Chapter 1
Introduction

Fig. 1.1 Bust of Heike Kamerlingh Onnes in Leiden

Physics is a science which aims at answering the big mysteries in Nature. Physicists have always been attracted by the greatest challenges. But sometimes even the most demanding problems reveal themselves little by little. On the 8th of April 1911 a discovery was made through an apparently simple experiment in a glass flask of very special design in a physics laboratory in Leiden, Holland. The experiment set in motion a series of events with few parallels in the history of science. But physics was far from ready for the advent of superconductivity, the enigmatic phenomenon which Heike Kamerlingh Onnes and his student Gilles Holst had just observed. Today, more than a hundred years later, after great scientific research efforts and big investments, and after many impressive scientific and technical breakthroughs,

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a cloud of mystery still hovers over aspects of superconductivity. Nature continues to play her elusive game with the best minds of physics.

It seems right, after passing the 100 year milestone, to take stock of the intellectual property upon which we stand in this field, and from which basis scientists launch further expeditions into the remaining enigma. Physicists' fascination with superconductivity prevails, and continues to attract new generations.

The year 1911 would turn out to be a great year in science history for an additional reason: The discovery of the atomic nucleus by Rutherford. Subsequently, the first model of atomic structure, the Bohr model, followed in 1913. The impact on science would be tremendous. 1911 will forever be a year hard to match in the annals of science.

It is not unusual in science history that an apparently simple observation opens a Pandora's box with wide-ranging consequences. H. K. Onnes studied electrical resistance in a metallic wire, hardly something that could change the world, you should think. In 1911 it was already known that electrical resistance in metals diminishes gradually and continuously as temperature is lowered more and more below the ambient. This fact had been carefully established by recent research, not only in Leiden. But Leiden had established itself as one of the central research arenas in the new field of low temperature physics, in a combination of curiosity driven search into new territory and development of fabulously sophisticated glass blown cooling devices. When H. K. Onnes and his team, in 1908, after many years of systematic efforts managed to condense the noble gas helium, the path was laid for unprecedented study of the low temperature properties of matter; gases, liquids and solids.

A problem which had been much debated at the time was what would be the ultimate low temperature behaviour of electrical resistivity on approaching zero degrees on the Kelvin scale. How low could the resistivity ultimately become? Would resistivity continue to decrease, and gradually vanish for all practical purposes? Or, would the current carriers eventually "freeze," or "stick to the atom" like some thought, thus preventing the charge carriers from participating in electrical conduction, forcing resistivity to increase again?

What H. K. Onnes and coworkers discovered, was something entirely different from both of these alternatives, and completely surprising: Resistance- and hence resistivity- in solid frozen mercury metal filaments vanished abruptly at about 4.2 K degrees above absolute zero, or at about minus 269 degrees centigrade, and remained zero at all lower temperatures. This phenomenon was called superconductivity. The temperature where it happens defines a dividing temperature which, as it would later turn out, is characteristic of each metal, and is called the superconducting transition temperature, T_c. In the pure metals of the periodic table, T_c would typically be below 10 K. As years went by, most but not all metals were found to be superconducting at low enough temperatures. Famous examples of nonsuperconductors, paradoxically it seemed, were the best metals like gold, silver and copper. Soon also a great variety of metallic alloys were found to possess the superconducting property. But no explanation could be found at the time.

It would be wrong to say that the world of science stood in awe of the new discovery. When H. K. Onnes received the Nobel Prize in physics in 1913, superconductivity was not even mentioned.[1] Rather, the emphasis was on Onnes' great feat in low temperature science and technology leading to condensation of the highly volatile inert gas of helium. It would later turn out that yet another important property of superconductors had still to be discovered. Nature reveals its secrets only when the appropriate questions are asked through precisely designed experiments. As is often the case, the problem was to know which question to ask.

