Superconductivity

The Open University

Superconductivity

OpenLearn | Free learning from The Open University

About this free course

This free course is an adapted extract from the Open University course SMT359 *Electromagnetism*: www3.open.ac.uk/study/undergraduate/course/smt359.htm.

This version of the content may include video, images and interactive content that may not be optimised for your device.

You can experience this free course as it was originally designed on OpenLearn, the home of free learning from The Open University - www.open.edu/openlearn/science-maths-technology/engineering-and-technology/engineering/superconductivity/content-section-0.

There you'll also be able to track your progress via your activity record, which you can use to demonstrate your learning.

The Open University, Walton Hall, Milton Keynes, MK7 6AA

Head of Intellectual Property, The Open University

The Open University

United Kingdom at the University Press, Cambridge

Contents

Introduction

The fascinating phenomenon of superconductivity and its potential applications have attracted the attention of scientists, engineers and businessmen. Intense research has taken place to discover new superconductors, to understand the physics that underlies the properties of superconductors, and to develop new applications for these materials. In this course you will read about the history of superconductors, taking a brief look at their properties. You will also learn about modelling the properties of superconductors and the two different types of superconductor that exist today.

Superconducting electromagnets produce the large magnetic fields required in the world's largest particle accelerators, in MRI machines used for diagnostic imaging of the human body, in magnetically levitated trains (Figure 8) and in superconducting magnetic energy storage systems. But at the other extreme superconductors are used in SQUID (superconducting quantum interference device) magnetometers, which can measure the tiny magnetic fields ($\sim 10^{-13}$T) associated with electrical activity in the brain, and there is great interest in their potential as extremely fast switches for a new generation of very powerful computers.

In this course we will focus on the macroscopic electrodynamic properties of superconductors, and particularly on some of the properties that can be explained in terms of electromagnetism concepts with which you should be familiar. A full understanding of superconductivity requires knowledge of materials science and quantum theory, and discussion of these aspects is beyond the scope of this course. We begin with a review of some of the main developments over the last hundred years, then describe in more detail some of the key electromagnetic properties. These can be modelled in a simple way without using quantum mechanics, and we shall show how this can be done. Finally, we distinguish between the type of superconductivity shown by most of the elemental superconductors, known as *type-I superconductivity*, and that shown by superconducting alloys that have commercial applications, known as *type-II superconductivity*.

This OpenLearn course is an adapted extract from the Open University course : SMT359 *Electromagnetism*.

Learning Outcomes

After studying this course, you should be able to:

- explain the meanings of the newly defined (emboldened) terms and symbols, and use them appropriately
- distinguish between perfect conduction and perfect diamagnetism, and give a qualitative description of the Meissner effect
- explain how observation of a persistent current can be used to estimate an upper limit on the resistivity of a superconductor, and perform calculations related to such estimates
- explain why the magnetic flux through a superconducting circuit remains constant, and describe applications of this effect
- show how the London equations and Maxwell's equations lead to the prediction of the Meissner effect.

1 Superconductivity

Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes (Figure 1) as he studied the properties of metals at low temperatures. A few years earlier he had become the first person to liquefy helium, which has a boiling point of 4.2 K at atmospheric pressure, and this had opened up a new range of temperature to experimental investigation. On measuring the resistance of a small tube filled with mercury, he was astonished to observe that its resistance fell from ~0.1 Ω at a temperature of 4.3 K to less than 3×10^{-6} Ω at 4.1 K. His results are reproduced in Figure 2. Below 4.1 K, mercury is said to be a superconductor, and no experiment has yet detected any resistance to steady current flow in a superconducting material. The temperature below which the mercury becomes superconducting is known as its **critical temperature** T_c. Kamerlingh Onnes was awarded the Nobel Prize for Physics in 1913 ‘for his investigations on the properties of matter at low temperatures which led, *inter alia*, to the production of liquid helium’ (Nobel Prize citation).

