Handbook of High-Temperature Superconductivity
J. Robert Schrieffer
Handbook of High-Temperature Superconductivity

Theory and Experiment

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Editor

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Front Cover Image: Angle resolved phase sensitive determination of the in-plane superconducting gap in YBa$_2$Cu$_3$O$_{7-\delta}$. Combined SQUID microscope images of a series of 2-junction YBCO/Nb rings, with one junction angle fixed at 167.5 degrees relative to the majority twin a-axis direction of the YBCO, and the other junction angle varying in 5 degree intervals. The images, each of a square area 150 microns on a side and taken after the rings were cooled in zero field, are arranged in a polar plot. They show that the rings were either in the $n = 0$ or $n = 1/2$ flux quantum states. The transitions from the $n = 0$ to $n = 1/2$ flux quantum states occur at angles slightly different from $(2m + 1) 45$ degrees, $m$ an integer, because of a small s-wave component in addition to the predominant d-wave component to the in-plane superconducting gap in this high temperature cuprate perovskite superconductor. Image appears courtesy of J.R. Kirtley. Data were originally published in J.R. Kirtley, C.C. Tsuei, Ariando, C.J.M. Verwijs, S. Harkema, and H. Hilgenkamp, *Nature Physics* 2, 190 (2006).
Low temperature superconductivity was discovered by H. Kammerlingh-Onnes in 1911, at the University of Leiden. He was awarded the 1913 Nobel Prize in Physics, partly for this discovery, i.e., that at low enough temperatures, certain metals become perfect conductors of electricity. In 1933, Meissner and Ossenfeld discovered that a superconductor (SC) is also a perfect diamagnet, i.e., that the magnetic field vanishes in the bulk of a SC. In 1957, J. Bardeen, L.N. Cooper and J.R. Schrieffer (BCS) advanced the pairing theory of superconductivity which gives a quantitative account of many properties of low temperature SCs, and makes a number of predictions of novel phenomena which have been confirmed in a large variety of experiments. BCS were awarded the Nobel Prize in 1972 for the pairing theory.

Through intensive experimental research, the maximum $T_c$ was raised to $21^\circ K$ in an alloy NbGeAl. In 1986, G. Bednorz and K.A. Müller discovered “high temperature superconductivity” in the layered cuprate La$_{2-x}$Ba$_x$CuO$_4$ at $30^\circ K$, for which they were awarded the 1987 Nobel Prize in Physics. $T_c \sim 93^\circ K$ was discovered by P. Chu in the ternary compound of YBaCuO soon there after.

The maximum $T_c$ found to date is in a mercury based cuprate, which has $T_c = 133^\circ K$ at ambient pressure ($\sim 160^\circ K$ under pressure). Through concerted experimental and theoretical efforts, strong evidence has been adduced that the attractive electron pairing interaction in HTS cuprates is magnetic in origin.

A lot has happened since 1986. The problem of high temperature superconductivity, and more generally that of metallic strongly correlated systems, remains a major open problem in condensed matter physics, and it is the focus of intensive research. As the reader will see from the many chapters to follow, the authors are meeting these challenges. There have been incredible advances in materials, in sample quality and in single crystals, in hole and electron doping, and in the development of sister compounds with lower $T_c$’s that allow access to the normal state with available high magnetic fields. Probes for structure and dynamics such as scanning-tunneling probe spectroscopy, angle resolved photoemission, and neutron scattering have greatly advanced. High precision resonance and thermodynamic methods, low energy optical probes, and high pressures have likewise been brought to bear on the problems. The authors’ statement in the introductory section of Chapter 3 articulates a broad central theme of this treatise: “This revolution...” (in this case in reference to ARPES) “...and its scientific impact result from dramatic advances in four essential components: instrumental resolution and efficiency, sample manipulation, high quality samples and well-matched scientific issues.” On the theoretical front, the deceptively simple problem of a “doped Mott Insulator,” when applied to the cuprates, turns out to be only the starting point of what rapidly becomes a huge
and complex problem. To go beyond BCS, new phenomena need new theories: not only high $T_c$, but pairing, interactions, symmetry, pseudogaps, inhomogeneity and stripes, the proximity of magnetism and superconductivity, sensitivity to impurities, and non-Fermi liquid normal state properties must all be addressed.