It would take another 22 years before that next step was achieved, in 1933, when the deeper nature of superconductivity was revealed in a magnetic experiment by Walther Meissner and Robert Ochsenfeld in Germany. Before discussing that experiment, let us first sidestep a little and recall some simple facts: The most common metals, like lead, tin and aluminium, are classified as very weak paramagnets. This important characteristic is due to the fact that although electrons have the ability to align their magnetic moments with an applied magnetic field, and thus reinforce an externally applied field, only a very tiny fraction, those with the highest kinetic energy, are allowed to do so in a metal. This is due to the lack of available quantum states for most electrons into which they can accomodate if their magnetic moment is turned parallel to the field. Therefore, the number of electrons oriented parallel and antiparallel to the field, respectively, are almost equal, and the magnetism of the "gas" of freely moving electrons in a metal is almost zero. This is what is characterized as weak paramagnetism.

The second aspect of superconductors, discovered in 1933, came just as unexpectedly as the sudden loss of electrical resistivity in 1911. A piece of metal was first held in the normal state above T_c, while its entire body was permeated by an externally applied magnetic field from the solenoid in which it was located. The resulting magnetic field inside the sample was then very nearly the same as that outside, as described above. The sample was then cooled through the critical temperature T_c. On passing T_c, it was recorded that the magnetic field inside was suddenly and completely expelled. Hence, by lowering the temperature by just a small fraction of a degree, the material changed its magnetic character completely, from weakly paramagnetic above T_c, to a state of complete screening, with no magnetic field in the body below T_c, i.e. perfect diamagnetism. This must have been caused by the sudden creation of an opposing field which exactly cancelled the applied field inside. This remarkable behaviour, never observed before, is referred to as the *Meissner effect*, a phenomenon which ranks among the greatest theoretical challenges ever encountered in the history of physics. It was demonstrated that this constituted a new thermodynamic state, and that it was *not* a consequence of infinite conductivity. The deeper nature of the Meissner effect as a realisation of the Higgs mechanism was discovered almost 30 years later by Anderson, as told by him in the Anderson chapter of this book. Further comments on the Higgs mechanism are given in Chap. 12.

[1] The citation for the Nobel Prize to H. K. Onnes in 1913 does not mention superconductivity explicitly. But there may be reason to argue that this was due to the short time between the discovery and the deadline for nominations. This was pointed out to the author by Tord Claeson.

Henceforth, zero resistivity and the Meissner effect were referred to as the two distinguishing characteristics of the superconducting state of metals. Only if both of these could be observed, would a material be counted as superconducting. It was further realized that since the Meissner effect was a persistent phenomenon caused by spontaneously created screening currents near the surface, the presence of the Meissner effect implied zero resistivity. The Meissner effect, or perfect diamagnetism, therefore is the true defining property of superconductivity. Only when this effect is observed, can one claim to have observed superconductivity.

The Meissner effect is named after professor Walther Meissner, who lead the experiment. It should rightfully be called the *Meissner-Ochsenfeld effect*, including the name of the student, but practice has been mostly to use the shorter name.

An important step was made by Fritz and Heinz London in 1935, when they proposed a description of the magnetic state of the superconductor in which the conduction electrons were divided into a normal part and a superconducting part. The screening of the interior of the sample against an applied magnetic field was described by the London equations as being upheld by a spontaneously created current of the superconducting electrons in a very thin surface screening layer, called the London penetration depth λ, its limiting value being less than a micrometer in simple metals. Such a phenomenological description was quite useful. Even so, the origin of the whole effect remained a mystery.

Onnes had quickly realized the potential for superconductors to replace conventional electromagnets since their current carrying capacity seemed enormous. To his disappointment, only quite weak magnetic fields could be created by superconducting solenoids he had available. Many properties of superconductors were not yet known, and lots of superconducting metals had not been discovered. It would take about 50 more years before useful, strong electromagnets could be made. The underlying limitations were due to limiting values of critical current density and critical magnetic field, the upper limits to how large currents and magnetic fields superconductors could tolerate. This called for the study of phase diagrams where such quantities were measured vs temperature. The field of superconductivity was growing ever wider.

