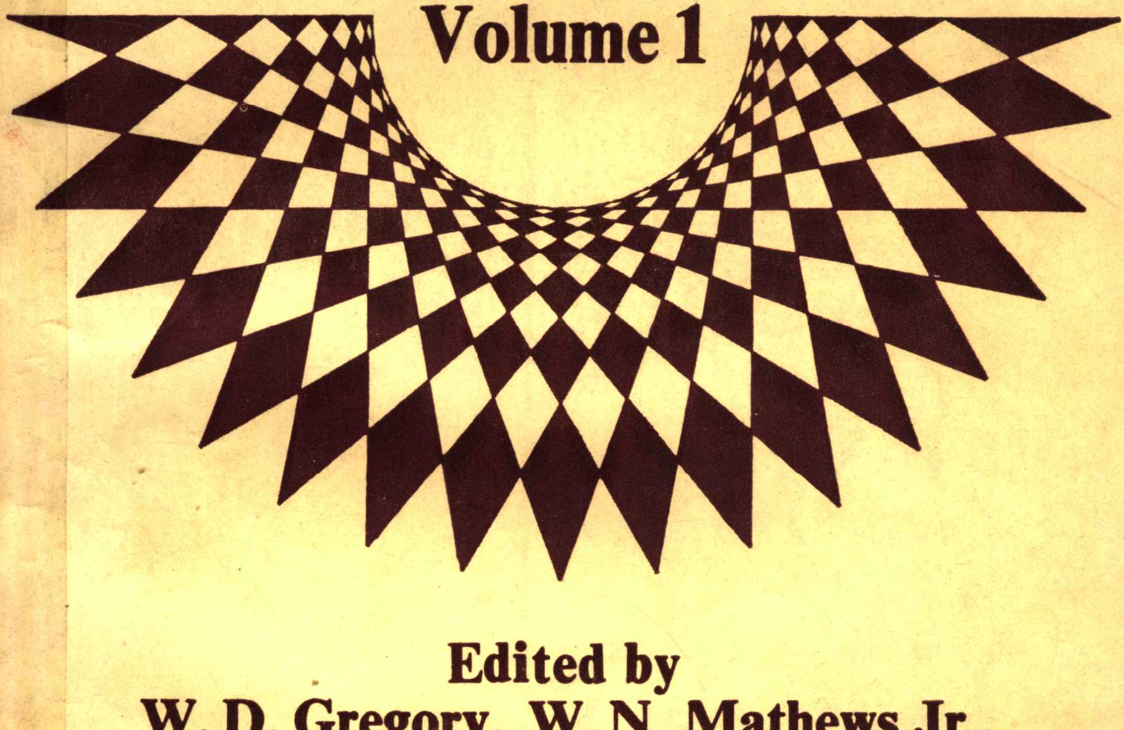
The Science and Technology of Superconductivity

Volume 1



Edited by
W. D. Gregory, W. N. Mathews Jr., and E. A. Edelsack

FOREWORD

Since the discovery of superconductivity in 1911 by H. Kamerlingh Onnes, of the order of half a billion dollars has been spent on research directed toward understanding and utilizing this phenomenon. This investment has gained us fundamental understanding in the form of a microscopic theory of superconductivity. Moreover, superconductivity has been transformed from a laboratory curiosity to the basis of some of the most sensitive and accurate measuring devices known, a whole host of other electronic devices, a soon-to-be new international standard for the volt, a prototype generation of superconducting motors and generators, and magnets producing the highest continuous magnetic fields yet produced by man. The promise of more efficient means of power transmission and mass transportation, a new generation of superconducting motors and generators, and computers and other electronic devices with superconducting circuit elements is all too clear. The realization of controlled thermonuclear fusion is perhaps totally dependent upon the creation of enormous magnetic fields over large volumes by some future generation of superconducting magnets. Nevertheless, whether or not the technological promise of superconductivity comes to full flower depends as much, and perhaps more, upon economic and political factors as it does upon new technological and scientific breakthroughs.

The basic science of superconductivity and its technological implications were the subject of a short course on "The Science and Technology of Superconductivity" held at Georgetown University, Washington, D. C., during 13-26 August 1971. This course brought together as speakers 25 experts in the field of superconductivity, including experimental and theoretical physicists, metallurgists, and electrical, mechanical, and cryogenic engineers, drawn from the academic, governmental, and industrial worlds. Together these speakers presented a comprehensive picture of the scientific and engineering fundamentals of superconductivity and its technological applications. The contents of this book are essentially the proceedings of that course.

