Introduction to the physics of high-temperature superconductors

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High Temperature Superconductivity (Ed.) **J. W. Lynn**, Springer-Verlag, New York, 1990, 403p. (Graduate Text in Contemporary Physics)

In the course of several years of studying high-temperature superconductors (HTSC) very many experimental and theoretical articles have been published. And although the solution of the majority of problems (including the basic ones regarding the mechanism of superconductivity in the HTSC) has not yet been attained, there is no question that there is a necessity for the appearance of detailed reviews and monographs describing the properties known now of particular compounds and modern theoretical approaches to the description of these properties. The book "High Temperature Superconductivity" is a collective monograph of this type. In its nature it is basically an introduction to the subject. The book is addressed to a wide circle of readers including graduate students and students of the upper years who are becoming acquainted with the physics of high-temperature superconductors.

The first three of the ten chapters of the book are of an introductory nature. The first chapter (J. W. Lynn) gives a brief introduction to the basic properties of superconductors (absence of a resistance to a direct current, ideal diamagnetism) and also to the basic initial assumptions and results of the BCS theory in a very simple presentation. The concept of superconductors of the second kind is introduced, and mention is made of the existence of magnetic superconductors with heavy fermions. The second chapter (D. Belitz) is devoted to the main ideas of theory of superconductors of the second kind. The Ginzburg-Landau equations are presented as well as the formulas for H_{c2}, H_{c3} and the expression for H_{c1}. The well-known microscopic approach to finding the transition temperature and the upper critical field is presented based on finding the pole of the pair Green's function corresponding to the instability of the ground state of the normal Fermi-liquid with respect to the formation of Cooper pairs. A brief discussion is given of the effect of impurities on the transition temperature (Anderson's theorem) and the theory of dirty superconductors. At the end of the chapter the question is raised of the region of strong disorder, when the usual theory of dirty superconductors becomes inapplicable and the effects of the Al'tshuler-Aronov type become essential.

In the third chapter (R. A. Ferrell) the Josephson effect is discussed. At first the phenomenological description is briefly presented of the steady-state and the time-dependent Josephson effects, and the influence is discussed of the intrinsic field of the Josephson current. Then the microscopic approach is used for the description of the Josephson effect based on using the tunnelling Hamiltonian in the BCS theory. A discussion is given of the energy of the Josephson coupling and the quantum fluctuation effects arising from the noncommutativity of the operators for the phase and the number of the Cooper pairs.

Starting with the fourth chapter the presentation is devoted primarily to specific properties of high-temperature superconductors. In the fourth chapter (A. Santoro) a description is given of the symmetry and structure of crystals of the main representatives of the HTSC. The advantages are explained of the method of neutron diffraction compared with the method of x-ray scattering for determining the crystal structure. The Ritweld method is described which enables one to carry out very effective theoretical analysis of experimental data on neutron diffraction in polycrystals and powders. At first the simplest structure is presented of perovskite $CaTiO_3$ (or more accurately, of the idealized perovskite of the cubic group $Pm3m$)—a representative of a large number of compounds with the general formula ABX_3. The octahedral surrounding of atoms of type A is shown. Then the structure is examined of the crystals of $BaPb_{1-x}Bi_xO_3$, as a function of x. In this compound the critical temperature has a maximum $T_c \approx 13$ K at $x \approx 0.25$, and for $x > 0.35$ this substance is a semiconductor at low temperatures. A discussion is given of the valency states of ions in the crystal. This set of questions is examined in particular detail further for $La_{2-x}M_xCuO_{4-y}$ ($M = Ba$, Sr) and $Ba_2MCu_3O_\delta$ ($M = Y$, Gd, Eu etc.), and also for $Ba_{2-x}La_{1-x}Cu_3O_\delta$ and $Bi_2CaSr_2Cu_2O_\delta$.

In the fifth chapter entitled "Electron structure, lattice dynamics and magnetic interactions" (Ching-ping S. Wang) the principal attention is devoted to the results of band calculations of the properties of the normal phase of the compounds $La_{2-x}(Ba, Sr)_xCuO_4$, $YBa_2Cu_3O_{7-x}$ and also of bismuth and thallium compounds. On the basis of the available calculations of the energy bands a discussion is given of the effect of doping with Sr or Ba atoms, and approximate nesting of the Fermi-surface, the effect of oxygen vacancies and the transition from the tetragonal phase into the orthorhombic one in $La_{2-x}(Ba, Sr)_xCuO_4$. Then a corresponding discussion is given for the other compounds indicated above. The dependence of the critical temperature on the number of $Cu - O_2$ layers is examined in bismuth and thallium superconductors, and the role of metallic nonconducting layers in the interstices between the $Cu - O_2$ layers. Separately (although only briefly) a discussion is given of the electron-phonon interaction, the Hall coefficient, plasmon frequencies, the band structure of antiferromagnetic Sc_2CuO_4 and La_2CuO_4, photoemission spectra, and magnetic interactions.

