at least one being nonmetallic, a temperature discontinuity ΔT is observed to occur at the interface. The ratio $\Delta T/\dot{Q}$ has been called the Kapitza thermal boundary resistance R_K. This thermal impedance at the interface persists even if the contact between the two materials is made as perfect as possible.

The first measurement of R_K was reported in 1941 by Kapitza for an interface between copper and liquid helium. Over the next $\simeq$ 20 years it became recognized that a Kapitza resistance also exists between two solid materials, and that this phenomenon should be related to the reflection and refraction of acoustic phonons at the interface. A theory based on the scattering of phonons at the interface has become known as the acoustic-mismatch model. During the following $\approx$ 20 years, steady progress in cryogenic instrumentaiton and measurement techniques permitted qualitative experimental verification of this model. By qualitative we mean that theory and experiment agree within $\approx$ 20% for a variety of interfaces over a temperature range from 0.01 K to $\simeq$ 100 K using no adjustable parameters.

A more quantitative comparison between theory and experiment requires, for the theorist, a consideration of the several effects caused by crystal anisotropy, a better understanding of phonon relaxation times within the solids and the effects of phonon dispersion within the solids. The experimentalist at the same time must provide a better characterization of the two solids near the interface since the presence of defects, as one example, can modify the apparent Kapitza resistance.

In low-temperature technology the Kapitza resistance can be both a hinderance in the transport of heat, or an assistance in providing thermal isolation. Generally, the Kapitza resistance must be considered when a system, such as superconducting film, is driven away from a state of thermal equilibrium with its immediate environment.

The paper will review briefly the historical development of the field, and will derive the acoustic-mismatch theory and the modifications introduced by several authors. The different experimental techniques will be discussed, and it will be pointed out why certain techniques correspond to particular modifications of the theory. Possible future developments will be suggested.

Background material for this subject includes texts on elastic waves (Musgrave, 1970; Fedorov, 1968) and on phonon thermal transport (Ziman, 1963). Alternatively, a knowledge of black-body radiation and the reflection and refraction of electromagnetic waves is useful because of the close analogy with phonon systems. The paper by Little (1959) provides a brief overview of the problem as it existed prior to 1959, and gives a good introduction to the acoustic-mismatch theory.

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Phonon propagation in liquid ^4He and through solid-liquid ^4He interfaces

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The two main topics that will be covered in the lectures are the Kapitza conductance and the propagation of excitations in liquid ^4He. These two topics are intimately connected; for to study phonons in the bulk liquid, they must be injected from a solid and it is now quite clear that without taking special measures the injected phonons have a much lower energy spectrum than those in the solid. Also many of the best techniques for studying the phonons transmitted through the interface, between the solid and liquid ^4He, require the phonons to travel in the liquid ^4He and so it is important to know if they have been affected.

The Kapitza conductance remains a problem as we do not know how heat is lost from a solid which is surrounded by liquid ^4He. The obvious suggestion is that phonons in the solid, which are incident on the interface, are partially transmitted and reflected according to the classical laws of elasticity. This model was considered in detail by Khalatnicov and by Little. It gives an average transmission coefficient ($\bar{\alpha}$) of a few percent and a critical cone of $\sim 5^{\circ}$ half angle for the phonons transmitted into the liquid ^4He. This channel has now been verified in some detail but it neither accounts for the measured values of $\bar{\alpha}$ as high as 0.3 nor for the phonons emitted outside of the critical cone. The major heat loss is via this second channel which will, because of its angular dependence, be called the background channel.

The classical model will be outlined for the solid liquid ^{4}He boundary and the experimental evidence for it reviewed. The inadequacy of this model to account for measured heat loss will be made clear and the problem which in principle must be solved will be stated. The progress towards this goal will be considered which will lead us to examine the background channel and its characteristics. The measurements of the ratio of the energy transmitted in the classical and background channels and how $\bar{\alpha}$ can be found from this data, will be given. It will be shown that the temperature variation of $\bar{\alpha}$ is similar to that found from thermal conductance measurements which leads to the conclusion that the anomalously large heat loss is due to the background channel. Other properties of the background channel come from reflection experiments and other types of transmission experiments. These will be reviewed. This will lead to a discussion of the symmetry of the transmission process from each side of the interface. The effect of the interface process on the emission from thin metal film phonon generators in liquid ^{4}He and on bolometer detectors will be considered.

The density and mean free paths of excitations in liquid ^{4}He will be briefly reviewed. The roton density dominates above 1K and phonons below. In the short mean free path regime we get second sound which dies out below 0.6K. Below 0.2K, phonons can have mean free paths of centimetres if the liquid is pressurised. The lecture will concentrate on ^{4}He at temperatures ~0.1K.

The propagation of injected phonons in liquid ^{4}He depends crucially on the detailed shape of the dispersion curve. If $\omega(q)$ bends downwards from linearity then 3 phonon decay processes are not allowed while if there is upward curvature then decay is allowed for some band of frequencies. The theory of 3 phonon decay will be outlined together with its consequences for phonon propagation. The experimental evidence for this theory will be shown to be excellent.

The consequences of 3 phonon decay are that phonons above a critical frequency have long mean free paths and those below it have very short ones. The change in mean free path at the critical frequency is many orders of magnitude. This means that ^{4}He is acting as a high pass filter and this property can be used to measure phonon spectra. The filter is tuneable by varying the pressure on the liquid. The decayed phonons increase the angular width of the beam which can give information on the deviation of $\omega(q)$ from linearity.

The measurements of the critical frequency will be reviewed and also the ways in which the frequency spectra of phonon beams can be assessed. Superconducting tunnel junction generators and detectors will be only mentioned briefly.

The three phonon process with its small angle leads to the concept of 'one' dimensional equilibrium. The spectrum then depends on the energy density in the beam. Evidence that the 3pp can create higher frequency phonons will be presented. The decay of various initial distributions and the possibility of new second sound models will be discussed.

Finally the propagation of ballistic rotons will be considered together with the interactions of phonons and rotons with the interface between liquid and vapour.