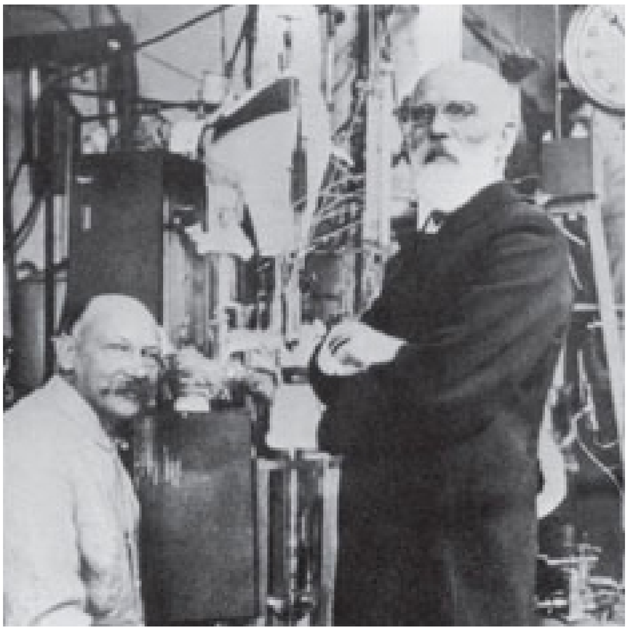

Figure 1 Heike Kamerlingh Onnes (left) and Johannes Van der Waals beside a helium liquefier (1908).

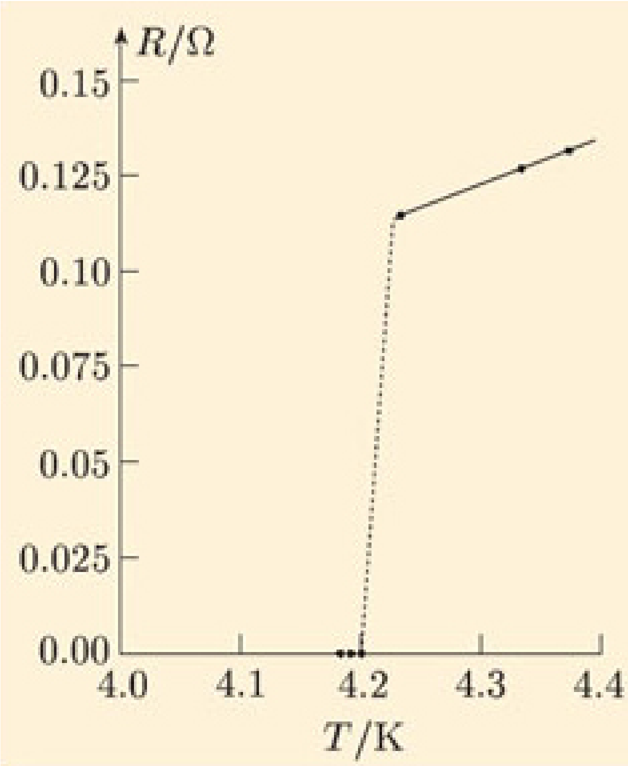

Figure 2 Graph showing the resistance of a specimen of mercury versus absolute temperature.

Since this initial discovery, many more elements have been discovered to be superconductors. Indeed, superconductivity is by no means a rare phenomenon, as the Periodic Table in Figure 3 demonstrates. The dark pink cells indicate elements that become superconducting at atmospheric pressure, and the numbers at the bottoms of the cells are their critical temperatures, which range from 9.3 K for niobium (Nb, Z = 41) down to 3 × 10^{-4} K for rhodium (Rh, Z = 45). The orange cells are elements that become superconductors only under high pressures. The four pale pink cells are elements that are superconducting in particular forms: carbon (C, Z = 6) in the form of nanotubes, chromium (Cr, Z = 24) as thin films, palladium (Pd, Z = 46) after irradiation with alpha particles, and platinum (Pt, Z = 78) as a compacted powder. It is worth noting that copper (Cu, Z = 29), silver (Ag, Z = 47) and gold (Au, Z = 79), three elements that are excellent conductors at room temperature, do not become superconductors even at the lowest temperatures that are attainable.