Physics is a science which moves forward in an intimate interplay between experiment and theory, each advancing the other, in alternating steps. After many years of experimental progress, theoretical insight was lagging behind experiments. The greatest theorists in the field at this time were found in the Landau group in Moscow. Landau had already been engaged in work on the penetration of magnetic field in superconductors. He had also formulated a general phenomenological theory for systems which undergo continuous phase transitions between thermodynamic states. Applications of this theory require identification of a special parameter, the order parameter, which is different from case to case, and contains the essence of the problem. For the mathematical procedure to work, the order parameter must be small, or vanishing at T_c, and grow gradually on lowering the temperature. In the case of superconductors, the fraction of superconducting electrons could be seen as such a parameter. This was the situation when Vitaly Ginzburg and Lev Landau applied the Landau theory to superconductivity in 1950, and thus gave science a tool which has been of enormous importance in all the ensuing years. When Ginzburg received the Nobel Prize 53 years later, in 2003, it represented the ultimate recognition of the importance of his work with Landau.

The Ginzburg-Landau theory very soon found important applications. Alexei Abrikosov, also from the Landau school, had become much interested in the magnetic properties of superconductors, mostly through experiments carried out in thin films by one of his colleagues. He felt that the Landau theory was a remarkable tool. The results he obtained already in 1953, were unexpected. In fact, they were so surprising that his revered and respected boss, Landau, did not believe they were correct, and hence would not allow their publication. What Abrikosov had found, was a periodically ordered magnetic field penetration in superconductors, narrow lines of quantized magnetic flux, what has later been named the Abrikosov lattice. This was very different from magnetic structures studied by Landau before in the simple metals mentioned above, and Landau's refusal came because Abrikosov could not give a simple physical argument for his finding.

However, after Feynman's work on superfluid liquid helium, a parallel to superconductivity, where a similar effect was found, Landau gave in. Abrikosov's work introduced a new kind of superconductor, a "superconductor of the second kind," nowadays mostly called "Type II superconductor," as distinct from "Type I," which Onnes and many others, including Landau, had worked on before. Abrikosov's work became extremely important for future applications of superconductors. As an example, modern MRI would not exist without the knowledge and technology Abrikosov's work contributed to. Other examples are levitation technology for trains, high power energy transfer lines, and the Large Hadron Collider at CERN, Geneva, where the Higgs boson for particle mass was recently discovered. The Nobel Prize in 2003, shared with Ginzburg, came late, but was much deserved.

Even so, a phenomenological theory does not explain the underlying mechanisms of superconductivity. This was what Bardeen wanted to do when he carefully set up his team with two young and bright physicists at University of Illinois at Urbana, what later became known as the BCS team of John Bardeen, Leon Cooper, and John Schrieffer. These three turned out to be a kind of star team seldom seen, and their work gave a huge breakthrough in superconductivity research. Cooper first found a mechanism for electron pairing in 1956, known today as Cooper-pairs. Since the effect of pairing was to lower the energy of freely moving electrons in a lattice of metal ions, this was a very promising step. With Schrieffer's additional idea to write down the quantum state of the whole system of electrons, many properties of superconductors could be predicted. After much hard work, the BCS theory was published in 1957. A central piece of the theory was the prediction of the size of an energy gap due to Cooper-pairing. This gap could subsequently be determined by several experimental techniques, and agreed with predictions. Also, the density of states was predicted, and later confirmed. BCS gave a very complete and realistic description of the phenomenon of superconductivity. The essence was the coherent quantum state made possible by the pairing mechanism, which in superconductors was due to the exchange of lattice vibrations, phonons. Schrieffer often emphasises that the BCS theory has a much wider span of applicability, including atomic nuclei and neutron stars, a strong theory, with predictive power.