The book is divided into six parts. Part I consists of the introductory lectures by the editors, F. Bloch's presentation of the basic theory of the Josephson effect, D. J. Scalapino's discussion of the consequences of charge conservation for time-dependent phenomena in superconductors, and Robert W. Stuart's review of the technology of refrigeration for superconducting devices. Part II is devoted to the consideration of superconducting materials. Part III deals with various technological applications of superconductivity. Part IV is a lightly edited transcript of the panel discussion on "The Scientific, Technological, and Economic Implications of Advances in Superconductivity" which was held during the course. Part V contains D. N. Langenberg's consideration of the technological implications of superconductivity for the next decade, and J. Bostock's brief summary of the course. Part VI contains four Appendices.

It is hoped that publication of this book will result in a greater awareness of the possibilities for exploiting the unique properties of superconductors, and that this increased awareness will in turn lead to an increase in the rate of advance of the science of superconductivity and its application.

The proceedings of the course are also available for distribution on video tape from Georgetown University.

We regret that H. T. Coffey's discussion of the application of superconducting technology for mass transportation and M. S. McAshan's review of the superconducting electron accelerator at Stanford were not available for publication.

We are grateful to the *Physical Review* for permission to reprint F. Bloch's paper on the theory of the Josephson effect.

We are grateful to the National Science Foundation and Georgetown University for sponsoring the course. We wish to thank Kenneth H. Fredgren and Constance Francis for their assistance in organizing and running the course, Ellen C. Cox, Madelyn Miller, Margaret Reinheimer, and Dawn E. Lechevet for their assistance in preparing the manuscript, and Mohamad Behravesh, Larry H. Capots, Nicholas C. Cirillo, Andrew J. Grekas, Richard Janik, Vishwanath Kalvey, Rassmidara Navani, Morris A. Olson, and Thomas B. Thompson for their assistance in running the course and preparing the subject and author indexes. A special note of thanks is due Dr. Jon N. Lechevet for carefully reading the manuscript and putting the indexes in their final form.

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Proceedings of a summer course held August 13-26, 1971, at Georgetown University, Washington, D. C.

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Part I

Introduction and Background

FUNDAMENTALS OF SUPERCONDUCTIVITY

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Washington, D. C.

This course on the science and technology of superconductivity comes at a most appropriate time in the over-all development of the field. The late 1950's and this past decade of the 1960's were in many ways the golden age of superconductivity. During that period of some fifteen years, superconductivity grew from little more than a laboratory curiosity being studied at a few low temperature centers, to a full fledged science and technology, being actively pursued by scores of industrial and academic laboratories throughout the world. The years between 1959 and 1962 saw a remarkable growth in the superconducting literature. Figure I shows that in 1959 superconducting publications represented some 6% of all low temperature publications. Three years later in 1962 it represented almost 17% of the total low temperature literature. This present decade is seeing a new and interesting development - the transformation of superconductivity research out of the laboratory into the realm of military and industrial practicality. Some applications are ripe for immediate practical development, others are still in the realm of basic and applied research. In their totality, they represent an impressive list of existing and potential applications. They include: magnets, motors, generators, magnetometers, infrared and millimeter wave detectors, gravity meters, gyroscopes, bolometers, nuclear particle detectors, voltmeters, ammeters, power transmission lines, dc transformers, computer elements, switches, passenger train suspension systems, accelerometers, antennas, amplifiers, microwave cavities, linear accelerators... This list is by no means complete. It continues to grow with the passage of time.

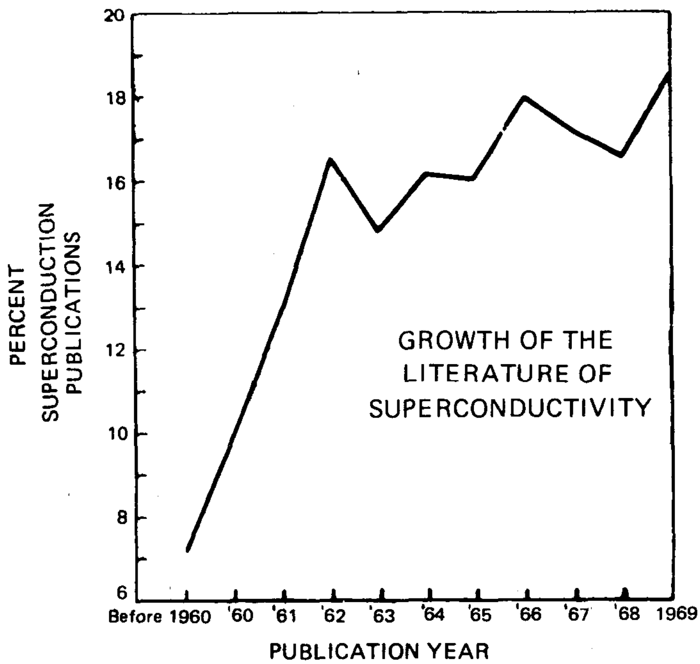


Figure I

This first lecture, presents a descriptive introduction to the fundamentals of superconductivity. It will be largely a panoramic survey of the major milestones in the development of the field. Figure II shows some of the major milestones we will be reviewing. This lecture is intended to provide a common stepping stone for appreciating the more advanced material of the subsequent speakers.

