Superconductivity

Second Edition

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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, O. Lopez, M. B. Maple, A. P. Mills, Jr., S. Misra, F. J. Owens, M. Pencarinha, A. Petrile, W. E. Pickett, S. J. Poon, A. W. Sleight, O. F. Schuette, C. Sisson, David B. Tanner, H. Testardi, C. Uher, T. Usher, and S. A. Wolf. We also thank the graduate students of the superconductivity classes for their input, which improved the book's presentation. We appreciate the assistance given by the University of South Carolina (USC) Physics Department; our chairman, F. T. Avignone; the secretaries, Lynn Waters and Cheryl Stocker; and especially by Gloria Phillips, who is thanked for her typing and multiple emendations of the BCS chapter and the long list of references. Eddie Josie of the USC Instructional Services Department ably prepared many of the figures.

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, layerng 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

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