In 1960, Ivar Giaever, an employee at the research laboratory of General Electric in Schenectady, New York was taking physics courses at Rensselaer Polytechnic Institute in Troy, where he heard lectures on superconductivity. Having done experiments on tunnelling of electrons through thin normal metal films, he realized he could modify the tunnelling characteristics if he performed the experiment on superconducting films. He so did, and thereby established thin film tunnelling in superconductors as a new and exciting tool in the investigations of superconductivity. The experiment gave a very direct answer to the question of the size of the energy gap due to Cooper-pairs in the BCS theory. Even better, it gave a precise graph of the BCS superconducting density of states. His work was seen by the Nobel committee as the ultimate confirmation of BCS theory. For this work he received the Nobel Prize in 1973, the year after the BCS team.

Giaever shared the Nobel Prize with the young English physicist Brian D. Josephson, who had carried the subject of electron tunnelling in superconductors one big step forward. In this case theory was again ahead of experiment. Under the influence of a series of talks by Phil Anderson, and inspiration from Brian Pippard, his thesis adviser, and with knowledge about the experiments of Giaever, the young student, only 21–22 years old, did his life's masterpiece when he predicted the tunnelling properties of very thin superconducting films. The Josephson effects comprise several physical effects, the most astonishing one being the transmission of a DC superconducting current at zero applied voltage. This effect is driven by a difference in phase of the superconducting wave function between the two sides of the film, which has an effect similar to an applied voltage. Furthermore, if in addition a voltage is applied, a microwave field is radiated. In practical terms, the main importance of the Josephson effects has been in making possible very sophisticated magnetic field detectors. The Superconducting QUantum Interference Device (SQUID) is by far the most sensitive detector of magnetic field ever made. It is widely used in the measurements of brain waves and other biomagnetic signals from the human body, as detector of radio waves, as voltage standard etc. The important difference between the Giaever experiments and the Josephson devices is that in the Giaever tunnelling experiments single particle tunnelling is responsible for the effects observed, while the Josephson effects owe their existence to Cooper pair tunnelling, implying that the superconducting wave function extends across the thin film barrier.

The BCS theory was in one sense an instant success. On the other hand there seemed to be problems with gauge invariance. While the BCS team was not worried about it, others were. One of them was Phil Anderson, at that time still at Bell Labs, who clarified the issue. He is known for his broad efforts in many areas of solid state physics, among them magnetism and superconductivity. He clearly inspired Josephson's work. With Kim he predicted how the magnetic vortex lattice discovered by Abrikosov could be "pinned," or immobilised, thus preventing energy loss during transportation of electrical current in a superconducting wire. These days, Anderson's claim to have discovered the Higgs mechanism during work on the Meissner effect in superconductivity is worth special attention.

Some of the best physicists form tightly collaborating groups or teams that have the character of a "school." We mentioned Landau above. Pierre-Gilles de Gennes' group at Saclay in Paris was such a school, referred to as the Saclay Group on Superconductivity. de Gennes is not famous for a particular discovery in superconductivity. Rather, his work was an inspiration for a generation of young physicists in superconductivity, and he was a discoverer in soft matter. Equally important, his unique lecturing style which brought him to meetings all over the world, and to high schools all over France, did a lot to promote science in general, and physics in particular in a wider context. Those who heard him lecturing, will never forget this great communicator of science.

Until 1986 a severe limitation of superconductivity was always present: A maximum of only about 23 K for the superconducting transition temperature T_c. All those who ever became interested in superconductivity have shared a common dream: That this fascinating phenomenon could one day be observed and used at room temperature. It would be one of the most wonderful gifts of science to the world. Can it happen? It surely will not happen without scientists who are ambitious and courageous enough to try to reach for the impossible. Two men who did, were K. Alex Müller and Johannes George Bednorz at the IBM Research Laboratory in Rüschlikon near Zürich. Their work rounds off the story of the great scientists and discoveries in this book. Their discovery, against all odds, of a new class of superconductors with higher T_c, raised the hopes of thousands of scientists all over the world. "The Woodstock of physics," as New York Times named the first international meeting on the new subject in New York in January 1987, is a unique event in the history of science. At this moment, 25 years later, we look back at these events, and experience here how extremely exciting and promising science can be, and how demanding and challenging it is for those involved.

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