The story of superconductivity here on earth had its genesis in the stars, particularly in one star - our sun. Just a little over a hundred years ago in 1868, a British astronomer, using a newly invented instrument called a solar spectroscope observed unusual spectral lines from the hot incandescent gases of the chromosphere of the sun. These spectral lines could not be accounted for, as being produced by any known substance on earth, at that time. Thus the gas was given the name "helium" deriving from the word "helios," the Greek word for sun. Twenty-seven years later in 1895, Sir William Ramsay, a British chemist, discovered helium on the earth and in 1908, the Dutch physicist, Kammerling Onnes, succeeded in liquefying helium gas at a temperature of 4 K. The subsequent discovery of the phenomenon of superconductivity was a direct consequence of this liquefaction of helium. A temperature interval down to about 1 K had now been opened for research.

MILESTONES IN SUPERCONDUCTIVITY

1911	**Discovery, H. K. Onnes. Persistent currents, critical fields.**
1933	**Flux exclusion, Meissner and Ochsenfeld.**
1935	**London Phenomenological theory and F. London's Proposal that superconductivity is a quantum phenomenon.**
1950	**Isotope effect, $T_c \propto M^{-1/2}$, Reynolds et al.; Maxwell. Importance of electron—phonon interactions; Froholich.**
1953	**Experimental evidence for an energy gap. Goodman, others.**
1957	**Microscopic theory based on pairing. Bardeen, Cooper, and Schrieffer.**
1960	**Tunnel effect. Giaever.**
1961	**Flux quantization. Deaver, and Fairbank; Doll and Nabauer.**
1962	**Supercurrent flow through tunnel barrier. Josephson.**

Figure II

One of the first investigations which Onnes carried out in this newly available low temperature range was a study of the variation of the electrical resistance of metals as a function temperature. It had been known for many years that the resistance of metals fell when cooled below room temperature, but it was not known what limiting value the resistance would approach, if the temperature were reduced to very close to 0 K. Onnes, experimenting with platinum, found that, when cooled, its resistance fell to a low value which depended on the purity of the specimen. At that time the purest available metal was mercury and, in an attempt to discover the behavior of a very pure metal, Onnes measured the resistance of pure mercury. He found that at very low temperatures the resistance became immeasurably small, which was not surprising, but he soon discovered that the manner in which the resistance disappeared was completely unexpected. Instead of the resistance falling smoothly as the temperature was reduced towards 0 K, the resistance fell sharply at about 4 K, and below this temperature the mercury exhibited zero electrical resistance. (See Figure III) Furthermore, this sudden transition to a state of zero resistance was not confined to the pure metal but occurred even if the mercury was quite impure. Onnes recognized that below 4 K mercury passed into a new state with electrical properties quite unlike those previously known.