Pre School reading

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NONEQUILIBRIUM PHONONS

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Summary

General

Elastic single-particle electron tunneling between two superconducting films separated by a thin oxide barrier leads to a nonequilibrium quasiparticle distribution. The succeeding quasiparticle transitions occur predominantly under phonon emission and result in a phonon population which also deviates significantly from thermal equilibrium. The thermalization of phonons is strongly impeded since the phonon mean free path in the superconductor exceeds or equals the film-thickness of the order of typically 1000 Å.

Tunneling, Phonon Detection, Quasiparticle Transitions and Phonon Spectra

For battery voltages $|eV| < 2\Delta$ applied to a tunneling junction composed of identical superconductors only a small temperature dependent current results from thermally excited quasiparticles. This current is increased by irradiation with phonons of the energy $\hbar\Omega > 2\Delta$ leading to additional quasiparticle excitations via Cooper-pair breaking. Thus, phonons of sufficient energy can easily be detected in the voltage range $|eV| < 2\Delta$.

At voltages $eV \geq 2\Delta$ the tunneling current increases discontinuously and approaches with higher voltages the normal conductor limit. In this regime quasiparticles are excited via pairbreaking by the battery energy leading to nonequilibrium injection into the films. The quasiparticle relaxation and recombination decay results in characteristic

structures of the phonon spectrum[1]. Most important is the upper edge of the relaxation spectrum at $\hbar\Omega = eV - 2\Delta$ which is used for tunable phonon spectroscopy[2,3,1].

Experimental Determination of the Emitted Phonon Spectra

Since all voltage dependent characteristic parts of the phonon spectrum shift to higher energies if the battery voltage is increased, it is possible to analyze the corresponding structures by phonon detection with a superconducting tunneling junction. While the detector is only sensitive to phonons with energies exceeding the detector gap $2\Delta_D$, the detector signal corresponds to the integral of the emitted phonon spectrum of the generator with a lower cut-off energy at $2\Delta_D$. Thus, by changing the battery voltage of the generator tunneling junction the spectrum of the emitted phonons (voltage dependent part) can be measured and compared with calculation.

Application to Phonon Spectroscopy

The upper edge of the relaxation phonon spectrum at the energy $\hbar\Omega = eV - 2\Delta_G$ can be used for phonon spectroscopy by differentiation; i.e. modulation techniques. The detector modulation signal in this case is mainly caused by phonons at the energy $eV - 2\Delta_G$ with a linewidth determined by the modulation amplitude[2,3,1]. For a substrate crystal containing defects or impurities with resonant phonon scattering the variation of the generator voltage thus allows absorption spectroscopy. This technique of acoustic phonon spectroscopy meanwhile has found wide applications; e.g.[2,3,4,5,6].

Quantitative Phonon Intensity Measurements

Quantitative phonon emission and detection by tunneling junctions have been studied for recombination phonons[7]. Comparison between various experiments and a theoretical model, taking account of the effective quasiparticle lifetime, the phonon escape probability and the anisotropic phonon energy propagation in the substrate crystal, indicates that a large fraction of phonons decay spontaneously to lower energies either in traversing the interface between the superconducting film and the substrate or in the bulk of the generator film. The origin of these decay processes is possibly related to impurities at the film-substrate boundaries.

Experimental Probing of the Quasiparticle Distribution and Application to Phonon Spectroscopy.

Tunneling measurements with junctions composed of superconducting films with different energy gaps can be used for an analysis of the energy distribution of excited quasiparticles[8,9,11]. This method has also found an important application[10] in the study of nonequilibrium quasiparticle distributions by the absorption of quasimonochromatic phonons, providing voltage tunable phonon detection.

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PHONON OPTICS IN SEMICONDUCTORS

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In this paper we will give a brief review of recent experimental work on energy transport by high frequency phonons in a variety of semiconductors (such as GaAs, InP, InSb, Ge, Si, etc.). The experiments utilize several types of phonon sources: these include, thin film metal heaters, superconducting tunnel junctions, direct excitation of e-h pairs in the semiconductor, layered epitaxial structures of n and/or p type material or pn junctions. The phonons propagate through a thick ($\sim$ 0.2 mm to 20 mm) sample of the semiconductor and are detected after a ballistic time of flight by either a bolometer (von Gutfeld 1968) or a tunnel junction (Eisenmenger 1976).

Among the physical phenomena which can be studied by such experiments are: 1) Energy relaxation of carriers. 2) Nonradiative recombination of e-h pairs. 3) "Focussing" or "channeling" of phonon beams due to elastic anisotropy. A simple description of this phenomena in terms of the Gaussian curvature of the slowness surface will be given. 4) Anisotropic electron-phonon coupling and carrier screening. 5) Interface effects which can be probed and minimized through the use of novel epitaxial transducer materials. Because of the large number of examples of heteroepitaxy in semiconductors, such experiments are generally useful for the understanding of transport processes in such materials. 6) Bragg diffraction of high frequency phonons by superlattice structures grown by molecular beam epitaxy. 7) Anisotropic phonon-defect interactions which yields information on the symmetries of impurities in the semiconductor.

The close analogy of some of the above experiments with other areas of low temperature physics will be discussed. These include, relaxation and recombination in non-equilibrium superconductors, Kapitza resistance between solid media and electron-phonon coupling (including screening) in metals. Because of the high degree of materials control, possible in the semiconductor case, such experiments can be particularly rewarding for the study of elementary excitations in solids.

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TUNNELING: A PROBE OF NONEQUILIBRIUM SUPERCONDUCTIVITY

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This lecture course will begin with a brief review of the essential results of the BCS theory of equilibrium superconductivity (e.g. Tinkham, 1975). Topics will include the energy gap equation, quasiparticle density of states $\rho(E)$ and coherence factors. From this, the Hamiltonian approach to superconducting tunneling will be developed. Current-voltage characteristics I(V) will be calculated for junctions in the normal metal-insulator-superconductor (NIS) configuration, as well as the S_a IS_b configurations in which both identical ($S_a \equiv S_b$) and different superconductors will be considered. The techniques for measuring $\rho(E)$ and the energy gap Δ will be outlined. The use of tunnel junctions to detect and create nonequilibrium states will be emphasized. Examples include: the generation of quasiparticles, phonons and photons by tunneling and the detection of optical, microwave and phonon irradiation. For a general reference to tunneling, see Solymar (1972).

