SUPERCONDUCTIVITY: THE NEXT REVOLUTION?

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In 1987 scientists and engineers were seized with excitement at the discovery of 'high temperature superconductors'; these new materials become superconducting at temperatures four times higher than any previously known superconductor. Suddenly all kinds of applications of superconductivity, from magnetically levitated trains to lossless power lines, became possible.

As a result of the intense media coverage of these discoveries, superconductivity has become almost a household word, although most people have only a vague idea of what it is. In this book Professor Vidali describes in plain, non-technical terms how conventional superconductivity was discovered 80 years ago, why it took nearly 50 years to understand it, and the physical explanation of why it exists. He chronicles the developments that led up to the discovery of high temperature superconducting materials, and describes the excitement generated by announcements of the new discoveries in 1987 at a scientific conference that became known as the 'Woodstock of physics'. Finally, he speculates on possible future applications of these new materials.

This book will fascinate layman and scientist alike. Anyone interested in a clear, non-technical account of high temperature superconductivity will find it of great interest.

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PREFACE

Why this book?

Is superconductivity going to be the next technological revolution? Will it have a tangible impact on our lives comparable to the inventions of the transistor and integrated circuits? Are we witnesses to a privileged moment in the history of science and technology? Or will this excitement, to which the media, oddly enough, have contributed little in comparison with the scientists' own enthusiasm, die away as it has in many other cases? Above all, *what is superconductivity?*

Naively, it would be logical to think that scientists, especially those working on superconductivity might best answer these questions; however, it is known that scientists enjoy speculating. It is impossible to make an exhaustive list of scientists' opinions regarding the impact of superconducting technology on our day-to-day lives. Today's opinions are often in stark contrast to those voiced just three or four years ago! In fact, we still don't know how high temperature superconductivity really works. How can we take advantage of a technology whose underpinnings we don't yet fully understand?

One of the points often overlooked in such discussions is that what appears to be scientifically possible is not always commercially realizable. An invention, even if superior in some technical way to pre-existing ones, might not be profitably produced or marketed for reasons which have little to do with science or technology. For example, high production costs or adverse environmental impact might stifle products or even technologies (the fate of the solar energy and nuclear industries in the United States comes to mind, although for different reasons).

Empowering the readers

Instead of reciting others' speculations, we throw the ball into the readers' court. By providing enough information and explanations we hope to enable readers to form their own opinions. Actually, the reader will get something extra from reading this book. As new events in superconductivity unfold (and we 'guarantee' they will), readers will be able to put them in perspective and judge for themselves the likely impact of a news-breaking discovery. While this book might become outdated, the readers will never be.

There are no convoluted, jargon-filled, obscure explanations. In fact, we require only some background in high school or introductory college physics and, most of all, a *keen curiosity*. We hope that by the time the readers reach the end of the book they will have received enough clues to speculate intelligently about these issues.

More specifically, we aim to give our readers an appreciation of the physical phenomena related to superconductivity and to illustrate how this knowledge (which is far from being complete and, at times, even satisfactory) has already affected and will continue to influence technological progress. We will not enumerate all the 'gee-whiz' gadgets that have been or will be shortly made, nor string together amusing (and often inaccurate) anecdotes, nor repeat mass-media accounts of recent discoveries. Instead, we shall focus on how scientific discoveries flow or sometimes leap from one to another. We shall start with the first discovery of the resistanceless flow of an electrical current 80 years ago, and proceed to examine events up to the latest developments in new high temperature superconducting materials.

Obviously, the task is easier when considering events of long ago, since we can distinguish between the discoveries or ideas which were seminal to a comprehensive understanding of the phenomena and those which were irrelevant. For more recent events, ones stemming from the discovery of high temperature superconductors in 1986 and 1987, we are not yet in a position to know which ideas will be fruitful and which will not, although in the past four years some trends (discussed later in the book) have certainly emerged.

Scientists and superconductivity

We are, indeed, fortunate to have witnessed the discovery of high temperature superconductors, to have been front-seat spectators, as it were, in this race towards higher and higher critical temperatures. The excitement in the laboratories is real.

While public awareness of scientists' enthusiasm has been awakened by the reporting of recent events, such excitement is not new in science; it is often found whenever a significant discovery is made or an understanding of a complex phenomenon is reached. It is an excitement comparable to the one felt by someone who has worked for a long time at a complex puzzle or riddle. All of a sudden all the gathered pieces which seemed somewhat important before but couldn't be placed in any sensible order, fall into their proper places. The riddle is finally solved and the sensation of accomplishment is overwhelming ('I've got it!!, Eureka!!'). The joy comes from the realization that we can see not only the meaning of each single piece, but can recognize a design which, until a few moments before, had been hidden from us.

In the realm of the natural sciences, most of the joy and euphoria comes from the discovery of, as many scientists say, 'how clever Nature can be.' One of the most important goals of this book is to try to catch this excitement and involve the reader as a participant in this joy. We hope to accomplish this by providing readers with an understanding of how the discoveries came about and what they meant, rather than through involvement as passive spectators of a newsreel of soon forgotten facts.

