

Superconductivity

Second Edition

Charles P. Poole Jr. , Horacio A. Farach

Richard J. Creswick , Ruslan Prozorov

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Preface to the First Edition

When we wrote our 1988 book, *Cooper Oxide Superconductors*, our aim was to present an early survey of the experimental aspects of the field of high temperature superconductivity as an aid to researchers who were then involved in the worldwide effort to (a) understand the phenomenon of cuprate superconductivity and (b) search for ways to raise the critical temperature and produce materials suitable for the fabrication of magnets and other devices. A great deal of experimental data are now available on the cuprates, and their superconducting properties have been well characterized using high quality untwinned monocrystals and epitaxial thin films. Despite this enormous research effort, the underlying mechanisms responsible for the superconducting properties of the cuprates are still open to question. Nevertheless, we believe that the overall picture is now clear enough to warrant the writing of a text-book that presents our present-day understanding of the nature of

the phenomenon of superconductivity, surveys the properties of various known superconductors, and shows how these properties fit into various theoretical frameworks. The aim is to present this material in a format suitable for use in a graduate-level course.

An introduction to superconductivity must be based on a background of fundamental principles found in standard solid state physics texts, and a brief introductory chapter provides this background. This initial chapter on the properties of normal conductors is limited to topics that are often referred to throughout the remainder of the text: electrical conductivity, magnetism, specific heat, etc. Other background material specific to particular topics is provided in the appropriate chapters. The presence of the initial normal state chapter makes the remainder of the book more coherent.

The second chapter presents the essential features of the superconducting state—the phenomena of zero resistance and

perfect diamagnetism. Super current flow, the accompanying magnetic fields, and the transition to this ordered state that occurs at the transition temperature T_c are described. The third chapter surveys the properties of the various classes of superconductors, including the organics, the buckminsterfullerenes, and the precursors to the cuprates, but not the high temperature superconductors themselves. Numerous tables and figures summarize the properties of these materials.

Having acquired a qualitative understanding of the nature of superconductivity, we now proceed, in five subsequent chapters, to describe various theoretical frameworks which aid in understanding the facts about superconductors. Chapter 4 discusses superconductivity from the view-point of thermodynamics and provides expressions for the free energy—the thermodynamic function that constitutes the starting point for the formulations of both the Ginzburg–Landau (GL) and the BCS theories. The GL theory is developed in Chapter 5 and the BCS theory in Chapter 6. GL is a readily understandable phenomenological theory that provides results that are widely used in the interpretation of experimental data, and BCS in a more fundamental, and mathematically challenging, theory that makes predictions that are often checked against experimental results. Most of Chapter 5 is essential reading, whereas much of the formalism of Chapter 6 can be skimmed during a first reading.

The theoretical treatment is interrupted by Chapter 7, which presents the details of the structures of the high temperature superconductors. This constitutes important background material for the band theory sections of Chapter 8, which also presents the Hubbard and related models, such as RVB and t - J . In addition, Chapter 8 covers other theoretical approaches involving, for example, spinons, holons, slave bosons, anyons, semions, Fermi liquids, charge and spin density waves, spin bags, and the Anderson

interlayer tunneling scheme. This completes the theoretical aspects of the field, except for the additional description of critical state models such as the Bean model in Chapter 12. The Bean model is widely used for the interpretation of experimental results.

The remainder of the text covers the magnetic, transport, and other properties of superconductors. Most of the examples in these chapters are from the literature on the cuprates. Chapter 9 introduces Type II superconductivity and describes magnetic properties, Chapter 10 continues the discussion of magnetic properties, Chapter 11 covers the intermediate and mixed states, and Chapter 12, on critical state models, completes the treatment of magnetic properties. The next two chapters are devoted to transport properties. Chapter 13 covers various types of tunneling and the Josephson effect, and Chapter 14 presents the remaining transport properties involving the Peltier, Seebeck, Hall, and other effects.

When the literature was surveyed in preparation for writing this text, it became apparent that a very significant percentage of current research on superconductivity is being carried out by spectroscopists, and to accommodate this, Chapter 15 on spectroscopy was added. This chapter lets the reader know what the individual branches of spectroscopy can reveal about the properties of superconductors, and in addition, it provides an entrée to the vast literature on the subject.