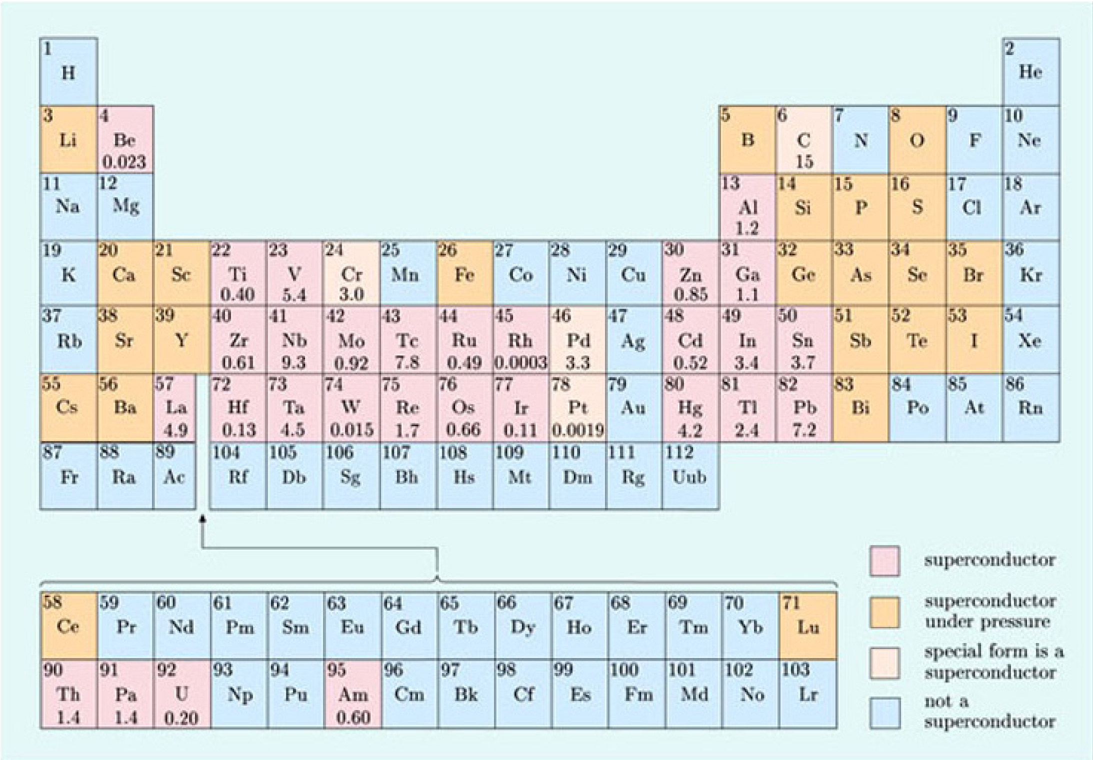

Figure 3 The Periodic Table showing all known elemental superconductors and their critical temperatures.

A major advance in the understanding of superconductivity came in 1933, when Walter Meissner and Robert Ochsenfeld discovered that superconductors are more than perfect conductors of electricity. They also have the important property of excluding a magnetic field from their interior. However, the field is excluded only if it is below a certain critical field strength, which depends on the material, the temperature and the geometry of the specimen. Above this critical field strength the superconductivity disappears. Brothers Fritz and Heinz London proposed a model that described the exclusion of the field in 1935, but it was another 20 years before a microscopic explanation was developed.

The long awaited quantum theory of superconductivity was published in 1957 by three US physicists, John Bardeen, Leon Cooper and John Schrieffer, and they were awarded the Nobel Prize for Physics in 1972 'for their jointly developed theory of superconductivity, usually called the BCS theory' (Nobel Prize citation). According to their theory, in the superconducting state there is an attractive interaction between electrons that is mediated by the vibrations of the ion lattice. A consequence of this interaction is that pairs of electrons are coupled together, and all of the pairs of electrons condense into a macroscopic quantum state, called the **condensate**, that extends through the superconductor. Not all of the free electrons in a superconductor are in the condensate; those that are in this state are called **superconducting electrons**, and the others are referred to as **normal electrons**. At temperatures very much lower than the critical temperature, there are very few normal electrons, but the proportion of normal electrons increases as the temperature increases, until at the critical temperature all of the electrons are normal. Because the superconducting electrons are linked in a macroscopic state, they behave coherently, and a consequence of this is that there is a characteristic distance over which their number density can change, known as the **coherence length** ξ (the Greek lowercase xi, pronounced 'ksye').

It takes a significant amount of energy to scatter an electron from the condensate – more than the thermal energy available to an electron below the critical temperature – so the superconducting electrons can flow without being scattered, that is, without any resistance. The BCS theory successfully explained many of the known properties of superconductors, but it predicted an upper bound of roughly 30 K for the critical temperature.

Another important theoretical discovery was made in 1957. Alexei Abrikosov predicted the existence of a second type of superconductor that behaved in a different way from elements like lead and tin. This new type of superconductor would expel the field from its interior when the applied field strength was low, but over a wide range of applied field strengths the superconductor would be threaded by normal metal regions through which the magnetic field could pass. The penetration of the field meant that superconductivity could exist in magnetic field strengths up to 10 T or more, which opened up the possibility of many applications. For this work, and subsequent research, Abrikosov received a Nobel Prize for Physics in 2003 'for pioneering contributions to the theory of superconductors and superfluids' (Nobel Prize citation).