Many important experiments have resulted from the use of two tunnel junctions: one to create the nonequilibrium state and another to measure it. This part of the lecture will include a compendium of experiments which use two superimposed tunnel junctions, i.e., in which one film is common to both junctions. Experiments related to charge imbalance relaxation and instabilities will be covered by other lecturers, and will only be mentioned. More detailed treatment of the techniques to detect the ac Josephson effect, to measure the quasiparticle-pair recombination time and to create an enhanced energy gap will be described. Another illustration of nonequilibrium superconductivity is the operating principle of the superconducting tunnel junction transistor.

The last part of the lecture course will provide a more comprehensive review of experimental techniques for measuring the nonequilibrium quasiparticle distribution function and the energy dependent quasiparticle scattering time. Some specific examples will be given to illustrate these techniques. The extension of the equilibrium BCS energy gap equation; quasiparticle density of states and coherence factors to nonequilibrium states will be reviewed.

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The Effect of Microwaves on Tunnel Junctions

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The radiation of tunnel junctions with microwaves is one of the earliest and most extensively studied phenomena in nonequilibrium superconductivity. If the width of the BCS singularity is smaller than the microwave frequency, photon-induced tunneling steps are observed which are interpreted as the quantum absorption and emission of an integer number of photons by the tunneling electrons. In the opposite limit no sharp structure appears on the I-V characteristic, but a splitting of the $\Delta_1 \pm \Delta_2$ structure is observed in conjuntion with a shift proportional to the microwave induced voltage across the tunnel junction. A recent unified explanation for the transition from the quantum to the classical limit will be presented. Josephson tunnel junctions exhibit additional steps in the presence of microwaves. The behavior of these effects as a function of power, frequency and orientation of microwave field will be presented. Some of the papers that will be partially reviewed are:

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For a recent review see reference 11.

ENHANCEMENT OF SUPERCONDUCTIVITY

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Given a certain superconductor at a certain temperature, one would expect that external disturbances such as electromagnetic radiation, acoustic waves and electric currents would tend to decrease the magnitude of the superconducting effects. Usually this is indeed observed. However, in some special cases superconductivity is found to be enhanced by such external influences. The enhancement is associated with a non-equilibrium occupation of quasi-particle states. If $\delta f(E) = f(E) - f^{o}(E)$ is the deviation of the quasiparticle occupation probability $f(E)$ from the equilibrium Fermi distribution f^{o}, the BCS gap equation near the equilibrium critical temperature of the superconductor T_c^{o} can be written as:

$$\frac{T_c^{o} - T}{T_c^{o}} - \frac{7\zeta(3)}{8\pi^2}\,\frac{\Delta^2}{(k_B T_c^{o})^2} - 2\int_{\Delta}^{\infty}\frac{dE}{(E^2-\Delta^2)^{\frac{1}{2}}}\,\delta f(E) = 0 \qquad (1)$$

Here T is the temperature, Δ the energy gap and E the quasiparticle energy; there is no position or time dependence. Negative values of $\delta f(E)$ have the effect of increasing Δ (occupied quasiparticle states block possibilities for Cooper pair formation).

A situation where $\delta f(E) \leq 0$ for all E was considered by Parmenter (1961). He pointed out that quasiparticles can be extracted from a superconductor by a tunneling current to a second superconductor with a higher gap. In that second superconductor fewer quasiparticles are excited at the same temperature. Experimental observation requires a careful choice of parameters; it has recently been accomplished.

The picture of gap enhancement, that was put forward by Eliashberg in 1970 (see Ivlev, Lisitsyn and Eliashberg, 1973) has a wider scope of application. In that picture the total number of quasiparticles may remain constant. Still, in equation (1) the integral can be negative if $\delta f(E)$ is negative for E close to Δ and positive at higher levels. This 'pumping up' of quasiparticles can be achieved by microwaves, phonons or tunnel currents. The photon or phonon frequency has to be high enough with respect to the inverse relaxation time to achieve a stationary non-equilibrium distribution. On the other hand, at too high frequencies or tunnel voltages pair breaking dominates. Eliashberg and co-workers performed calculations in a linear, relaxation time, approximation, assuming that the phonons provide a thermal reservoir. They predict enhancement of the gap and non-zero solutions for Δ at temperatures above T_c^o. Schmid investigated the stability of the various solutions.

Chang and Scalapino added to the Eliashberg picture by also considering the non-equilibrium distribution of the phonons which is necessarily connected with the electron non-equilibrium. They performed numerical calculations based on Boltzmann equations for both the electrons and the phonons. The enhancement saturates at a certain applied power. Also, due to the higher recombination rate at higher quasiparticle levels, the total number of quasiparticles decreases as an indirect result of the Eliashberg mechanism.

The experimental observation of enhancement will be reviewed. Historically, these effects were first seen when microwaves were applied to microbridges and their critical current was found to increase. This 'Dayem/Wyatt effect', to be discussed at the ASI by Dayem, was originally explained in terms of suppression of fluctuations. Lindelov later suggested that spatial 'smearing' of Cooper pairs from the banks into the bridge might occur under the influence of the high-frequency electric field. Both these mechanisms apply for weak-link situations only.

Enhancement of the critical current of microbridges and point contacts by phonons was observed by Tredwell and Jacobsen. They conclude to good agreement with the Eliashberg theory.

Enhancement due to tunnel currents was seen by Gray and by Chi and Clarke. The conditions of the latter authors' experiment apply to the Parmenter mechanism of enhancement whereas with Gray the Eliashberg picture with re-distribution of quasiparticles is relevant.