We have selected the title “Handbook of High Temperature Superconductivity” to describe this treatise since many of the articles go into considerable depth in both experimental and theoretical methodologies.

The treatise begins in Chapter 1 with Müller’s review of hole-doped cuprates where he argues that the dynamical coexistence of bipolarons and fermions are essential features of both the normal and superconducting states. In Chapter 2 Kirtley and Tafuri briefly review the information obtained from tunneling into conventional superconductors and describe why the situation is more complicated and interesting in the cuprates. They then describe experimental methods for making tunneling contacts, the evidence for and implications of d-wave symmetry, the superconducting gap, the pseudogap, quasiparticle interactions, and other aspects of high temperature superconductors. In Chapter 3, the technique of angle resolved photoemission spectroscopy (ARPES) is described in some detail by Zhou, Cuk, Devereaux, Nagaosa, and Shen, and the impact of ARPES on our understanding of the electronic structure, such as Fermi surface, gap anisotropy and d-wave character, and pseudogap behavior is reviewed. Of special importance is their presentation of the latest results on the electron-phonon interaction in the cuprates. In Chapter 4 Bonn and Hardy review microwave studies of high temperature superconductors, where considerable background and detail is given to the methods employed. Results on the penetration depth leading to the “superfluid stiffness” parameter, the surface resistance that yields the microwave conductivity, and a discussion of the role of superconducting fluctuations are presented. In Chapter 5 Slichter reviews the area of magnetic resonance (predominantly NMR, but also briefly ESR) in high temperature superconductors. The spin lattice relaxation time, transverse relaxation time, and the Knight shift are discussed for both YBCO, LSCO in terms of information gained on the electron spin susceptibility, and on the pairing state. In Sr doped and undoped LCO, analysis of line widths and shapes yield information about local (spatial) spin modulations, and spin glass behavior.

Neutron scattering in the cuprates is presented in Chapter 6 by Tranquada in the context of magnetic excitations and antiferromagnetic correlations for both hole and (briefly) electron doped systems. The evolution of the spin dynamics with doping, from the antiferromagnetism of the parent insulators through the universal magnetic excitation spectrum found near optimal doping, is discussed. The nature of stripe order and its possible relevance are also covered. In the summary, the nature of magnetic excitations revealed by neutron scattering is discussed in the context of current theoretical work. In Chapter 7 Orenstein treats optical conductivity and spatial inhomogeneity in the cuprates, first in an overview of the field. An additional spectral feature seen in the so-called “terahertz gap” in many cuprates is discussed, and is assigned to the spatial variation of the superfluid density. It is shown that optical conductivity can provide critical information about inhomogeneity in the cuprates. In Chapter 8 Geballe and Koster consider the wide range of superconducting transition temperature ($T_c$) values in the cuprates and re-visit the notion that interactions are confined to the CuO$_2$ layers. They provide evidence that $T_c$ enhancements found in the cuprates that contain charge reservoir layers can be understood in terms of pairing interactions in the charge reservoir layers, and also propose linear quasiparticles to account for superconductivity in the one dimensional double chain cuprates. In Chapter 9, Fisher, Gordon, and Phillips review the thermodynamic properties of high temperature superconductors. More recent results (mostly specific heat) based on better samples and new interpretations are featured, and are reported for the energy gap, fluctuation
effects, vortices, flux-lattice melting, the pseudogap, stripes, and chemical substitutions. Some attention is also given to experimental methodology.

