

Preface

The discovery of high-temperature superconductivity (HTS) by Bednorz and Müller [1] in 1986 brought a flurry of investigations of the mystery of high- T_c cuprates. About 20 years later we have the first handbook [2] giving a global view of this phenomenon, with more than 2,500 references. Large number of books have been published on this subject and superconductivity became an integral part of university physics education [3]. The present status of our knowledge on high- T_c materials is based on more than 100,000 scientific articles, Fig. 0.1. Given this enormous activity, the question poses itself as to which principles of high- T_c physics can be explained in the volume of an introductory monograph.

This book starts at the level of standard courses on quantum mechanics and statistical physics and finishes with discussion of the perspectives for

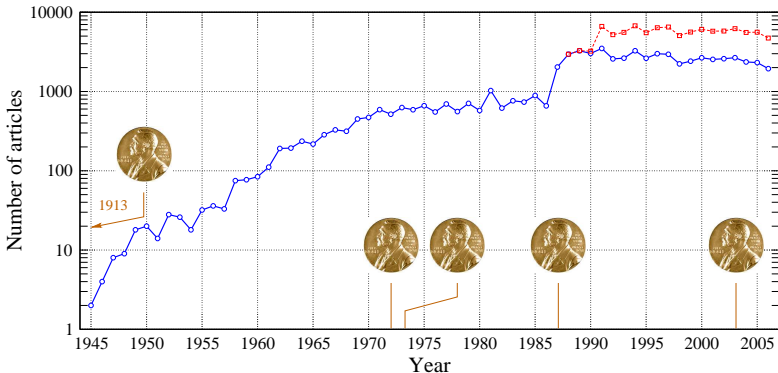


Fig. 0.1 Number of articles published in the period 1945–2006 containing ‘superconduct*’ in the title (○), or any of the title, abstract or the list of keywords (□) according to Science Citation Index Expanded (www.isiknowledge.com).

further understanding of HTS theory. The selection of topics to be covered was made on the basis of the aesthetic criterion for simplicity. We advocate the idea that the pairing mechanism is common for all cuprates and can be unraveled for levels of doping where the material properties are least perturbed by accessories such as stripes, pseudogap, space inhomogeneities, etc. This is the case of the overdoped cuprates that are the subject of the present book. For doping slightly above the optimal, the electron spectrum is well described by self-consistent band theory, outlined in the opening Chapter 1. For perovskites, the linear combination of atomic orbitals (LCAO) method is an adequate fundament to account for interaction effects.

More than 20 years of development of HTS physics have produced overwhelming hints that the electron exchange mediates the pairing. Among all exchange processes in condensed matter, the intraatomic s - d exchange is the most intensive one. In Chapter 2 we demonstrate how the s - d exchange can be incorporated into the standard Bardeen–Cooper–Schrieffer (BCS) scheme and derive the d -wave superconducting gap $\Delta_{\mathbf{p}}(T)$. The rationale of the correlation between the critical temperature T_c and the $Cu4s$ energy level is the crucial test for the theory of HTS. The specific heat $C(T)$ and penetration depth $\lambda(T)$ functionals are expressed through the superconducting gap $\Delta_{\mathbf{p}}(T)$ in Chapter 3. It is shown that the analytical expressions for $C(T)$ and $\lambda(T)$ can be employed to fit and analyze experimental data for practically all superconductors with anisotropic gap. These formulas represent a generalization of the original isotropic-gap BCS results. Chapter 3 further offers a methodological derivation of parameters of the Ginzburg–Landau theory: penetration depth, coherence length, effective mass, and the heat capacity jump. We should emphasize that all results are derived from a microscopic Hamiltonian within the standard statistical physics methods. Special attention is also paid to the methodological derivation of the order parameter equation for anisotropic-gap superconductors. Chapter 4 is dedicated to some electrodynamic properties of high-temperature superconductors, such as the plasmons, predicted by one of the authors of this book [4, 5], and the electric-field effects giving access to the Cooper pair effective mass [6].

Due to the small coherence length, the fluctuation phenomena in high-temperature superconductors are much more pronounced compared to conventional superconductors. The investigation of these phenomena takes significant portion of HTS physics. Thus, Chapter 5 has a review character, focusing exclusively on the self-consistent Gaussian fluctuations that have

broadest application. Using the ζ -function method for ultra-violet regularization we derive general expressions for the fluctuation heat capacity and magnetization. Discussion is also provided on how systematic investigations of the fluctuation phenomena can lead to reliable determination of fundamental material parameters of high-temperature superconductors. In Chapter 6, the kinetic equation for fluctuation Cooper pairs is derived within the time-dependent Ginzburg–Landau theory and applied to obtain expressions for the fluctuation conductivity. This standard kinetic approach is then employed in Chapter 7 to investigate fluctuation superconductivity in strong electric fields.

Another classical statistical problem — the electric field fluctuations between the CuO_2 layers — is considered in Chapter 8 and shown to explain the linear temperature dependence of the resistivity. Until recently, this dependence was interpreted as evidence for anomalous and unconventional behavior in the normal phase of high-temperature superconductors.

The final Chapter 9 treats the important technical problem of whether high-temperature superconductors can be used as active media for generation of electromagnetic waves in the THz range. So far this electromagnetic range is weakly used and known as a “THz gap” — a gap between the worlds of the transistor and the laser. Besides the plasmons that have already produced promising results [7, 8], in this Chapter it is shown that the negative differential conductivity presents a new, yet unexplored opportunity for generation of THz oscillations.

If one searches Google for “mystery” and “high temperature superconductivity”, the webpage hits are tens of thousands. The problem of HTS has been a true intellectual challenge for contemporary physics. What we believe has been achieved in the offered book could be phrased as “completing ‘the Bardeen program’” — the mystery is revealed: we have the microscopic theory of HTS, we understand the observable properties and can predict technical applications.

Essential parts of each book chapter have been taught to undergraduate and graduate students in courses on superconductivity, statistical physics, solid state physics, and condensed-matter field theory. Starting from the level of such courses, students can reach the complexity of contemporary unsolved problems in HTS, e.g., the anisotropy of the scattering rate in the normal phase, etc. Bridging the gap between the textbook and monograph levels was the driving force for writing of this book.

Last but not least, the book is a testimonial in itself to the persistence and fruitfulness of a professor (T.M.)–student (E.P.) collaboration—one that has been almost entirely informal and dating back to the early 1990's.

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