This book contains extensive tabulations of experimental data on various superconductors, classical as well as high T_c types. Figures from research articles were generally chosen because they exemplify principles described in the text. Some other figures, particularly those in Chapter 3, provide correlations of extensive data on many samples. There are many cross-references between the chapters to show how the different topics fit together as on unified subject.

Most chapters end with sets of problems that exemplify the material presented and

sets of references for additional reading on the subject. Other literature citations are scattered throughout the body of each chapter. Occasional reference is made to our earlier work, *Copper Oxide Superconductors*, for supplementary material.

One of us (C.P.P.) taught a graduate-level superconductivity course three times using lecture notes which eventually evolved into the present text. It was exciting to learn with the students while teaching the course and simultaneously doing research on the subject.

We thank the following individuals for their helpful discussions and comments on the manuscript: C. Almasan, S. Aktas, D. Castellanos, T. Datta, N. Fazyleev, J. B. Goodenough, K. E. Gray, D. U. Gubser, D. R. Harshman, A. M. Herman, Z. Iqbal, E. R. Jones, A. B. Kaiser, D. Kirvin,

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Preface to the Second Edition

It has been an exciting two decades spending most of my time playing a relatively minor role in the exciting world-wide Superconductivity Endeavor. My involvement began on March 18th, 1987, when I attended what became known later as the "Woodstock of Physics", the "Special Panel Discussion on Novel High Temperature Superconductivity" held at the New York meeting of the American Physical Society. I came a half hour early and found the main meeting room already full, so several hundred physicists and I watched the proceedings at one of the many TV monitors set up in the corridors of the hotel. That evening in the hotel room my colleague Timir Datta said to me "Why don't we try to write the first book on high temperature superconductivity?" When we arrived back in Columbia I enlisted the aid of Horacio, my main collaborator for two prior decades, and the work began. Timir and I spent many nights working until two or three in the morning gathering

together material, collating, and writing. We had help from two of our USC students M. M. Rigney and C. R. Sanders. In this work *Copper Oxide Superconductors* we managed to comment on, summarize, and collate the data by July of 1988, and the book appeared in print toward the end of that year.

By the mid 1990's the properties of the cuprates had become well delineated by measurements carried out with high quality untwinned single crystals and epitaxial thin films. There seemed to be a need to assemble and characterize the enormous amount of accumulated experimental data on a multitude of superconducting types. To undertake this task and acquire an understanding of the then current status of the field, during 1993 and 1994 I mailed postcards to researchers all over the world requesting copies of their work on the subject. This was supplemented by xerox copies of additional articles made in our library, and provided a collection of over 2000 articles on superconductivity.

These reprints and xeroxes were sorted into categories which became chapters and sections of the first edition of this present book. For several months the floor of my study at home remained covered with piles of reprints as I proceeded to sort, peruse, and transpose data and information from them. This was a tedious, but nonetheless very exciting task.

There were some surprises, such as the relatively large number of articles on spectroscopy, most of which were very informative, and they became Chap. 15. This chapter contained material that most closely matched my pre-superconductivity era research endeavors, and I was pleased to learn how much spectroscopy had contributed to an understanding of the nature of superconductors. There were also many articles on magnetic properties, critical states, tunneling, and transport properties, which became Chapters 10, 12, 13, and 14, respectively. Most of the relatively large number of articles on the Hubbard Model did not, in my opinion, add very much to our understanding of superconductivity. Some of them were combined with more informative articles on band structure to form Chap. 8. There was a plethora of articles on the crystallographic structures of various cuprates, with a great deal of redundancy, and the information culled from them constituted Chap. 7. Chapter 9, Type II Superconductivity, summarized information from a large number of reprints.

The Intermediate and Mixed States Chapter 11 depended much less on information garnered from the reprints, and much more on classical sources. The same was true of Chap. 3 Classical Superconductors, Chap. 4 Thermodynamic Properties, Chap. 5 Ginzburg-Landau Theory, and Chap. 6 BCS Theory written by Rick. Finally the beginning of the First Edition text, namely Chap. 1 Properties of the Normal State, and Chap. 2 The Phenomenon of Superconductivity, were introductory in nature, and relied very little on material garnered from the reprint collection. Thus our first edition provided an

overall coverage of the field as it existed at the end of 1994.

In 1996 and 1999, respectively, the books *The New Superconductors* and *Electromagnetic Absorption in Superconductors* were written in collaboration with Frank J. Owens as the principal author.