By far the most experimental results have been obtained for enhancement by microwaves. Latyshev and Nad', Klapwijk and Mooij and Pals and Dobben used the critical current of long one-dimensional strips as a measure of the magnitude of the superconducting properties. Power and frequency dependence will be discussed. Kommers and Clarke directly observed enhancement of the gap, measured with a tunnel junction. Later experiments by others failed to yield similar results. The difficulties involved with these measurements will be discussed with reference to Schuller's lectures. Pals and Dobben measured the order parameter (pair density) in cylindrical aluminum films, which quantity similarly increased in a microwave field. Attention will also be paid to these authors' determination of the characteristic time constants involved.

Stimulation of superconductivity above T_c^o, as predicted by Eliashberg, has been observed under the influence of microwaves only. Enhancement of the critical temperature by around 5% has been found. The unstable behaviour of the induced superconducting state above T_c^o will be discussed.

Relatively little attention will be paid to critical current enhancement of short microbridges, in which several processes occur simultaneously. The 'dynamic enhancement' in bridges will be treated by Tinkham. 'Smearing' enhancement as proposed by Lindelov may play a role in microbridges together with the Eliashberg mechanism.

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HEATING AND DYNAMIC ENHANCEMENT IN
VARIABLE THICKNESS MICROBRIDGES

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Heating effects limit the voltage and hence Josephson frequency to which metallic weak links can operate. These effects, and other nonequilibrium effects, are minimized by a three-dimensional geometry, as in variable-thickness bridges (VTB's) and point contacts. Under strong heating conditions, a spatial profile of a local effective temperature $T^*(r)$ can be found by a simple approximation (Tinkham et al 1977) which treats the generation and conduction of heat as though the metal were fully normal. Quite generally one finds that the temperature in the center of the constriction with voltage V applied is $T_m = [T_o^2 + 3(eV/2\pi k_B)^2]^{\frac{1}{2}}$, where T_o is the bath temperature. This maximum temperature T_m can be far above T_c, even as high as 70K in Nb point contacts which still show an ac Josephson effect. Thus these heating effects are not necessarily a small perturbation. The predicted temperature profile has been confirmed by 3 independent experimental tests: 1) The noise temperature is predicted to be $T_N \approx \frac{1}{2}(T_m + T_b)$, which can also greatly exceed T_b. This prediction was confirmed by measurements of noise rounding of far-infrared-induced steps on Nb point contacts by Weitz et al (1978). 2) The critical current is predicted to fall approximately as e^{-P/P_o}, where P is the power dissipated in the junction and P_o is typically $\sim 10\mu W$. This decrease in J_c under finite voltage conditions is reflected in the cutoff in the maximum widths of microwave-induced steps observed by Octavio et al (1977). 3) The energy gap is reduced by heating in the vicinity of the constriction, causing a downward shift in the voltage at which subharmonic gap structure is observed in plots of dV/dI vs. V. (Octavio et al 1977). The degree of consistency of these various measures of heating effects lends considerable credibility to the simple analysis.

In addition to this time-average heating effect which inevitably accompanies dissipation, a more subtle nonequilibrium effect gives rise to the "foot" feature observed at I_c in the I-V curves of VTB's. The time variation of the magnitude of the energy gap during each cycle of the Josephson current leads to a cyclic departure of the quasiparticle populations from the instantaneous equilibrium values associated with the instantaneous gap values. If the gap variation is rapid compared with the inelastic relaxation time τ_E, there is an adiabatic cooling effect on each cycle, which enhances the maximum supercurrent by as much as a factor of 2. At lower Josephson frequencies (or voltages), the populations remain near equilibrium, but differ by an amount proportional to $\omega\tau_E$. This shift is a cooling effect during the forward half cycle, but a heating effect during the reverse half cycle, leading to a time-average forward current proportional to the voltage. This is equivalent to a sharply reduced normal resistance, which causes the initial voltage rise above I_c to have a very small slope; the resulting feature is a "foot" at the base of the I-V curve. Models of such effects were first given by Golub and by Aslamazov and Larkin. Experiments of Octavio, et al (1978) confirmed their existence, and motivated the development of the qualitative discussion given here (Tinkham, 1979). Results of more recent work of Schmid et al (1980), which has achieved satisfactory agreement with data by a new quantitative development of these ideas, will also be summarized.

Using the same sort of procedures, involving an effective quasiparticle temperature T* which depends on the past variation of Δ, one can readily rederive the form of time-dependent Ginzburg-Landau equation which applies to superconductors with an energy gap, in which the characteristic time is not $\tau_{GL} \propto (T_c - T)^{-1}$, but the longitudinal relaxation time of Schmid $\tau_R^{(L)} \propto (T_c - T)^{-1/2}$. This accounts at least roughly for the results of Pals and Wolter on the time required for the appearance of a voltage in a superconducting filament subjected to a current in excess of the critical current.

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PROPERTIES OF NONEQUILIBRIUM SUPERCONDUCTORS: A KINETIC EQUATION APPROACH

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A theoretical study of the nonequilibrium properties of superconductors using the kinetic equation approach will be presented. Taking into account the electron-phonon interaction, we will derive using the golden-rule approximation the coupled kinetic equations which govern the quasiparticle and phonon distributions in the nonequilibrium steady state. The coupled equationswill be subsequently linearized and used to discuss the properties of superconductors driven out of equilibrium, but not far from equilibrium. Specifically, the temperature- and energy-dependent microscopic quasiparticle and phonon lifetimes associated with various collision processes will be calculated. Various combinations and averages of the microscopic lifetimes measured by different experiments will be indentified and discussed.

Properties of superconductors driven far from equilibrium will be discussed using the full set of coupled kinetic equations with the aid of a modified BCS gap equation. Only cases in which quasiparticle tunel injection serves as the driving mechanism will be discussed. (The details of the mechanism will be discussed by K.E. Gray). The distribution functions for the quasiparticles and phonons will be presented. It will be shown that in superconductors with high phonon trapping, heating effects dominate. However, in superconductors with low phonon trapping, signatures of the driving mechanism will remain and can lead to interesting effects. In particular, it is possible to have gap enhancement due to the redistribution and reduction of the quasiparticle density resulting from the tunneling processes. The dependence of the gap enhancement on the phonon trapping factor, the strength of the driving forces and the junction bias voltage will be discussed.

