

Superconductivity

Progress in High Temperature Superconductivity — Vol. 27

Proceedings of the XXIV Italian National School on Condensed Matter Physics

SUPERCONDUCTIVITY

GNSM-CNR and CONSORZIO INFM

Bra, Italy 18 — 28 September 1989

Editors

S. Pace

*Dipartimento di Fisica
Università degli Studi di Salerno*

M. Acquarone

*CNR c/o Dipartimento di Fisica
Università degli Studi di Parma*



World Scientific

Singapore • New Jersey • London • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.

P O Box 128, Farrer Road, Singapore 9128

USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661

UK office: 73 Lynton Mead, Totteridge, London N20 8DH

**SUPERCONDUCTIVITY — PROCEEDINGS OF THE
XXIV ITALIAN NATIONAL SCHOOL ON
CONDENSED MATTER PHYSICS**

Copyright © 1991 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

ISBN 981-02-0328-4

Printed in Singapore by Utopia Press.

Preface

This volume is based on the lecture notes of the XXIV Italian National School on Condensed Matter organized by the Gruppo Nazionale di Struttura della Materia (GNSM) of the Consiglio Nazionale delle Ricerche (CNR) and by the Consorzio Interuniversitario Nazionale per la Fisica della Materia (INFN). The course was devoted to Low Temperature Superconductors and was held in Bra, Italy from 18th to 28th September 1989.

The aim of the School was mainly to give an up-to-date presentation of the "old" superconductivity in a form suitable to a rather inhomogeneous audience composed of graduate and post-graduate students with a background either in Physics, or Chemistry or Materials Engineering. In the rush of new theoretical models and experimental problems connected with the high- T_c superconductors, the need was felt to assess what was the actual content of the "classical" theory of superconductivity. The aim was twofold: on one hand, as that topic is only marginally covered in the regular University courses in Italy, many young researchers were approaching the field with insufficient information; on the other hand, there was the risk (not limited to young researchers) of considering some phenomenology as completely unusual, only because of a superficial knowledge of the BCS and derived models. As a typical example of such a misleading attitude one can mention the often heard claim that the smallness or absence of the isotope effect ruled out any phonon contribution to the pairing.

As for the style of the presentation, the authors have rearranged and expanded their notes in order to present them in a volume, trying carefully to preserve the original didactic bias. An effort was required to put all the participants at the same level of knowledge about the basic tools, particularly with respect to the theoretical methods for many-body problems. This explains the somehow detailed discussion of some basic formalism, which could otherwise, for a more homogeneous audience, have been taken for granted. However, we hope that this will make the book useful to a broader range of users. Not all the lectures given at the school can be found in this book, since some talks on particular topics, such as the electron-phonon interaction, have been given following the well-known literature on these subjects.

The order of the contributions have been changed with respect to that of the talks, grouping arguments with similar content. The presentation starts from a phenomenological approach, which is developed at increasing levels of

sophistication up to the Landau-Ginzburg theory in the first four contributions. Chapter 5 is, in a sense, the bridge to the three subsequent ones. Chapters 6 to 8 deal with specific microscopic interactions and model Hamiltonians, mainly by using the Green function technique, which is presented in some detail and applied in various forms.

The following Chapters 9 to 14 discuss some important aspects of the phenomenology of the tunnel effect. Both the single particle tunnelling and the Cooper pair tunnelling, i.e. the Josephson effect, are analysed. Even though the emphasis is on the experimental point of view, the necessary theoretical support is also summarized. Beside these arguments, the SQUIDS, viewed as the main application of the Josephson effect, and some particular topics on Josephson junction arrays are analyzed.

Finally, Chapters 15 to 17 are devoted to non-standard low- T_c superconductors such as the heavy fermion systems, superconducting superlattice and magnetic superconductors. The last Chapter introduces the BSCCO, as a material representative of the high- T_c superconductors. During the course, one lecture was given also on YBCO, but it was impossible to include the related text in this book.

In choosing the contributions to the school, it was unavoidable to exclude some topics which would deserve as much attention as the ones included. The present book is not an exception: indeed, nothing is said about NMR or optical properties, just to mention two very important fields of activity. However, we hope that the material presented here will provide the reader with a satisfactory basic knowledge, in such a way that he will be able to move confidently to other available publications about any specific field of interest.