The next project was the *Handbook of Superconductivity*, published during the millennial year 2000. It assembled the experimental data that had accumulated up to that time. Chapters in this volume were written by various researchers in the field. Of particular importance in this work were Chapters 6 and 8 by Roman Gladyshevski and his two coworkers which tabulated and explicated extensive data on, respectively, the Classical and the Cuprate Superconductors. His classification of the cuprate materials is especially incisive.

Seven years have now passed since the appearance of the Handbook, and our understanding of the phenomenon of Superconductivity is now more complete. Much of the research advances during this period have been in the area of magnetism so I enlisted Ruslan Prozorov, who was then a member of our Physics Department at USC, and an expert on the magnetic properties of superconductors, to join Horacio, Rick, and myself in preparing a second edition of our 1995 book. In the preparation of this edition some of the chapters have remained close to the original, some have been shortened, some have been extensively updated, and some are entirely new. The former Chap. 10, Magnetic Properties, has been moved earlier and becomes Chap. 5. Aside from this change, the first six chapters are close to what they were in the original edition. Chapter 7, BCS Theory, has been rewritten to take into account advances in some topics of recent interest such as d-wave and multiband superconductivity. Chapter 8, on the Structures of the Cuprates, has material added to it on the superconductor Sr_2RuO_4 , layering schemes, and infinite layer phases.

Chapter 9 on Nonclassical Superconductors describes superconducting materials which do not fit the categories of Chap. 3. It discusses the properties of the relatively recently discovered superconductor magnesium diboride, MgB_2 , as well as borocarbides, boronitrides, perovskites such as MgCNi_3 , charge transfer organics, heavy electron systems, and Buckminsterfullerenes. The chapter ends with a discussion of the symmetry of the order parameter, and a section that treats magnetic superconductors and the coexistence of superconductivity and magnetism. The coverage of the Hubbard Model and Band Structure in Chap. 10 is significantly shorter than it was in the first edition. Chapter 11, Type I Superconductors and the Intermediate State, includes some recent developments in addition to what was covered in the first edition. Chapter 12 describes the nature and properties of Type II Superconductors, and is similar to its counterpart in the first edition. Chapter 13, Irreversible Properties, discusses critical states and the Bean model, the treatment of the latter being much shorter than it was in the first edition. In addition there are sections on current-magnetic moment conversion formulae, and susceptibility measurements of a perfect superconductor.

Chapter 14, Magnetic Penetration Depth, written by Ruslau is entirely new. It covers the topics of isotropic London electrodynamics, the superconductivity gap and Fermi surfaces, the semiclassical model for superfluid density, mixed gaps, s- and d-wave pairing, the effect of disorder on the penetration depth, surface Andreev bound states, nonlocal electrodynamics of

nodal superconductors, the nonlinear Meissner Effect, the Campbell penetration depth, and proximity effect identification. Chapter 15, Energy Gap and Tunneling, includes a new section on tunneling in unconventional superconductors. Finally Chapters 16 and 17 discuss, respectively, transport properties and spectroscopic properties of superconductors, and are similar in content to their counterparts in the first edition. Recent data on superconducting materials have been added to the tables that appeared in various chapters of the first edition, and there are some new tables of data. References to the literature have been somewhat updated.

Two of us (Horacio and I) are now octogenarians, but we continue to work. Over the decades Horacio has been a great friend and collaborator. It is no longer "publish or perish" but "stay active or perish." We intend to remain active, *deo volente*.

Professor Prozorov would like to acknowledge partial support of NSF grants numbered DMR-06-03841 and DMR-05-53285, and also the Alfred P. Sloan Foundation. He wishes to thank his wife Tanya for her support, and for pushing him to finish his chapters. He also affirms that: "In my short time with the USC Department of Physics, one of the best things that happened was to get to know Charles Poole Jr., Horacio Farach, Rick Creswick, and Frank Avignone III whose enthusiasm was contagious, and I will always cherish the memory of our discussions."