INSTABILITIES OF NONEQUILIBRIUM SUPERCONDUCTING STATES

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A superconductor forced sufficiently far from equilibrium will of course undergo a transition to the normal state. However, there now exists a considerable body of experimental evidence which indicates that a homogeneous superconductor subjected to external perturbations (e.g., tunnel injection of quasiparticles or irradiation by photons or phonons) may become unstable toward formation of states which are more complex (and therefore more interesting) than the homogeneous normal state. For example, experiments on optically irradiated superconductors have been interpreted as indicating the formation of a nonequilibrium "intermediate" state consisting of superconducting and normal regions (Sai-Halasz *et al.*, 1974; Hu *et al.*, 1974; Golovashkin *et al.*, 1975). These observed transitions were continuous (second-order-like) rather than abrupt (first-order-like). In tunnel-injected superconductors Fuchs *et al.* (1977) and Iguchi (1978) have reported abrupt transitions, probably to some sort of spatially inhomogeneous state. Other experiments on tunnel-injected superconductors (Dynes *et al.*, 1977; Gray and Willemsen, 1978; Iguchi and Langenberg, 1980) have revealed transitions to totally superconducting states with spatially inhomogeneous gap parameters.

These experiments fall short of providing a complete and coherent picture of the possible instabilities of nonequilibrium superconductors.

They do suggest that the nature of the instability (or instabilities) which can occur depends critically on the type of perturbation used to drive the superconductor out of thermal equilibrium and on the characteristics of the relaxation processes of quasiparticles and phonons in the superconductor.

There have been numerous theoretical studies of the stability of nonequilibrium superconducting states (see, for example, Aronov and Spivak, 1978; Eckern et al., 1979). Our theoretical understanding of the problem, like our experimental understanding, remains incomplete, and a satisfactory connection between experiment and theory remains to be established.

In these lectures we shall review the present experimental situation with regard to instabilities of nonequilibrium superconducting states. The emphasis will be on the experimental side, though we shall attempt to make connections with theoretical ideas discussed by other lecturers as appropriate.

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STABILITY OF NONEQUILIBRIUM SUPERCONDUCTING STATES

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Instabilities are first introduced with a simple example (Haken 1975) to illustrate linear and non-linear stability analysis and the effects of noise on stability. Then the general problem of stability for superconductors perturbed by external probes is considered from a general point of view using a set of equations for the gap and for the distribution functions of the quasiparticles and phonons. Since this most general problem is intractable, we need to concentrate on a few soluble examples: In the first set of examples, I discuss linear stability without noise, first for simplified rate equations and then for a more general set of equations for the gap and quasiparticles when the phonons are assumed in equilibrium (Aronov and Spivak 1978; Eckern, Schmid, Schmutz and Schön 1979). For the second set of examples, I show how to take into account the effect of thermal noise and how to introduce the concept of generalized free energy via the Fokker-Planck equation for nonequilibrium superconductors (Schmid 1977) and I discuss theory and experiments to which this concept has been applied. The problems of nucleation rates is also briefly mentioned. Whenever appropriate in this lecture, the results of experiments are used to

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illustrate the theoretical concepts introduced. The conclusion briefly compares the study of instabilities in superconductors and in other nonequilibrium systems and summarizes the general agreement or disagreement between theory and experiment.

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NORMAL-SUPERCONDUCTOR BOUNDARIES

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Review of experimental results on thermal and electrical resistance of N-S boundaries in the intermediate state and in heterojunctions.

Boundary conditions satisfied by excitations, and Andreev reflection; qualitative discussion of the difference between thermal and electrical conduction across an interface.

Elementary exposition of the semi-classical approach and Boltzmann equation; processes involved in the equilibration of excitation populations; the role of the chemical potential and the necessity for electric fields associated with gradients of excitation density.

Enhancement of boundary resistance by impurities.

Resistance at 0 K due to scattering of evanescent modes - an unsolved problem?

[The treatment will be, as far as possible, descriptive and non-mathematical, with the aim of establishing visualisable physical models as a background to later lectures.]

QUASIPARTICLE CHARGE IMBALANCE

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We will begin with an experimental description of the tunneling generation and tunneling detection of the quasiparticle charge Q*. In the limit $eV_{inj} << k_BT$, where V_{inj} is the injection voltage, a simple analytical result can be given for the rate of generation of Q*, and, assuming a charge relaxation rate τ_{Q*}^{-1}, for the measured voltage. The perturbation of the quasiparticle distribution from equilibrium is calculated in this limit. The more general and useful case $V_{inj} >> k_BT$, Δ, where Δ is the energy gap, will be tackled using a kinetic equation approach. Typical computer-generated results for the distribution function and τ_{Q*}^{-1} will be presented as a function of injection voltage and temperature for the case of inelastic charge relaxation.

In the presence of gap anisotropy, elastic scattering also relaxes Q*. The kinetic equation can be extended readily to include this relaxation process. The results of this calculation will be compared with experimental data. Magnetic impurities or the presence of a supercurrent also relax Q*. Experimental results for these situations will be presented, and compared with the predictions of the theory.

Other experimental configurations in which quasiparticle charge plays a role will be discussed. A simple model for the boundary resistance of the normal-superconducting interface near T_c will be compared with experimental data, and used to determine values of τ_E^{-1}, the inelastic scattering rate at the Fermi energy at T_c. Experiments on phase slip centers will be described. Measurements on the charge generated in a superconducting film by a supercurrent in the presence of a temperature gradient will be compared with several conflicting theories.

KINETIC EQUATIONS FOR SUPERCONDUCTORS

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Summary of lecture to be given at the NATO Advanced Study Institute in Maralear, Italy, 1980.

I. INTRODUCTION

A short review on the BCS theory in which Cooper pairs and quasiparticles are introduced.