In the sixth chapter (R. N. Shelton) the technique of synthesizing and the main properties of high-temperature superconductors in a magnetic field (the Meissner effect, the upper and lower critical fields, the competition of magnetic and superconducting ordering) are examined. Also results are given of resistive measurements for superconducting transitions and some information concerning the density of critical current. The HTSC belong to superconductors with a very high value of the Ginzburg-Landau parameter. Very

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low values of the lower critical field ($H_{c1}(0) \lesssim 10$ mT) and exceptionally high values of the upper critical field ($H_{c2}(0) \gtrsim 50$ T) are characteristic for them.

In the seventh chapter (J. E. Crow, Nai-Phuan Ong) a detailed discussion is given of the temperature dependences of the Hall effect, of the anisotropic conductivity and of the heat capacity of the HTSC compounds.

The dependence of the Hall coefficient on the concentration of oxygen vacancies and on the temperature is examined. The dependence of the heat capacity on the temperature is described both for the normal and for the superconducting phases. The change in the heat capacity and the fluctuation contribution to the heat capacity in the case of the superconducting transition both for ordinary superconductors and for the HTSC are examined. Data are given concerning the isotopic effect in the HTSC. A detailed discussion is given of the question of the density of the phonon states in the HTSC and of the use of the Eliashberg equations for the description of the properties of HTSC.

The eighth chapter (J. W. Lynn) is devoted to the magnetic properties of HTSC. The magnetic properties of the compounds $La_{2-x}Sr_xCuO_{4-\delta}$ and $RBa_2Cu_3O_{6+x}$ (R is the rare earth atom) are determined, primarily, by the behavior of the copper ions which have an uncompensated spin. The magnetism of the rare-earth atoms here usually manifests itself only at very low temperatures. The phase diagram of $La_{2-x}Sr_xCuO_{4-\delta}$ is examined as a function of T and x on the assumption that the value of δ is such that for $x = 0$ the compound is an antiferromagnetic dielectric with the highest possible Néel temperature ($T_N \sim 300$ K). Regions are described corresponding to the tetragonal and orthorhombic crystals. For the orthorhombic phase the boundary of the metal—dielectric transition is schematically noted, the regions are indicated for the existence of the superconducting and antiferromagnetic phases, and also for a spin glass. A concrete antiferromagnetic ordering of spins of the copper atoms is described on the basis of data on magnetic scattering of neutrons, and also on muon precession.

For the phase diagram of $RBa_2Cu_3O_{6+x}$ in its dependence on T and x the presence in the tetragonal crystalline phase of two magnetic phase transitions is characteristic (in addition to the magnetic ordering of spins of rare-earth atoms at low temperatures).

At first ($T_{N1} \sim 400$–500 K) as the temperature is lowered a so-called high-temperature transition occurs in which only the $Cu - O_2$ layers take part in the antiferromagnetic ordering. In the layers containing chains of copper atoms the spins remain unordered. At lower temperatures ($T_{N2} \sim 40$–80 K the temperatures T_{N1} and T_{N2} depend, in particular, on the value of x) a new antiferromagnetic phase arises when all the copper-oxide layers (with chains of copper atoms and without chains) participate to an equal extent in the antiferromagnetic ordering. Further data are given (obtained from experiments on neutron scattering and Raman scattering) on the spectra of spin excitations, magnetic fluctuations in the paramagnetic and superconducting phases of HTSC. The role played by magnetic fluctuations in the formation of Cooper pairs and in the formation of unusual properties of HTSC is so far not clear. At the end of the eighth chapter a description is given of the low-temperature ordering of magnetic moments of rare-earth atoms in $RBa_2Cu_3O_{6+x}$.

In the ninth chapter (P. B. Allen) the fundamentals are presented of the theoretical description of the state of superconducting electrons. The formation of Cooper pairs, and the phenomenon of Bose-condensation are examined. A brief presentation is given of the BCS theory, and the Eliashberg theory is discussed. The possible role played in the formation of Cooper pairs by excitons, plasmons and spin fluctuations is examined. In conclusion a discussion is given of the theories of bipolar superconductivity and resonance valence coupling. In the last, tenth chapter (F. D. Bedard) a description is given of the main superconducting electron devices—cryotron, Josephson junctions, magnetometer based on squids, etc.

The book contains a large amount of data obtained in recent years for compounds of HTSC, and also extensive lists of references brought up to the beginning of 1989. The schematic, sketchy nature of the presentation of modern theoretical approaches to the description of the properties of the HTSC could have been included among the defects of the book, except that many of the theoretical discussions in the field under consideration are at the present time in an indefinite state. This book will without question be useful both for students and for graduate students becoming acquainted with the physics of HTSC, and also for specialists in the field of the physics of condensed media.

Translated by G. M. Volkoff