Salerno, Parma, 1991

S. Pace
M. Acquarone

Table of Contents

Preface	v
1. Remarks on Phenomenology and Phenomenological Theoretical Analysis	1
<i>S. Pace and L. Liberatori</i>	
1. Introduction	1
2. Perfect Fluid versus Superconducting Electron Gas	7
3. London Theory	13
4. Thermodynamic Analysis	25
5. Conclusions	26
References	27
2. Ginzburg - Landau Theory and the Magnetic Properties of an Ideal Superconductor	28
<i>A. Siri</i>	
1. Introduction	28
2. The Ginzburg-Landau Theory	29
3. G-L Characteristic Lengths	34
4. Surface Energy and Intermediate State	37
5. Critical Current and Parallel Field of a Thin Film and Quantisation of the Fluxoid	41
6. Linearized G-L Equations: Nucleations at H_{C2} and at H_{C3} and the Abrikosov Vortex State near H_{C2}	43
7. The Mixed State Far from the Transition: H_{C1} and the Structure of an Insulated Vortex	49
References	53
3. Basic Aspects of Flux Creep	54
<i>A. M. Testa</i>	
1. Introduction	54
2. The Critical State Model	56
3. Flux Creep	57
4. Concluding Remarks	61
References	62

4. Thermal Properties of Superconductors: Specific Heat and Thermal Conductivity	63
<i>M. Putti</i>	
1. Specific Heat in a Metal	63
2. Specific Heat in a Superconductor	65
3. Thermodynamics of a Superconducting System	66
4. Theoretical Models	70
5. Thermal Conductivity of Metals	72
6. Electronic Thermal Conductivity	73
7. Thermal Conduction in a Crystalline Lattice	78
8. Thermal Conductivity in Superconductors	83
9. Thermal Conductivity in Magnetic Field	85
References	87
5. An Introduction to Superconductivity	88
<i>C. Di Castro and R. Raimondi</i>	
1. Preface	88
2. Phenomenology of Superconductors: London Theory and Landau Criterion	89
3. The Condensation Criterion and the Order Parameter	94
4. Order Parameter and Symmetry	102
5. Landau Theory of Second Order Phase Transitions. Its Limit of Validity	107
6. Paraconductivity	116
7. The Microscopic Approach	120
Appendix A: A Microscopic Derivation of the Time-Dependent Landau-Ginzburg Equations	133
References	144
6. Hubbard Correlation and Electron-Phonon Interaction Effects in the Normal and Superconducting States	148
<i>M. Acquarone</i>	
1. The Hubbard Correlation	148
2. The Hubbard Hamiltonian	151
3. Gutzwiller Approach and Derived Variational Models	153
4. Correlation and Magnetism	162
5. Electron-Phonon Interaction for Tightly Bound Electrons	164

6. Green Functions Description of the Electron-Phonon System.	
The Normal State	173
7. The Superconducting State	187
8. Effective Hamiltonian for Correlated Electrons and Phonons	203
Appendix A: Change of Representation for the Hubbard Hamiltonian	210
Appendix B: Useful Operator Relations	212
References	217
7. Green Functions Methods in Superconductivity	220
<i>M. Marinaro, C. Noce, and A. Romano</i>	
1. Introduction	220
2. The Dyson Equation for the Normal State	220
3. The Dyson Equation for the Superconducting State	226
4. Strong Coupling Theory - Eliashberg Equations	232
5. Weak Coupling Theory	235
References	239
8. Impurity Effects in Superconductivity	241
<i>F. Mancini</i>	
1. Introduction	241
2. The Model	242
3. The Two-Point Green Function	246
4. Electromagnetic Properties in the Linear Response	257
5. Electromagnetic Field in the Microscopic Theory	265
6. The Ginsburg-Landau Parameter	273
7. Type-I and Type-II Superconductivity	274
8. Concluding Remarks	278
References	279
9. Superconducting Tunnel Junctions	283
<i>S. Pace and A. Saggese</i>	
1. Introduction and Historical Overview	283
2. Excited States in Normal Metals	286
3. Tunnel between Normal Metals	289
4. Density of States in BCS Superconductors	293
5. Tunnel Effect in Superconductors	301
6. Strong Coupling Superconductors	305
7. Proximity Effect Junctions	308
References	312