II. KINETIC EQUATIONS IN THE EXCITATION REPRESENTATION

1. General Theory. According to Aronov and Gurevich, kinetic equations are introduced in which the local distribution function $n_{\vec{p}}(\vec{r};t)$ of the quasiparticles and their local energies $\hat{E}_{\vec{p}}(\vec{r};t)$ play the most important role. The general form of the quasiparticle energies valid also in non-equilibrium situations is given by

$$\hat{E}_{\vec{p}} = E_p + \vec{p}\vec{v}_S \; ; \; \tilde{E}_p = \sqrt{\tilde{\epsilon}_p^2 + \Delta^2} \quad ,$$

where $\vec{p}$ is the momentum of the excitations, and where

$$\tilde{\epsilon}_p = \epsilon_p - \Phi + \tfrac{1}{2} mv_S^2 \; ; \; \epsilon_p = \frac{p^2}{2m} - \mu_F \quad .$$

In general, the superfluid velocity v_S, the energy gap Δ, as well as the pair potential Φ depend on space and time. The distribution function is obtained by solving a kinetic equation of the Boltzmann type,

$$\dot{n}_{\vec{p}} + \left[E_{\vec{p}}, n_{\vec{p}}\right]_{PB} + I\left\{n_{\vec{p}}\right\} = 0 \quad ,$$

where $[\cdots]_{PB}$ denotes the Poisson bracket and where the collision integral I describes impurity and phonon scattering.

2. Ginzburg-Landau equation. In the case where deviations from local equilibrium are small, the Ginzburg-Landau equation is a very useful limiting form of the gap equation. In addition, the form of current and charge density in this limit are discussed.

3. Linearized Boltzmann Equation. This section contains mainly a discussion on the linearized electron-phonon collision integral. The main features of the temperature dependence of quasiparticle collision times will be explained. In addition, an approximation is introduced for the electron-phonon collision integral which conserves the charge.

III. COLLECTIVE MODES AND RELAXATION PROCESSES.

1. Carlson-Goldman Mode. This mode can be considered as a non-hydrodynamic sound wave of the superfluid. Since the frequency is rather large, one can neglect electron-phonon collisions but impurity collisions have to be taken into account.

2. Relaxation of Branch Imbalance. This is the low frequency limit of a phenomenon which in the high frequency limit has been discussed in the previous section. Inelastic electron-phonon collisions play a central role in this relaxation process. In addition, the relationship between τ_{Q^*} and $\tau_R^{(T)}$ are explained.

3. Relaxation of the Gap. The rate of the gap relaxation depends crucially on inelastic electron-phonon collisions.

IV. KINETIC EQUATIONS IN THE CHARGE REPRESENTATION.

1. General Theory. In the BCS theory, there exists an alternate description of a general (in particular, a non-equilibrium) superconducting state. Instead of the quasiparticle distribution $n_{\vec{p}}$, one introduces the distribution of charges $f(E,\hat{p})$ with respect to states that are labeled by their energy E and the direction $\hat{p}$ of their momentum. In the case of an isotropic distribution function, one finds that

$$\delta f^{(+)}(E) = \frac{\tilde{\epsilon}_p}{\tilde{E}_p} \delta n_{\vec{p}}^{(-)} \quad ; \quad \delta f^{(-)}(E) = guE \, \delta n_{\vec{p}}^{(+)} \quad ,$$

where $E = \pm \tilde{E}_p$ and where the superscript denotes the parity with respect to E and $\tilde{\epsilon}$, respectively.

2. Charge versus Quasiparticle Representation. The advantage of the latter is mostly its conceptual simplicity. On the other hand, the charge representation works well even in the presence of strong impurity scattering and of pair breaking where the other method fails.

SUMMARY

Charge imbalance in nonequilibrium superconductors

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1. Quasiparticle and condensate charge
2. Generation of quasiparticle charge
3. Charge relaxation
4. Diffusive and oscillatory motion

1. Quasiparticle and condensate charge

The lecture introduces the concept of quasiparticle and condensate charge by demonstrating how changes in the total charge are naturally divided into two components. The changes in the quasiparticle charge (the normal component) arise from changes in the quasiparticle distribution function, while changes in the condensate charge (the superfluid component) are due to changes in the BCS coherence factors u and v. As a consequence of this separation an energy-dependent effective charge u^2-v^2 (in units of the electronic charge) is associated with each quasiparticle state. The change in the normal charge is the sum over all states of this effective charge times the change in the quasiparticle distribution function.

The physical motivation for the separation of charge into its normal and superfluid components is that the normal charge is the quantity directly observed in branch imbalance experiments. A large number of non-equilibrium phenomena in superconductors can be simply interpreted as involving diffusive or oscillatory motion of the normal charge, accompanied by a compensating change in the condensate charge.

We show how the normal and superfluid components obey separate continuity equations, which include conversion terms responsible for the relaxation towards equilibrium. The current of normal charge differs in general from the normal current of the conventional two-fluid model. We consider the response of the superfluid and normal parts of the charge to a change in chemical potential and derive expressions for the temperature dependent susceptibilities associated with these changes. The important distinction between global and local equilibrium is discussed, and we indicate the circumstances under which the non-equilibrium quasiparticle distribution may be characterized by a shifted chemical potential.

2. Generation of quasiparticle charge

In this lecture we discuss a number of ways in which quasiparticle charge may be generated. The first example is direct injection by tunneling. We show how the injected current drives the quasiparticles out of equilibrium and formulate the Boltzmann equation, which is satisfied by the quasiparticle distribution function. The relevant symmetry properties of the solution to the Boltzmann equation are discussed and compared to those characterizing other non-equilibrium phenomena such as gap relaxation and thermal conductivity. The detected voltage in a tunneling injection experiment is a direct measure of the deviation from local equilibrium of the quasiparticle charge. Its magnitude is determined by the charge relaxation time, which under isotropic conditions and in the absence of magnetic impurities is determined solely by inelastic scattering.