By the early 1960s there had been major advances in superconductor technology, with the discovery of alloys that were superconducting at temperatures higher than the critical temperatures of the elemental superconductors. In particular, alloys of niobium and titanium (NbTi, T_c = 9.8 K) and niobium and tin (Nb_3Sn, T_c = 18.1 K) were becoming widely used to produce high-field magnets, and a major impetus for this development was the requirement for powerful magnets for particle accelerators, like the Tevatron at Fermilab in the USA. At about the same time, Brian Josephson made an important theoretical prediction that was to have major consequences for the application of superconductivity on a very small scale. He predicted that a current could flow between two superconductors that were separated by a very thin insulating layer. The so-called Josephson tunnelling effect has been widely used for making various sensitive measurements, including the determination of fundamental physical constants and the measurement of magnetic fields that are a billion (10^9) times weaker than the Earth's field. The significance of his work was recognised when he was awarded a Nobel Prize for Physics in 1973 'for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects' (Nobel Prize citation).

The hunt for superconductors with higher critical temperatures continued in the decades following publication of the BCS theory, in spite of its prediction that the upper limit for T_c was less than 30 K. The holy grail for scientists working in this area was a material that was superconducting at the temperature of liquid nitrogen (77 K), or, even better, at room temperature. This would mean that all of the technology and costs associated with use of liquid helium for cooling could be dispensed with, and applications of superconductivity would immediately become far more economically worthwhile. The breakthrough came in 1986, when Georg Bednorz and Alex Muller discovered that ceramics made of barium, lanthanum, copper and oxygen became superconducting at 30 K, the highest known critical temperature at that time. The discovery was particularly surprising because this material is an insulator at room temperature. The following year they received the Nobel Prize for Physics 'for their important breakthrough in the discovery of superconductivity in ceramic materials' (Nobel Prize citation), and the unprecedented rapidity with which the prize followed publication of their results reflects the importance attached to their work.

As a result of this breakthrough, a scientific bandwagon started to roll and many other scientists began to examine similar materials. In 1987, Paul Chu produced a new ceramic material by replacing lanthanum by yttrium, and found that it had a critical temperature of

90 K. This great jump in the critical temperature made it possible to use liquid nitrogen as a coolant, and with the promise of commercial viability for the new materials, a scramble ensued to find new high-temperature superconductors and to explain why they superconduct at such high temperatures. At the time of writing (2005), the highest critical temperature was 138 K, for a thallium-doped mercuric-cuprate, $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$. Figure 4 shows the progress of the highest known superconducting critical temperature over the last century.