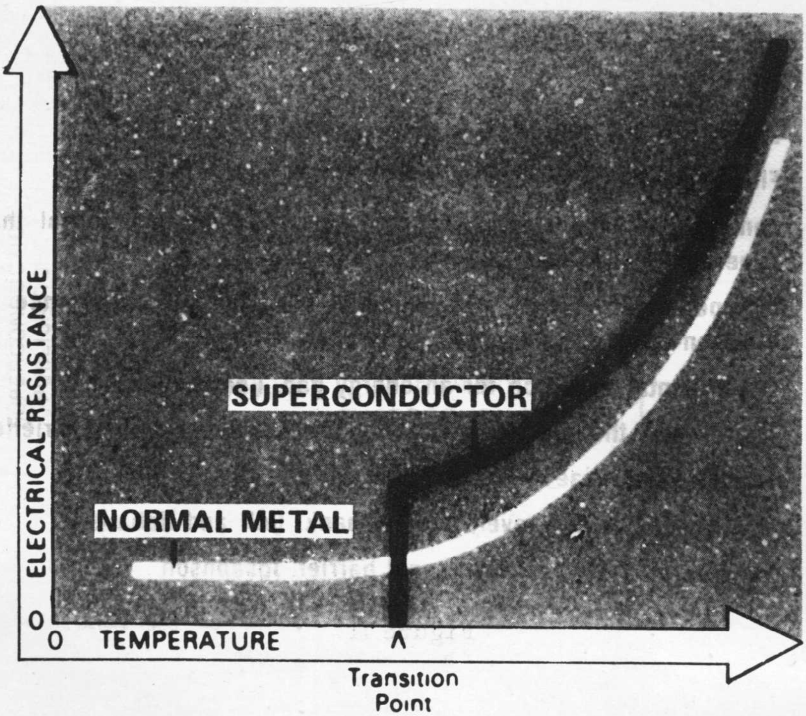
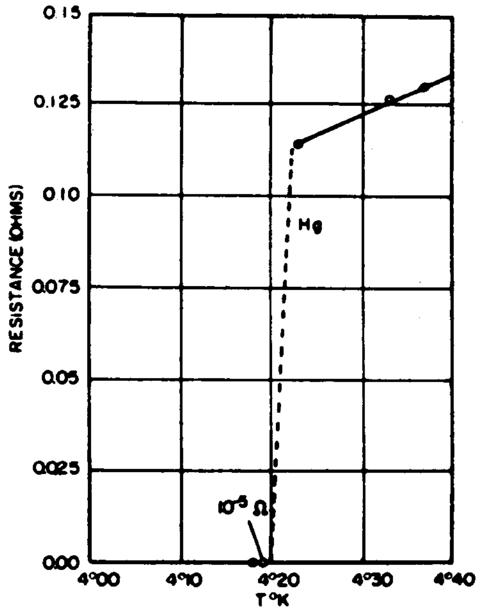


Figure III

Figure IV is a graph taken from Onnes' earliest paper which marks the discovery of superconductivity. In reading Onnes' first paper one can almost feel the sense of elation he must have had. He writes: "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state. There is left little doubt, that, if gold and platinum could be obtained absolutely pure, they would also pass into the superconductive state at helium temperatures. The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity."

Often the question is asked, "Is the resistance of a superconductor truly zero? A long series of measurements on superconducting rings and coils by Onnes and others were attempted to answer this question. In 1956 an experiment was performed by Professor Collins at Massachusetts Institute of Technology in which a superconducting ring carrying an induced current was maintained for over two years. The absence of any measurable decay of the persistent circulating current during this period allowed Professor Collins to place an upper limit of 10^{-21} ohm-cm on the resistivity of the superconductor. This is to be compared to the value of 10^{-9} ohm-cm for the low temperature resistivity



Resistance in ohms of a specimen of mercury vs. absolute temperature. This plot by Kamerlingh Onnes marked the discovery of superconductivity in 1911.

Figure IV

of pure copper. More recently, Professor Little at Stanford University has calculated the upper limit of the lifetime of persistent currents in superconductors of finite dimensions by considering the effects of thermodynamic fluctuations in the superconducting specimen. These fluctuations provide a means by which the persistent current can decay. Decay by these means should be observable in wires a few hundred angstroms in thickness. Figure V shows the results of these calculations. For all practical purposes the dc electrical resistance of a bulk superconductor is zero. I stress here dc because superconductors do have ac electrical resistance losses.

The temperature at which a material transforms from its normal or resistive state to the superconducting state is called the transition temperature, T_c. The sharpness of the transition depends on the purity and state of the material. In some favorable cases it can occur within a temperature interval of less than 0.001 K.

Computed lifetimes for two Sn wires, one of 100 Å diameter and the other of 360 Å

Lifetime	100 Å wire (°K)	360 Å wire (°K)
~10^{-14} sec	3.7	3.7
10^{-7} sec	2.0	3.4
10^{-4} sec	1.5	3.26
1 sec	1.25	3.10
10 days	1.0	3.06
10^6 years	0.75	2.90

Figure V

Figure VI shows the periodic table with those elements which now are known to be superconducting. Today over a thousand compounds and alloys are superconductors. Figure VII shows the distribution of superconductors as a function of transition temperature.

Following the discovery of superconductivity, Onnes soon found that a mercury wire loses its superconductivity and normal resistance reappears above a critical current. This was soon explained when Onnes discovered that a magnetic field in excess of a maximum value forces the superconductor into its normal resistive state. This value is called the critical magnetic field and is usually denoted by the symbol H_c. For all superconductors there exists a region of temperatures and magnetic fields within which the material is superconducting. Outside this region the material is normal. This parabolic curve shown in Figure VIII can be approximated by

$$H_c \simeq H_0 \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$$