Charles P. Poole, Jr.
June 2007

Contents

Preface to the First Edition ...	xvii
Preface to the Second Edition .	xxi

XIII.	Electromagnetic Fields	14
XIV.	Boundary Conditions	15
XV.	Magnetic Susceptibility	16
XVI.	Hall Effect.....	18
	Further Reading	20
	Problems	20

1 *Properties of the Normal State*

I.	Introduction	1
II.	Conduction Electron Transport	1
III.	Chemical Potential and Screening	4
IV.	Electrical Conductivity	5
V.	Frequency Dependent Electrical Conductivity	6
VI.	Electron-Phonon Interaction	7
VII.	Resistivity	7
VIII.	Thermal Conductivity	8
IX.	Fermi Surface	8
X.	Energy Gap and Effective Mass	10
XI.	Electronic Specific Heat	11
XII.	Phonon Specific Heat	12

2 *Phenomenon of Superconductivity*

I.	Introduction	23
II.	Brief History	24
III.	Resistivity	27
	A. Resistivity above T_c	27
	B. Resistivity Anisotropy	28
	C. Anisotropy Determination	31
	D. Sheet Resistance of Films: Resistance Quantum	32
IV.	Zero Resistance	34
	A. Resistivity Drop at T_c	34
	B. Persistent Currents below T_c	35

V.	Transition Temperature	36
VI.	Perfect Diamagnetism	40
VII.	Magnetic Fields Inside a Superconductor	43
VIII.	Shielding Current	44
IX.	Hole in Superconductor	45
X.	Perfect Conductivity	48
XI.	Transport Current	49
XII.	Critical Field and Current	52
XIII.	Temperature Dependences	52
XIV.	Two Fluid Model	54
XV.	Critical Magnetic Field Slope	55
XVI.	Critical Surface	55
	Further Reading	58
	Problems	58

III.	Discontinuity at T_C	89
IV.	Specific Heat below T_C	90
V.	Density of States and Debye Temperature	90
VI.	Thermodynamic Variables	91
VII.	Thermodynamics of a Normal Conductor	92
VIII.	Thermodynamics of a Superconductor	95
IX.	Superconductor in Zero Field	97
X.	Superconductor in a Magnetic Field	98
XI.	Normalized Thermodynamic Equations	103
XII.	Specific Heat in a Magnetic Field	105
XIII.	Further Discussion of the Specific Heat	107
XIV.	Order of the Transition	109
XV.	Thermodynamic Conventions	109
XVI.	Concluding Remarks	110
	Problems	110

3 *Classical Superconductors*

I.	Introduction	61
II.	Elements	61
III.	Physical Properties of Superconducting Elements	64
IV.	Compounds	67
V.	Alloys	71
VI.	Miedema's Empirical Rules	72
VII.	Compounds with the NaCl Structure	75
VIII.	Type A15 Compounds	76
IX.	Laves Phases	78
X.	Chevrel Phases	80
XI.	Chalcogenides and Oxides	82
	Problems	82

4 *Thermodynamic Properties*

I.	Introduction	83
II.	Specific Heat above T_C	84

5 *Magnetic Properties*

I.	Introduction	113
II.	Susceptibility	114
III.	Magnetization and Magnetic Moment	114
IV.	Magnetization Hysteresis	116
V.	Zero Field Cooling and Field Cooling	117
VI.	Granular Samples and Porosity	120
VII.	Magnetization Anisotropy	121
VIII.	Measurement Techniques	122
IX.	Comparison of Susceptibility and Resistivity Results	124
X.	Ellipsoids in Magnetic Fields	124
XI.	Demagnetization Factors	125
XII.	Measured Susceptibilities	127