The various anomalies in the normal state transport properties of cuprates are reviewed by Hussey in Chapter 10. Experimental work on in-plane and inter-plane electrical transport, Hall effect and Kohler’s rule, thermal transport, and the Nernst-Ettinghausen effect, are reviewed for materials over a wide range of doping. Despite the wide-range of crystallographic structures in the different cuprate families, a remarkably generic picture emerges, suggesting the transport behavior is largely associated with a single CuO\(_4\) unit. Theoretical attempts at explaining this mysterious behavior are also summarized. A comprehensive review of high pressure effects on elemental, binary, and high \(T_c\) superconductors is given by Schilling in Chapter 11. Hydrostatic, non-hydrostatic, and uniaxial pressure effects are discussed. One conclusion is that pressure effects seem to point to the structure of the CuO\(_2\) planes as the most important parameter that determines \(T_c\), where “the closer the planes are to being square and flat, and the smaller their area A, the higher the value of \(T_c\)”. The result \(T_c \sim A^{-2}\) is considered to be one of the most important results that pressure has yet given us for high temperature superconductors. Future prospects for combining pressure with other simultaneous measurements to resolve other aspects of the high \(T_c\) problem are also discussed. In Chapter 12 Brooks reviews in parallel quasi-one and quasi-two dimensional organic superconductors, and their close relationship to the Mott Hubbard model. Both conventional and unconventional (p-wave and d-wave) superconducting properties are discussed, and similarities and differences between organic and cuprate and perovskite systems are described.

In the next three chapters theoretical aspects of high temperature superconductivity are treated. Scalapino, in Chapter 13, reviews numerical studies of the two-dimensional one-band Hubbard model which show that this model exhibits the basic phenomena seen in the cuprates. These show that, at half-filling, the ground state of the system is a Mott-Hubbard antiferromagnetic insulator. Then, upon doping the system away from half filling a pseudogap can appear and at low temperatures evidence for d-wave pairing and striped phases are found. The near degeneracy of these phases is also reminiscent of the behavior of the actual cuprate materials. This chapter concludes with a discussion of what numerical methods tell us about the momentum, frequency and spin structure of the pairing interaction in this model. In Chapter 14 Lee reviews previous theoretical work on high temperature superconductivity, and argues that the one-band Hubbard model in the strong coupling limit (\(t-t'\) model with \(t'\)) can capture the physics. To make further progress, the treatment involves the constraint of no-double occupancy and thereby gauge theories. The predicted pseudogap and vortex structure lead to a description of the phase diagram and the onset of \(T_c\). A number of other fundamental theoretical issues including RVB, spin liquids, fractionalization and emergent phenomena are also discussed. Kivelson and Fradkin, in Chapter 15, consider the role of inhomogeneity for the mechanism of high temperature superconductivity. In reviewing the field, the authors observe that superconductivity is common, but high temperature superconductivity is rare and confined to a small subset of materials. They analyze a class of model inhomogeneous doped Mott insulators, which are shown conclusively to exhibit high temperature superconductivity. Generalizing from this, they propose that an optimal degree (and form) of inhomogeneity (probably self-organized) is an essential feature of the mechanism. The relation of this notion to the occurrence of competing orders is clarified. The chapter contains an interesting appendix on “what defines high temperature superconductivity?”.

We depart from the cuprates in Chapter 16 where Pugh, Saxena and Lonzarich consider novel quantum states and unconventional forms of superconductivity which may occur on the border of long range magnetic order in heavy-fermion and related itinerant electron magnetic
materials. The chapter begins by considering the simplest deviations from the standard low temperature theory of metals that are observed on the border of long-range ferromagnetic order in metals where no superconductivity arises. It then describes cases on the border of antiferromagnetism where superconducting instabilities are prevalent. The effective dimensionality and proximity of density instabilities in some heavy-fermion superconductors are considered in light of Cooper pair formation. The case of superconductivity on the border of ferromagnetism is also described. Open questions to our current understanding are highlighted and possible future advances are discussed. Some of the materials described in the chapter have some similarities with high temperature superconductors and these are considered. An important aspect of this chapter is the description of the next generation of high pressure and low temperature instrumentation to further advance research in the important area of magnetic metals, quantum phase transitions and superconductivity.

We think you will find this treatise essential to obtain a global view of high temperature superconductivity, including the experimental and theoretical methods involved, the materials, the relationships with heavy-fermion and organic systems, and the many formidable remaining problems and challenges.

J.R. Schrieffer
J.S. Brooks
Acknowledgments

The contributors would like to acknowledge that the origin of this treatise arose from the insight, enthusiasm and persuasive influence of J.R. Schrieffer. We have all greatly benefited from his kind and personal manner, and his fundamental advances in the field of condensed matter physics.
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