As a second example of generation of quasiparticle charge we consider the combined effect of a temperature gradient and an imposed supercurrent. We formulate the Boltzmann equation for the distribution function and show that the asymmetry introduced by the presence of a superfluid velocity makes impurity scattering effective, in contrast to the injection experiment considered above. In a steady state the rate of generation of quasiparticle charge is balanced by the decay of quasiparticle charge into the condensate. As a result one may detect a thermoelectric voltage, which reverses sign upon reversal of the temperature gradient and the imposed supercurrent.

3. Charge relaxation

The magnitude of the voltage detected as a result of charge generation depends on the particular relaxation mechanism under consideration. We review the effects of electron-phonon scattering as well as scattering due to magnetic and non-magnetic impurities. In the tunneling injection experiment the dominant effect of electron-phonon scattering near the transition temperature may be interpreted as giving rise to a quasiparticle distribution function which is a Fermi function with a shifted chemical potential. This provides the microscopic justification for a set of two-fluid equations near the transition temperature T_c, with a charge relaxation time equal to the normal state inelastic scattering time (at T_c and at the Fermi energy) times $4k_BT_c/\pi\Delta(T)$.

The role of magnetic impurity scattering and scattering by ordinary impurities in the presence of gap anisotropy or superflow is briefly reviewed. When the generation of charge is due to the simultaneous presence of a supercurrent and a thermal gradient, the impurities play an important role in the relaxation. We discuss and compare recent calculations of the charge relaxation time for this situation, pointing out the similarities and differences between the various approaches.

4. Diffusive and oscillatory motion

Under space- and time-dependent conditions the two-fluid equations may be combined into one second order differential equation for the charge imbalance. We discuss the solutions of this equation in a number of physically interesting situations.

At sufficently high frequencies the equation of motion for the normal charge possesses a propagating solution, the Carlson-Goldman mode. We express the mode velocity in terms of the susceptibility of the superfluid component introduced earlier, and show that the resulting velocity is identical with that determined by microscopic theory. Under stationary, but spatially inhomogeneous conditions, the equation of motion reduces to a diffusion equation. The characteristic diffusion length involves the relaxation time for quasiparticle charge and therefore diverges near the transition temperature. As a final application of the two-fluid equations we consider the NS boundary resistance near T_c by solving for the variation in the quasiparticle chemical potential (which is equivalent to the deviation from local equilibrium of the quasiparticle charge), relating its value at the NS-boundary to the applied current.

In conclusion we stress that the validity of the two-fluid approach outlined in these lectures is not restricted to the clean limit, as many of the results discussed here apply to dirty superconductors as well.

THERMOELECTRIC EFFECTS IN SUPERCONDUCTORS

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The first measurement of a thermoelectric transport coefficient in a superconductor was reported by Meissner in 1927. It was found that a circuit consisting of two metals gave rise to no thermoelectromotive force when both metals were superconducting. This, and many subsequent experiments, have shown that with the exception of flux flow and certain electrostatic phenomena most conventional thermoelectric coefficients (Seeback coefficient, Thompson and Peltier heats) vanish in the superconducting state. However, as Ginzburg first noted, there exists in a superconductor the possibility of a simultaneous flow of a normal current of density $\vec{j}_n = L_T(-\nabla T)$ and a supercurrent $\vec{j}_s = -\vec{j}_n$. The supercurrent counterflow ordinarily cancels the normal current, although recent work shows that the cancellation is not complete in anisotropic materials. Also, the interaction of the supercurrent with the temperature gradient can give rise to measurable effects.

Experiments to detect thermoelectric effects in superconductors held in thermal gradients can be grouped in the following classes:

1. Classical. Measurements of the Seeback effect, Peltier effect and Thompson heat.
2. Thermo-electrostatic. Bernouli voltage due to finite supercurrent velocity and Fountain Effect voltage due to work function variation.

3. Fountain Effect Current Flow. Experiments to detect the supercurrent counterflow using weakly coupled superconductors.

4. Bi-Metallic Loops. Detection of thermally induced magnetic flux in loops consisting of two different superconductors.

5. Tunneling. Detection of pair-quasiparticle potential differences with and without an externally driven supercurrent.

A comprehensive review of these experiments will be undertaken. Since it is expected that detailed descriptions of appropriate microscopic theories will be covered in other papers, emphasis will be given to discussions of experimental phenomena, two fluid descriptions, and unifying principles. Wherever appropriate, reference will be made to microscopic results, although no attempt will be made to include rigogorous derivations.

COLLECTIVE MODES OF THE SUPERCONDUCTING ORDER PARAMETER

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A generalization of Josephson pair tunneling has led to the experimental determination of the imaginary part of the wave-vector and frequency-dependent pair-field susceptibility of superconductors. This has been possible despite the order parameter not having a classical laboratory field which couples to it. (Scalapino 1970, Giaquinta and Mancini 1978) The pair-field susceptibility has been studied in detail in a variety of geometries. Above the transition temperature, the measurements have been found to be generally consistent with order-parameter dynamics governed by a generalized time-dependent Ginzburg-Landau picture. (Carlson and Goldman 1976) Below the transition temperature, the explanation of the measurements requires the full power of the theory of dynamical nonequilibrium phenomena which describes the coupled system of Cooper pairs, quasiparticles and phonons. (Schmid and Schön 1975)

In the superconducting state the dynamical behavior of the order parameter can be separated into parts associated with oscillations in the magnitude and phase of the order parameter which are known as the longitudinal and transverse modes respectively. The experimental discovery that the transverse mode of the order parameter was propagating, albeit under restricted conditions, overcame the widespread opinion that collective oscillations associated with charged superfluids would always be high-frequency plasma oscillations. (Carlson and Goldman 1976) These results have stimulated a number of theoretical works examining the collective modes of the superconducting order parameter. In the theory the propagating mode is associated with local oscillations in the quasi-particle charge and pair charge in which there is a counterflow of super-current and normal current. (Pethick and Smith 1979) In other language the mode may be considered to be a propagating branch imbalance wave. (Kadin, Smith and Skocpol 1980)

The connection between the excess current due to pair tunneling and the pair-field susceptibility will be examined in detail both experimentally and theoretically. Susceptibility data below T_c will be presented and compared with specific predictions of theories which are qualitatively similar but different in detail.