Acknowledgments

This book couldn't have been completed without the help of Carole, my wife, who spent countless nights reading, criticizing and editing the manuscript. I would like also to thank Dr Simon Capelin, senior editor of Cambridge University Press, for his constant encouragement.

This work was completed while I was spending my sabbatical leave at Princeton University. The hospitality of the Chemistry Department is gratefully acknowledged.

G. Vidali

Syracuse, 1992

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Introduction and overview

1.1 March 1987

'THE FASCINATION OF SUPERCONDUCTIVITY is associated with the words perfect, infinite, and zero', muses Brian Maple, Professor of Physics at the University of California, San Diego.

In the language of superconductivity *perfect* is the expulsion of magnetic fields from a chunk of material that has become superconducting, *infinite* is the electrical conductance, and *zero* is the electrical resistance. Perfect and infinite are words that any of us might use many times a day often absent-mindedly. We might talk excitedly of 'perfect parties', although we realize that, on second thought, we have attended even better ones. And we boast of having 'infinite patience' before we recognize it is often tried beyond its limits. Everybody understands this, and seldom is anyone asked to explain what perfect and infinite really mean. But scientists, and physicists in particular, when not at parties or shouting at their children, have different ideas about 'perfect, infinite and zero'. In fact, if they belong to that group that likes to tinker in basements of university buildings – more correctly called 'experimentalists in laboratories' – they are especially reluctant to use such words as perfect, absolute, and infinite. When talking about facts of science, they have been trained to disregard such words, since nothing can be made perfectly, nor be measured infinitely large or small. When discussing superconductivity, however, physicists go wild and use these and other rather hyperbolic adjectives quite freely and without hesitation. Why?

Let us turn the clock back a couple of years. New York City, 1987.

'Where do you want to eat?' asked a couple of people in the group, almost simultaneously.

'We better find something quick. It's gonna be pretty crowded.'

At about 5:30 p.m., midweek, on a crisp March day in mid-Manhattan it shouldn't have been a problem to find a place to eat. But we, a loosely bound group of five or six physicists attending the American Physical Society Meeting, knew we had to find a reasonable place to have dinner near the Hilton, where our meeting rooms were located. We knew that three thousand or so colleagues were on the same hunt at the same time.

Time was indeed the issue. At seven o'clock, a special session was going to be held in which new results about the new superconductors were to be presented. Many speakers were scheduled to give short presentations of their latest work in superconductivity, and results which had not yet appeared in print were likely to be announced.

When we arrived at the hotel, about half an hour before the scheduled opening of the session, we immediately realized that we didn't need to ask for directions. A huge crowd of people, discussing animatedly, was pressing at the doors, still closed, of the hallway leading to the big ballroom where the meeting was about to begin. When the doors opened, a rush to the empty chairs quickly ended and most people had to find much less comfortable positions on the floor around the perimeter of the large room or in the hallway (Figure 1.1). A long night had begun.

For hours, group leaders from famous scientific institutions as well as lone scientists from small universities and colleges went to the microphone and transparency projector to illustrate their new discoveries. TV camera crews and photographers were constantly moving around often creating a human wall in front of the speaker. But with some ingenuity and luck, one could grasp most of what was said from the podium. New superconducting materials! New

Figure 1.1 The Woodstock of physics: the special session on superconductivity held during the 1987 March Meeting of the American Physical Society (Hilton Hotel, New York City). (Courtesy of the American Institute of Physics Niels Bohr Library.)

mechanisms for superconductivity! Unheard-of transition temperatures! Here is a sample of a superconducting tape! Everybody was excited. It was an important moment in the history of twentieth century science.

That was March 1987. What of those events is left today? What have we learned in four or five years? Should we still be excited about these high temperature superconductors? Do we understand how they work? What do scientists and engineers say about them? And whatever happened to the superconductivity gadgets people were talking about a few years ago? Superconducting trains, cars and power lines: are they being built? And what is superconductivity, anyway?

1.2 Superconductivity before 1986

Perhaps the time has come to consider and reflect upon the events of 1987, when superconductivity not only became a hot topic of conversation at scientific institutes around the world, but was introduced to a great many people who had never even heard the word before.

In fact, many don't know that superconductivity was discovered 'long ago', more than 80 years ago by Kamerlingh Onnes at the University of Leiden, in the Netherlands. Since then researchers at universities and in industrial laboratories have spent countless hours trying to find those special materials that, when cooled below a certain temperature (called the *critical* or *transition* temperature) possess those spectacular characteristics which we now associate with the name superconductivity. There are two properties of