10. Dependence of I-V Characteristics of Tunnel Junctions on the Barrier Shape	315
<i>A. Saggese</i>	
1. Introduction	315
2. The Metal Oxide Interface in Tunnel Barriers	317
3. A First Determination of the Barrier Height and Thickness	322
4. The Image Potential in Tunnel Junctions	330
5. The Niobium Oxide Barriers	333
6. Anomalous Tunnel Effects on Nb Oxide Barriers	337
7. Permanent Changes on the Oxide Barrier	340
8. Conclusions and Acknowledgements	342
References	343
11. The Josephson Effect	346
<i>G. Costabile</i>	
1. The Josephson Equations	346
2. The ac Josephson Effect	350
3. Josephson Tunneling Junctions	354
4. Magnetic Field Effects	356
5. The Josephson Junction Electrodynamics	357
6. Magnetic Flux Propagation in Long Junctions	361
References	363
12. SQUIDS: Theory and Applications	365
<i>C. Cosmelli</i>	
1. Introduction	365
2. RF-SQUID	368
3. DC-SQUID	375
4. Noise in SQUIDS	386
5. SQUID's Applications	394
References	398
13. Microscopic Quantum Phenomena in Granular Superconductors	401
<i>G. Giaquinta</i>	
1. Introduction	401
2. MCE and MQE in the Single Josephson Junction	403
3. Fluctuations in Granular Superconductors and Josephson Junction Arrays	405
References	412

14. Critical Phenomena in Josephson Junction Systems	414
<i>A. Giannelli and C. Giovannella</i>	
1. Introduction	414
2. 3D Granular Systems in Zero Magnetic Field	417
3. Influence of Disorder on 3D Systems	421
4. Influence of Magnetic Field on 3D Systems	422
5. Recent Experiments on 3D Granular Systems	423
6. 2D Systems	424
7. Recent Simulations on 2D Systems	424
8. Conclusions	425
References	425
15. Superconductivity and Magnetism	427
<i>C. Attanasio, L. Maritato and R. Vaglio</i>	
1. Introduction	427
2. Dilute Alloys	429
3. Superconductivity in Magnetic Compounds	437
4. High Critical Temperature Superconductors	446
References	449
16. Superconducting Superlattices	452
<i>L. Maritato, A. Nigro and R. Scafuro</i>	
1. Introduction	452
2. Deposition Techniques	453
3. Structural and Normal State Properties	455
4. Superconducting Superlattices	458
5. Speculation on High T_c Superconductors	470
References	471
17. Heavy Fermion Systems	473
<i>C. Noce</i>	
1. Introduction	473
2. Phenomenology of HF Systems	475
3. Theoretical Models for HF	485
4. f-itinerant Electrons	488
5. Conclusions	491
References	492

18. Properties of BSCCO	495
<i>G. Balestrino</i>	
1. Structural Properties	495
2. Preparation	499
3. Transport Properties	499
4. Magnetic Measurements	502
References	504

REMARKS ON PHENOMENOLOGY AND PHENOMENOLOGICAL THEORETICAL ANALYSIS

S. Pace, L. Liberatori†

*Dipartimento di Fisica, Università degli Studi di Salerno
I-84081, Salerno, Italy*

*†Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
Via E. Fermi 40, 00044 Frascati, Roma, Italy*

1. Introduction

In this work we have restricted our analysis to low-temperature metallic superconductors even though, for the most of key points regarding the superconducting state, high-temperature ceramic superconductors appear to be qualitatively identical to the usual ancient superconductors. On this subject a large number of phenomenological reviews exist in the literature [1,2,3,4], so we believe that it is better to summarize the main properties which have been the basis for the understanding of the superconducting state from a quantum mechanical point of view.

Their well known main features are:

- 1) the resistive transition,
- 2) the perfect diamagnetism,
- 3) the existence of critical magnetic fields and critical currents,
- 4) the magnetic flux quantization,
- 5) the Josephson effect,
- 6) the existence of interference phenomena in superconducting loops linked

by weak links,

7) the isotopic effect,

8) the behaviour of the specific heat,

9) the behaviour of tunnel devices.