XIII. Sphere in a Magnetic Field 128

XIV. Cylinder in a Magnetic Field 129

XV. ac Susceptibility 131

XVI. Temperature-Dependent Magnetization 134

 A. Pauli Paramagnetism 134

 B. Paramagnetism 134

 C. Antiferromagnetism 136

XVII. Pauli Limit and Upper Critical Field 137

XVIII. Ideal Type II Superconductor 139

XIX. Magnets 141

 Problems 142

6 **Ginzburg–Landau Theory**

I. Introduction 143

II. Order Parameter 144

III. Ginzburg–Landau Equations 145

IV. Zero-Field Case Deep Inside Superconductor 146

V. Zero-Field Case near Superconductor Boundary 148

VI. Fluxoid Quantization 149

VII. Penetration Depth 150

VIII. Critical Current Density 154

IX. London Equations 155

X. Exponential Penetration 155

XI. Normalized Ginzburg–Landau Equations 160

XII. Type I and Type II Superconductivity 161

XIII. Upper Critical Field B_{C2} 162

XIV. Structure of a Vortex 164

 A. Differential Equations 164

 B. Solutions for Short Distances 165

 C. Solution for Large Distances 166

Further Reading 168

Problems 169

7 **BCS Theory**

I. Introduction 171

II. Cooper Pairs 172

III. The BCS Order Parameter 174

IV. The BCS Hamiltonian 176

V. The Bogoliubov Transformation 177

VI. The Self-Consistent Gap Equation 178

 A. Solution of the Gap Equation Near T_c 179

 B. Solution at $T = 0$ 179

 C. Nodes of the Order Parameter 179

 D. Single Band Singlet Pairing 180

 E. S-Wave Pairing 180

 F. Zero-Temperature Gap 182

 G. D-Wave Order Parameter 184

 H. Multi-Band Singlet Pairing 185

VII. Response of a Superconductor to a Magnetic Field 188

 Appendix A. Derivation of the Gap Equation Near T_c 190

 Further Reading 192

8 **Cuprate Crystallographic Structures**

I. Introduction 195

II. Perovskites 196

	A. Cubic Form	196
	B. Tetragonal Form	198
	C. Orthorhombic Form	198
	D. Planar Representation	199
III.	Perovskite-Type Superconducting Structures	200
IV.	Aligned $\text{YBa}_2\text{Cu}_3\text{O}_7$	202
	A. Copper Oxide Planes	204
	B. Copper Coordination	204
	C. Stacking Rules	205
	D. Crystallographic Phases	205
	E. Charge Distribution	206
	F. YBaCuO Formula	207
	G. $\text{YBa}_2\text{Cu}_4\text{O}_8$ and $\text{Y}_2\text{Ba}_4\text{Cu}_7\text{O}_{15}$	207
V.	Aligned HgBaCaCuO	208
VI.	Body Centering	210
VII.	Body-Centered La_2CuO_4 , Nd_2CuO_4 and Sr_2RuO_4	211
	A. Unit Cell of La_2CuO_4 Compound (T Phase)	211
	B. Layering Scheme	212
	C. Charge Distribution	212
	D. Superconducting Structures	213
	E. Nd_2CuO_4 Compound (T' Phase)	213
	F. $\text{La}_{2-x-y}\text{R}_x\text{Sr}_y\text{CuO}_4$ Compounds (T* Phase)	216
	G. Sr_2RuO_4 Compound (T Phase)	217
VIII.	Body-Centered BiSrCaCuO and TlBaCaCuO	218
	A. Layering Scheme	218
	B. Nomenclature	219
	C. Bi-Sr Compounds	220
	D. Tl-Ba Compounds	220
	E. Modulated Structures	221
	F. Aligned Tl-Ba Compounds	222
	G. Lead Doping	222
IX.	Symmetries	222
X.	Layered Structure of the Cuprates	223
XI.	Infinite-Layer Phases	225
XII.	Conclusions	227

Further Reading	227
Problems	228

9 *Unconventional Superconductors*

I.	Introduction	231
II.	Heavy Electron Systems	231
III.	Magnesium Diboride	236
	A. Structure	236
	B. Physical Properties	237
	C. Anisotropies	237
	D. Fermi Surfaces	239
	E. Energy Gaps	241
IV.	Borocarbides and Boronitrides	243
	A. Crystal Structure	243
	B. Correlations of Superconducting Properties with Structure Parameters	244
	C. Density of States	245
	D. Thermodynamic and Electronic Properties	247
	E. Magnetic Interactions	249
	F. Magnetism of $\text{HoNi}_2\text{B}_2\text{C}$	254
V.	Perovskites	256
	A. Barium-Potassium-Bismuth Cubic Perovskite	256
	B. Magnesium-Carbon-Nickel Cubic Perovskite	257
	C. Barium-Lead-Bismuth Lower Symmetry Perovskite	258
VI.	Charge-Transfer Organics	259
VII.	Buckminsterfullerenes	260
VIII.	Symmetry of the Order Parameter in Unconventional Superconductors	262
	A. Symmetry of the Order Parameter in Cuprates	262

	a. Hole-doped high- T_c cuprates	262
	b. Electron-doped cuprates	263
B.	Organic Superconductors	264
C.	Influence of Bandstructure on Superconductivity	266
	a. MgB_2	266
	b. $NbSe_2$	267
	c. $CaAlSi$	268
D.	Some Other Superconductors	268
	a. Heavy-fermion superconductors	268
	b. Borocarbides	269
	c. Sr_2RuO_4	269
	d. $MgCNi_3$	270
IX.	Magnetic Superconductors	270
	A. Coexistence of superconductivity and magnetism	270
	B. Antiferromagnetic Superconductors	272
	C. Magnetic Cuprate Superconductor – $SmCeCuO$	272