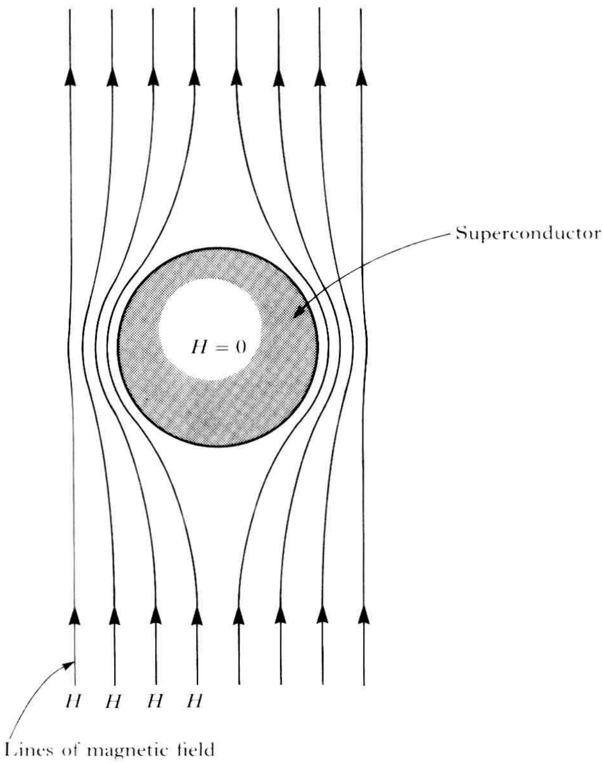

Figure 1.2 A superconductor expels an external magnetic field. Lines and arrows show the direction of the magnetic field.

superconductors which cannot be easily missed. First, when a chunk of matter becomes superconducting, the resistance to the passage of an electrical current goes to zero. It doesn't just become very small, it really becomes zero. This is a very remarkable property. Electric power is expensive to produce, as we all know; it is also expensive to transport since to overcome this resistance some additional power has to be provided. Every trick has to be used to minimize losses since electric power has to be transported for hundreds if not thousands of miles. Even using the best conductive materials available, such as copper, an appreciable amount of power is lost in overcoming this resistance. Other tricks to minimize losses, such as carrying electricity at very high voltages (100000 volts or more), often present drawbacks, such as an adverse environmental impact.

The second property is less apparent than the first, but not less important. Let us take the same chunk of material and place it near a magnet. The magnet will exert an influence on this piece of matter; we will call this influence 'the magnetic field' and this has been known since antiquity. By the way, we could prove that there is indeed something there by moving a compass needle near the magnet; the compass will align its needle in certain directions (called magnetic field lines) pointing toward (or away from) the pole of the magnet. In short, we will say that our chunk of material is in a magnetic field. In most cases, experimentation shows that the magnetic field will penetrate the sample and exit from the other side. At ordinary temperatures, unless this chunk is ferromagnetic, such as a piece of iron, nothing remarkable will happen. However a remarkable thing occurs when this chunk is cooled down; all of a sudden the material expels the magnetic field from its interior. The magnetic field lines which went through the sample are now rerouted to its periphery (Figure 1.2). In other words, the inside of this sample becomes shielded from any magnetic force. It turns out that the temperature at which the magnetic field is expelled is the same as that at which the sample shows no electrical resistance. If the sample is cooled down further, these two properties remain (and we say that the matter is in a 'superconducting state'); if the sample is warmed up above this temperature, these effects disappear (and the matter is now in the 'normal state').

Contrary to popular belief, superconductivity (to be defined for now by the two effects mentioned above) is not as rare as it might have seemed at first, since many metals (and other types of substances as well) are indeed superconductors. The fact is that most superconductors become so at what most people would consider extremely low temperatures, much colder than any temperatures measured on Earth (except in laboratories!). At the beginning of this century, Onnes was the only one who had the technology to reach these low temperatures. In fact, he had found a way to produce the coolant needed for reaching these temperatures, liquid helium. Thus, it was just a matter of time before one of the most striking properties of superconductivity (specifically: infinite electrical conductivity) was discovered in a number of materials.

Kamerlingh Onnes soon realized the practical significance of this amazing discovery. Electrical power could be transported without appreciable loss over great distances, and electromagnets, in which the magnetic field is produced by an electrical current, could be built that would have magnetic fields otherwise unattainable. To Onnes's great disappointment, this discovery couldn't be applied as easily as he and his contemporaries first thought. He soon found that a modest magnetic field, comparable to the one generated by a small household horse-shoe magnet, could easily make the material switch from a perfect conductor to an ordinary material with a finite, instead of infinite, electrical conductivity. Onnes also found that an electrical wire of a given size, when in the superconducting state, could carry electrical current only up to a certain limit before resistance to the passage of the electric current set in. As before, the 'superconducting state' is destroyed and the material acquires back its 'normal' electrical properties. To be sure, this resistance can be exploited for useful purposes. Electrical resistance causes an electrical current to dissipate heat and this phenomenon (Joule heating) is used to run hot water tanks or baseboard heaters. However, in many other instances, such as the transport of electrical power, the resistance should be minimized, or some electrical power will be spent in unwanted heat dissipation. Furthermore, the maximum temperature at which these materials still showed superconducting properties didn't go much higher than the astoundingly small temperature 4 K (K is for Kelvin or about −452 °F) of the original