Before a brief description of each point, three remarks are necessary:

a) very often the actual experimental behaviour is quite different from the expected one, which is actually the result of an idealization process;

b) in spite of the idealization process, only points 1-6 are verified in each low temperature superconducting material, so that points 7-9 do not appear necessary for the traditional superconducting state, neither does their absence necessarily imply a new superconducting state;

c) if points 1-6 led to a particular microscopical state, it seems to us highly unlikely that the new ceramic materials, which substantially show the same qualitative behaviour, can correspond to a very different microscopical state.

Coming back to a short description of each point, the existence of a resistive transition means the existence of a well defined temperature, named "critical temperature" (T_c), below which the direct current (DC) metallic resistance becomes zero. In DC conditions this fact implies the complete absence of power dissipation. On the contrary, frequency-dependent dissipative effects are present in AC conditions.

Anyway, more than perfect conductivity, the existence of perfect diamagnetic behaviour is the main characteristics of the superconducting state; it appears in two different ways:

a) as an almost perfect shielding effect, so that, after a cooling down below the transition temperature in the absence of an external magnetic field H (Z.F.C. conditions), the application of a "low" field leaves the magnetic induction $B = 0$ inside the material,

b) as the Meissner effect, that is the expulsion of low magnetic fields obtained by cooling down the material below the transition temperature. As a matter of

fact, 22 years (from 1911 to 1933) were necessary for the discovery of such an effect since it actually only appears in almost perfect materials. In the presence of impurities the magnetic flux is trapped inside the material and only partial expulsion occurs.

The existence of critical fields means that perfect diamagnetic behaviour persists up to an upper threshold, above which the magnetic field penetrates the sample. For ideal materials two classes of behaviour can be distinguished:

a) in type-one superconductors, above a critical field H_c , the materials revert to the normal state;

b) in type-two superconductors, above a lower critical field H_{c1} , (lower than H_c), a continuous penetration of the magnetic field starts; as the field H increases, the magnetic induction increases more and more, however the perfect conductivity state persists up to an upper threshold H_{c2} corresponding to the complete penetration of the magnetic field. In ideal samples (soft superconductors) this behaviour is completely reversible. Actually in the presence of localized impurities (hard superconductors) a more complex irreversible behaviour appears, as described in more details by A. Testa in a different paper in this book. Critical fields are monotonically decreasing functions of the temperature, almost constant for $T < T_c/2$ and going continuously to zero as T approaches T_c .

Analogously in direct current measurements too, the absence of dissipative effects persists up to a current threshold, named critical current I_c above which power dissipation appears; as the current still increases the details of the re-establishment of the normal state depend on the superconductor type.

The presence of the Meissner effect in ideal samples guarantees the uniqueness of the state for a fixed external field; however this result is valid only for simply connected samples. Indeed, the magnetic state of a superconducting ring is a function of its history: when the ring is cooled down in an external magnetic field, the magnetic induction becomes zero only in the body of the ring and it is different from zero inside the vacuum core of the ring. On the contrary, if the same field is applied after Z.F.C., the shielding effect leads to zero magnetic induction both in the body and in the core. Moreover a subsequent removal of

the field leads in the first case (F.C. condition) to magnetic flux trapping inside the hole, while in the second one (Z.F.C. condition) the field removal leads to the complete absence of the field. The flux trapping effect is strictly related to the perfect conductivity since by Maxwell equations $d\Phi(B)/dt = E$ and by Ohm law $E = \rho j$, so that in the superconducting state the perfect conductivity implies that the flux linked to a ring must be a constant. Nevertheless it generated a serious problem since in classical thermodynamics the state of any thermodynamic system must be completely determined by the values of thermodynamic variables. Luckily quantum mechanics removes the problem. Indeed not only the flux is constant but it is quantized:

$$\Phi(B) = n\Phi_0 \quad (1)$$

where n is an integer and Φ_0 is the flux quantum: $\Phi_0 = hc/2e$. In this way an infinite number of metastable states exists and the ground state corresponds to the thermodynamic equilibrium.

The presence of a flux quantization phenomenon is the first evidence of the existence of a macroscopical quantum state of particles with charge $2e$.

As shown in more details in two other papers in this book by G. Costabile and C. Cosmelli, the quantum macroscopical behaviour is also the basis of the Josephson effect and of quantum interference phenomena which clearly appear in superconducting rings closed by Josephson junctions. Indeed, in the first case the superconducting current flows through a junction weakly coupling two superconducting electrodes in the absence of applied voltage. This current is a sinusoidal function of a macroscopical phase which characterizes the two electrodes. In the second case the maximum superconducting current, which can cross through two junctions in parallel in a superconducting ring, shows a sinusoidal dependence on the flux inside the ring. Such an effect is particularly surprising from a classical point of view, since it is also present in the complete absence of any field inside the superconducting material.