10 *Hubbard Models and Band Structure*

I.	Introduction	275
II.	Electron Configurations	276
	A. Configurations and Orbitals	276
	B. Tight-Binding Approximation	277
III.	Hubbard Model	281
	A. Wannier Functions and Electron Operators	281
	B. One-State Hubbard Model	282
	C. Electron-Hole Symmetry	283

	D. Half-Filling and Antiferromagnetic Correlations	284
E.	t - J Model	285
F.	Resonant-Valence Bonds	286
G.	Spinons, Holons, Slave Bosons, Anyons, and Semions	287
H.	Three-State Hubbard Model	287
I.	Energy Bands	288
J.	Metal-Insulator Transition	289
IV.	Band Structure of $YBa_2Cu_3O_7$	290
	A. Energy Bands and Density of States	291
	B. Fermi Surface: Plane and Chain Bands	292
V.	Band Structure of Mercury Cuprates	293
VI.	Band Structures of Lanthanum, Bismuth, and Thallium Cuprates	299
	A. Orbital States	299
	B. Energy Bands and Density of States	299
VII.	Fermi Liquids	302
VIII.	Fermi Surface Nesting	303
IX.	Charge-Density Waves, Spin-Density Waves, and Spin Bags	303
X.	Mott-Insulator Transition	304
XI.	Discussion	305
	Further Reading	305
	Problems	305