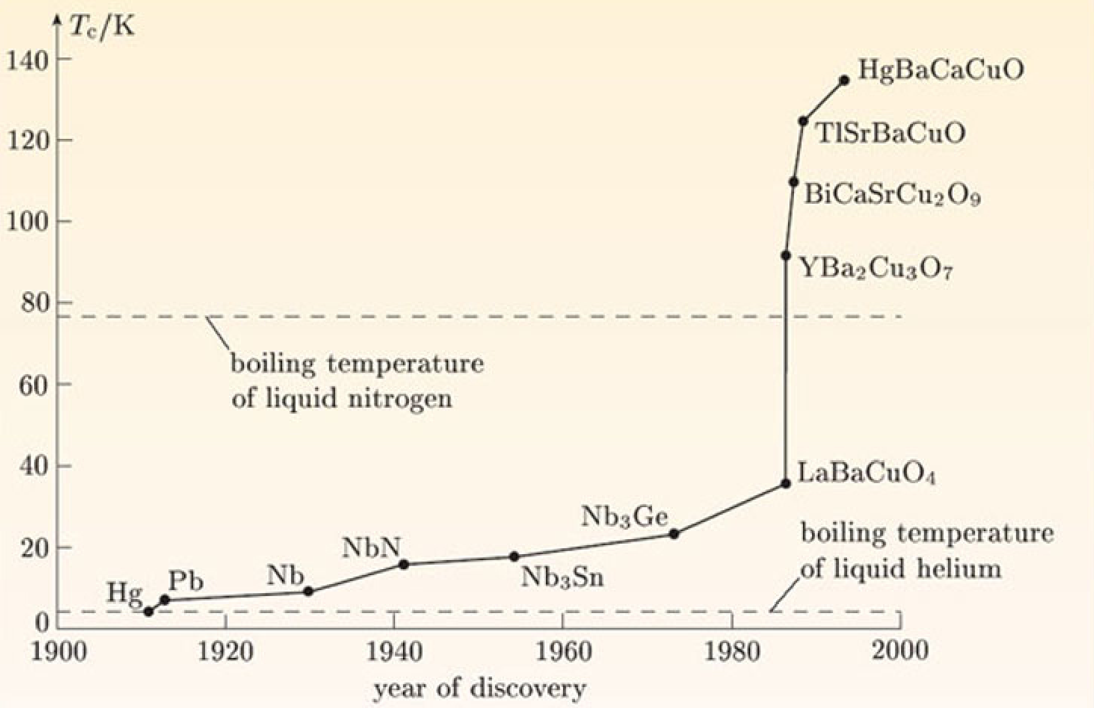

Figure 4 The critical temperature T_c of various superconductors plotted against their discovery date.

In recent years, no materials with significantly higher critical temperatures have been found, but other discoveries of equal importance have been made. These include the discovery that, against conventional wisdom, several materials exhibit the coexistence of ferromagnetism and superconductivity. We have also seen the discovery of the first high-temperature superconductors that do not contain copper. Startling discoveries like these are demanding that scientists continually re-examine long-standing theories on superconductivity and consider novel combinations of elements.

Unfortunately, no superconductors have yet been found with critical temperatures above room temperature, so cryogenic cooling is still a vital part of any superconducting application. Difficulties with fabricating ceramic materials into conducting wires or strips have also slowed down the development of new applications of high-temperature superconductors. However, despite these drawbacks, the commercial use of superconductors continues to rise.

2 Properties of superconductors

2.1 Zero electrical resistance

In this section we shall discuss some of the most important electrical properties of superconductors, with discussion of magnetic properties to follow in the next section.

The most obvious characteristic of a superconductor is the complete disappearance of its electrical resistance below a temperature that is known as its critical temperature. Experiments have been carried out to attempt to detect whether there is any small residual resistance in the superconducting state. A sensitive test is to start a current flowing round a superconducting ring and observe whether the current decays. The current flowing in the superconducting loop clearly cannot be measured by inserting an ammeter into the loop, since this would introduce a resistance and the current would rapidly decay.

SAQ 1

Suggest a method of monitoring the current that does not involve interfering with the superconducting loop.

Answer

The magnetic field generated by the current in the loop could be monitored.

The magnitude of the magnetic field is directly proportional to the current circulating in the loop, and the field can be measured without drawing energy from the circuit. Experiments of this type have been carried out over periods of years, and the magnetic field – and hence the superconducting current – has always remained constant within the precision of the measuring equipment. Such a **persistent current** is characteristic of the superconducting state. From the lack of any decay of the current it has been deduced that the resistivity ρ of a superconductor is less than 10^{-26} Ω m. This is about 18 orders of magnitude smaller than the resistivity of copper at room temperature ($\approx 10^{-8}$ Ω m).

Resistivity is the reciprocal of conductivity, that is, $\rho = \sigma^{-1}$. We prefer to describe a superconductor by $\rho = 0$, rather than by $\sigma = \infty$.

In the following Exercise you can estimate an upper limit for the resistivity of a superconductor.

Exercise 1

(a) A circuit, with self-inductance L, has a current I_0 flowing in it at time $t = 0$. Assuming that the circuit has a small residual resistance R but contains no source of emf, what will be the current in the circuit after a time T has elapsed?

(b) In a classic experiment performed by Quinn and Ittner in 1962, a current was set up around the 'squashed tube', shown in Figure 5, which was made from two thin films of superconducting lead separated by a thin layer of insulating silicon oxide. The inductance L of the tube was estimated to be 1.4×10^{-13} H. No change in the magnetic moment due to the current could be detected after 7 hours, to within the 2 per cent precision of their measurement, so the current was at least 98 per cent of its initial value. Estimate the maximum possible resistance of the tube for circulating currents.

(c) The dimensions of the tube used in the experiment are shown in Figure 5. Estimate the maximum possible resistivity ρ_{max} of the lead films. Compare your answer with the resistivity of pure lead at 0°C, which is $1.9 \times 10^{-7} \Omega$ m.