Although pair-field susceptibility experiments below T_c measure a sum of contributions from the longitudinal and transverse modes, modern computer-fitting procedures allow the extraction of the parameters of both modes. Thus a spectroscopy of order parameter dynamics is possible. The results of this spectroscopy will be discussed with attention paid to the effects of magnetic impurities on the propagating character of the transverse mode, (Aspen and Goldman 1979, Entin-Wohlman and Orbach 1979) the coupling between the transverse and longitudinal modes in a current carrying state, (Gerd Schön and Vinay Ambegaokar 1979) and hitherto unreported features of the longitudinal mode.

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NONEQUILIBRIUM EFFECTS IN 1-D SUPERCONDUCTORS

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The experimental nonequilibrium phenomena observed in one-dimensional superconducting filaments (whisker crystals and thin film microstrips) will be surveyed and explained within a simple T*, Q* approximation. The local temperature T* is determined by a heat flow equation which balances Joule heating against surface heat transfer and conduction along the filament. The local charge density in the quasiparticle system eQ* is determined using the equivalent circuit model described by Kadin, Smith and Skocpol (1980) which summarizes (near T_c) the sort of two-fluid theory developed by Pethick and Smith.

These ideas will first be applied to the case of a normal segment in the filament, for comparison with other approaches described at the Institute. At low current densities the description of the boundary resistance $R_B(T_o)$ at each S/N interface follows that of Hsiang and Clarke (1980). At higher current densities, the temperature rise due to Joule heating causes the boundary resistance to increase. When T* varies slowly because $\eta_{th} > \Lambda_{Q^*}$, a simple heating model $R = R_N = 2R_B(T^*)$, $T^* = T_o + \text{const } I^2R$ accounts for the observed data. Beyond I_c* where $T^* = T_c$ at the interface, the interface moves and one has a self-heating hotspot as described by Skocpol, Beasley and Tinkham (1974a). Such normal hotspots almost completely determine the I-V curves of the filament far from T_c.

Near to T_c, T* phenomena are less important and Q* phenomena dominate the situation. Experiments by a number of researchers on thin-film microstrips and on whisker crystals reveal the formation of spatially localized dissipative regions dubbed "phase-slip centers". Such spatial localization is expected to occur even in ideally homogeneous filaments and leads to step structure in the dc I-V curves. Kadin's simple model of a Josephson oscillator (at the center) connected to the equivalent circuit transmission line (on either side) gives a useful qualitative model of the dc and ac potentials inside such a phase-slip center. The dc averages of μ_p and μ_{qp} agree with the earlier Skocpol, Beasley, and Tinkham (1974b) picture (with $\Lambda_Q{}^*$ instead of Λ_E) and have been experimentally confirmed. The dc quasiparticle currents carried nearby can affect the apparent critical currents of nearby phase-slip centers. The ac potentials and currents can also be calculated, and should play an important role in the synchronization between closely spaced phase-slip centers or thin-film microbridges. More sophisticated theories based on TDGL theory and nonequilibrium generalizations of it have revealed the existence of phase-slip-center type solutions in long filaments very near to T_c and I_c, but have not yet tackled the more complicated experimentally accessible regime.

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STATIC AND DYNAMIC INTERACTION BETWEEN SUPERCONDUCTING WEAK LINKS

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I. INTRODUCTION

a) Description of different types of weak links and phase-slip centers.

b) Two-fluid description of Josephson tunnel junctions (tunnelling picture) and weak links with conductive barriers (Ginzburg-Landau theory; Ohm's law).

c) Voltage-controlled versus current-controlled weak links. - The RSJ model.

d) Josephson's voltage-frequency relation and the generation of electromagnetic radiation. Injection locking.

e) Static and dynamic non-equilibrium states of the electrodes in different types of weak links. Temperature profile, charged branch imbalance, and neutral non-thermal branch imbalance. Phonon generation.

II. LONG RANGE INTERACTION BETWEEN TWO WEAK LINKS

a) Phase locking of the A.C. Josephson oscillations in two weak links by way of the electromagnetic field given by distributed or lumped circuit passive elements. (Resistive shunts, resonance circuits or transmission lines). Coupling via loops with flux quantization. Considerations of the emitted microwave power, matching problems.

b) Interaction, due to incoherent 2Δ-phonons, between two weak links.

III. SHORT RANGE INTERACTION BETWEEN TWO WEAK LINKS

Interaction between two weak links or phase-slip centers in close proximity. Injection of normal excitations from one superconducting junction into another, when placed back to back.

Two microbridges or proximity bridges with a common intermediate superconducting film. Order parameter interaction, magnetic field interaction, charged branch imbalance mode interaction and heating effects. Voltage and Josephson frequency locking.

IV. LARGE COHERENT SYSTEMS

a) Granular superconductors.

b) Coherent properties of a moving vortex lattice.

c) Coherent networks of many interacting Josephson oscillators in series/parallel. Experimental realizations. Superradiance and linewidth. Flux quantization problems.

MOTION OF MAGNETIC FLUX STRUCTURES

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1) Introduction:

Linear and nonlinear range of non-equilibrium behavior

2) Lorentz Force:

Phenomenological Force Equation

Flux-Flow Resistance

Hall-Effect

Ettinghausen and Peltier Effect

Josephson Relation

3) Thermal Force:

Phenomenological Force Equation

Nernst and Seebeck Effect

Transport Entropy

4) Experiments:

Magneto-optical Flux Detection

Magnetic Coupling

Electrical Noise Power

5) Comments on Flux Pinning:

Fundamental Concepts

6) Time-Dependent Theories:

Comparison of experimental data with phenomenoligical theories including the time-dependent Ginzburg-Landau theory

7) Current-Induced Dissipative State:

Nucleation of Flux-Tube Trains in Constricted Films of Type I

Experiments with High time Resolution

Theoretical Model

introductory reading material:

R. P. Huebener, Magnetic Flux Structures in Superconductors,
Springer Verlag Berlin 1979

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