11 *Type I Superconductivity and the Intermediate State*

I.	Introduction	307
II.	Intermediate State	308

III. Surface Fields and Intermediate-State Configurations308

IV. Type I Ellipsoid310

V. Susceptibility311

VI. Gibbs Free Energy for the Intermediate State313

VII. Boundary-Wall Energy and Domains315

VIII. Thin Film in Applied Field317

IX. Domains in Thin Films318

X. Current-Induced Intermediate State322

XI. Recent Developments in Type I Superconductivity326

 A. History and General Remarks326

 B. The Intermediate State329

 C. Magneto-Optics with In-Plane Magnetization – a Tool to Study Flux Patterns330

 D. AC Response in the Intermediate State of Type I Superconductors ...332

XII. Mixed State in Type II Superconductors333

 Problems334

12

Type II Superconductivity

I. Introduction337

II. Internal and Critical Fields338

 A. Magnetic Field Penetration338

 B. Ginzburg-Landau Parameter340

 C. Critical Fields342

III. Vortices345

 A. Magnetic Fields346

 B. High-Kappa Approximation347

 C. Average Internal Field and Vortex Separation349

 D. Vortices near Lower Critical Field350

 E. Vortices near Upper Critical Field352

 F. Contour Plots of Field and Current Density352

 G. Closed Vortices354

IV. Vortex Anisotropies355

 A. Critical Fields and Characteristic Lengths356

 B. Core Region and Current Flow357

 C. Critical Fields357

 D. High-Kappa Approximation361

 E. Pancake Vortices363

 F. Oblique Alignment.....363

V. Individual Vortex Motion364

 A. Vortex Repulsion364

 B. Pinning367

 C. Equation of Motion368

 D. Onset of Motion.....369

 E. Magnus Force369

 F. Steady-State Motion370

 G. Intrinsic Pinning.....371

 H. Vortex Entanglement371

VI. Flux Motion371

 A. Flux Continuum371

 B. Entry and Exit372

 C. Two-Dimensional Fluid ...372

 D. Dimensionality.....373

 E. Solid and Glass Phases374

 F. Flux in Motion.....374

 G. Transport Current in a Magnetic Field.....375

 H. Dissipation376

 I. Magnetic Phase Diagram377

VII. Fluctuations378

 A. Thermal Fluctuations378

 B. Characteristic Length378

 C. Entanglement of Flux Lines379

 D. Irreversibility Line379

E. Kosterlitz-Thouless Transition	381
Problems	381

VII. Perfect Type-I Superconductor	405
VIII. Concluding Remarks	406
Problems	406

13 Irreversible Properties

I. Introduction	385
II. Critical States	385
III. Current-Field Relationships	386
A. Transport and Shielding Current	386
B. Maxwell Curl Equation and Pinning Force	387
C. Determination of Current-Field Relationships	388
IV. Critical-State Models	388
A. Requirements of a Critical-State Model	388
B. Model Characteristics	388
V. Bean Model	389
A. Low-Field Case	389
B. High-Field Case	390
C. Transport Current	392
D. Combining Screening and Transport Current	393
E. Pinning Strength	395
F. Current-Magnetic Moment Conversion Formulae	396
a. Elliptical cross-section	396
b. Rectangular cross-section	396
c. Triangular cross-section	396
d. General remarks	397
VI. Reversed Critical States and Hysteresis	397
A. Reversing Field	398
B. Magnetization	401
C. Hysteresis Loops	401
D. Magnetization Current	403

14 Magnetic Penetration Depth

I. Isotropic London Electrodynamics	409
II. Penetration Depth in Anisotropic Samples	411
III. Experimental Methods	413
IV. Absolute Value of the Penetration Depth	414
V. Penetration Depth and the Superconducting Gap	416
A. Semiclassical Model for Superfluid Density	416
a. Isotropic Fermi Surface	417
b. Anisotropic Fermi Surface, Isotropic gap function	418
B. Superconducting Gap	418
C. Mixed Gaps	419
D. Low-Temperatures	420
a. s-wave pairing	420
b. d-wave pairing	420
c. p-wave pairing	420
VI. Effect of Disorder and Impurities on the Penetration Depth	421
A. Non-Magnetic Impurities	421
B. Magnetic Impurities	422
VII. Surface Andreev Bound States	423
VIII. Nonlocal Electrodynamics of Nodal Superconductors	425
IX. Nonlinear Meissner Effect	426
X. AC Penetration Depth in the Mixed State (Small Amplitude Linear Response)	428

XI.	The Proximity Effect and its Identification by Using AC Penetration Depth Measurements	430
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15 *Energy Gap and Tunneling*

I.	Introduction	433
II.	Phenomenon of Tunneling	433
	A. Conduction-Electron Energies	434
	B. Types of Tunneling	435
III.	Energy Level Schemes	435
	A. Semiconductor Representation	435
	B. Boson Condensation Representation	436
IV.	Tunneling Processes	436
	A. Conditions for Tunneling	436
	B. Normal Metal Tunneling	438
	C. Normal Metal – Superconductor Tunneling	438
	D. Superconductor – Superconductor Tunneling	439
V.	Quantitative Treatment of Tunneling	440
	A. Distribution Function	440
	B. Density of States	442
	C. Tunneling Current	442
	D. N–I–N Tunneling Current	444
	E. N–I–S Tunneling Current	444
	F. S–I–S Tunneling Current	445
	G. Nonequilibrium Quasiparticle Tunneling	447

H.	Tunneling in unconventional superconductors	449
	a. Introduction	449
	b. Zero-Bias Conductance Peak	450
	c. c-Axis Tunneling	451
VI.	Tunneling Measurements	451
	A. Weak Links	452
	B. Experimental Arrangements for Measuring Tunneling	452
	C. N–I–S Tunneling Measurements	454
	D. S–I–S Tunneling Measurements	454
	E. Energy Gap	455
	F. Proximity Effect	457
	G. Even–Odd Electron Effect	459
VII.	Josephson Effect	459
	A. Cooper Pair Tunneling	460
	B. dc Josephson Effect	460
	C. ac Josephson Effect	462
	D. Driven Junctions	463
	E. Inverse ac Josephson Effect	466
	F. Analogues of Josephson Junctions	469
VIII.	Magnetic Field and Size Effects	472
	A. Short Josephson Junction	472
	B. Long Josephson Junction	476
	C. Josephson Penetration Depth	478
	D. Two-Junction Loop	479
	E. Self-Induced Flux	480
	F. Junction Loop of Finite Size	482
	G. Ultrasmall Josephson Junction	482
	H. Arrays and Models for Granular Superconductors	485
	I. Superconducting Quantum Interference Device	485
	Problems	486