Coming back to properties 6), 7), and 8), such features are not always present even in classical superconductors, so that their presence or absence cannot play

any basic role for the definition of the microscopical nature of the superconducting state.

Anyway the isotopic effect, that is the dependence of the critical temperature on the isotopic mass M of the superconducting element ($T_c \propto M^{-1/2}$), opened the way to the understanding of role of the electron-phonon interaction in low T_c superconductors. However metals or metallic alloys with a higher critical temperature ($T_c \cong 10K$) show a lower dependence or even do not show any appreciable dependence on the isotopic mass. Indeed, as reported in more details by A. Saggese and S. Pace in another paper in this book, the Bardeen-Cooper-Schrieffer (BCS) microscopical theory shows that the electron-phonon interaction gives rise to the $M^{-1/2}$ dependence only in the "weak coupling" limit.

As far as the specific heat is concerned, at the transition point, in the absence of an external magnetic field, a jump of the specific heat appears with the transition from a linear metallic behaviour to an exponential one. These features indicate respectively the presence of a second-order phase transition, and an energy band completely empty of states, a gap, at the Fermi surface. However, in this case too, the presence of impurities is sufficient to drastically change the height of the jump. Moreover the exponential behaviour below T_c is not present in some superconducting material like in the presence of particular magnetic impurities concentrations.

In an analogous way in most of the cases the current-voltage characteristics of tunnel junctions show the presence of an energy gap at the Fermi surface. As shown in more details by S. Pace and A. Saggese in another paper in this book, tunnel measurements show the presence of a gap not only in the dispersion relation but also in the density of states (DOS) (the difference between the two cases is analysed by the contribution of M. Acquarone). However, as stated before, in particular conditions, states can be present in the forbidden band, leading in some cases to the complete absence of any gap both in the dispersion relation and in the DOS. This fact appears, for instance, in the presence of well defined magnetic impurities concentrations or in metal-superconducting sandwiches where by the proximity effect superconductivity is induced in the normal metal. In these cases, the survival of the perfect conductivity, of the perfect diamagnetism and of

macroscopical quantum phenomena demonstrate that the presence of a gap is not really necessary for the superconducting state.

Coming back to our main purpose, the implication of the described experimental features can be analysed.

Considering the first two fundamental properties, i.e. perfect conductivity and diamagnetism, at the beginning it was not clear that they are related to the same phenomenon. As in any other material, the magnetic behaviour was related to microscopical atomic currents. On the contrary by the Maxwell equation $\text{curl } \mathbf{h} = \mathbf{j}$,* it is clear that both the shielding and the trapping effect of a ring can arise only due to the presence of persistent macroscopic currents in the sample. In this way perfect conductivity and perfect diamagnetism are easily explained by a superfluid model: the current is driven by a superfluid electron gas.

Obviously the presence of a finite current density can generate only a gradient of the magnetic field, in such a way that the field can penetrate near the surface on the superconducting sample at a depth of the order of a characteristic length λ depending on the material.

In any case the presence of dissipative effects in AC conditions proves the contemporary presence of "normal" electrons. For these reasons, in close analogy to the superfluid He^4 theory, the two-fluid model has been developed, starting with the equations:

$$n = n_s + n_n \quad (2a)$$

* Some care has to be taken about the symbols used. Usually \mathbf{h} is the microscopical magnetic field: $\mathbf{h} = \text{curl } \mathbf{A}$, where \mathbf{A} is the vector potential, \mathbf{H} is the field generated by the macroscopical external currents, while \mathbf{B} is the mean value of \mathbf{h} . In our case a difficulty arises, since in a superconductor the diamagnetic currents, which usually are microscopical, are almost macroscopical, with spatial variations in ranges of the order of hundreds of angstroms, and the real microscopical currents do not play any role. For these reasons we prefer to indicate by \mathbf{h} the magnetic field generated by both external and "macroscopical" internal currents, while \mathbf{H} is generated only by external currents. All the equations will be written in Gaussian units.