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Preparing teachers to discuss superconductivity at high school level: a didactical approach

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Abstract

We present an introduction to superconductivity that is intended to support the teaching and learning of this subject at a high school level. As a first step we propose to focus on the main properties of superconducting materials, i.e. zero electrical resistivity and the Meissner effect. Physics teachers and students will thereby be enabled to distinguish between a perfect conductor and a superconductor.

Introduction

Superconductivity is a fascinating and challenging field of condensed matter physics. The ability to carry electric current without resistance has puzzled the scientific community since the first observation of the phenomenon in 1911. Experimental and theoretical physicists all over the world have put a considerable amount of effort into understanding the microscopic origin of the complete loss of electrical resistivity that takes place in some materials, named superconductors, when they are cooled to sufficiently low temperatures. At the same time, a number of material scientists and engineers have been working to improve the properties of superconductors in order to establish a superconductor-based technology.

The scientific developments in the field of superconductivity research are closely related to advances in our understanding of matter. At the beginning of the twentieth century the existing models of the structure of matter were based on a classical approach. However, superconductivity is a quantum phenomenon, and it is not surprising that a successful theoretical explanation of it had to wait almost 50 years to be formulated, once the basis of quantum mechanics was well consolidated. The so-called BCS microscopic theory succeeds in explaining most of the properties of the existing conventional superconductors. But new superconducting materials, like the ceramic high temperature superconductors, have been discovered since then with a diversity of properties that do not seem to follows the BCS theory.

Superconductivity cannot be observed in our everyday life because the phenomenon occurs at extremely low temperatures—temperatures a few degrees above absolute zero (0 K). Until 1987 experimental observation of the properties of a superconductor was restricted to researchers in their scientific laboratories. The discovery in that year of materials that become superconducting at the temperature of liquid nitrogen (77 K) made the demonstration of superconductivity much more accessible. It is now possible to perform a classroom demonstration of magnetic levitation using a superconducting tablet, a small magnet

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and liquid nitrogen. This simple experiment always captures the attention of the public, from school teachers and students to even the more experienced researchers. That possibility has motivated the discussion of the phenomenon in high school classes, and a number of articles and materials have been proposed since then. Most are classroom demonstrations based on the properties of superconductors (Abd-Shukor and Lee 1998, Guarner and Sánchez 1992, González-Jorge and Domarco 2004), while many others explore the technological application of superconducting materials (Gough 1998, for instance).

A reasonable understanding of this topic requires previous knowledge of classical physics (particularly thermodynamics and electromagnetism) as well as concepts of quantum mechanics and solid state physics that are not usually taught at high school level. Thus, superconductivity might provide an interesting bridge between concepts usually discussed in high school and new ones that should be incorporated in order to update the curriculum (Ostermann 2000). Due to the complexity of the subject, we propose as a first step starting by discussing the two main properties of a superconductor. The idea is that teachers will be able to distinguish between a perfect conductor and a superconductor. To accomplish this goal, we need to examine the mechanism of conduction and the magnetic behaviour of an ordinary metal.

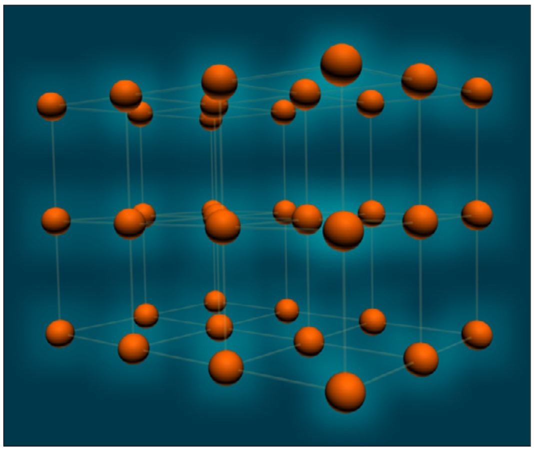

Figure 1. A simple metal model.

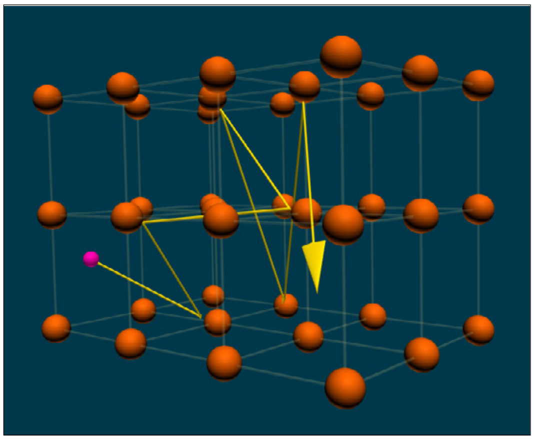

Figure 2. Random movement of a free electron.

Electronic conduction in a metal

A simple metal model

When the atoms of a certain element are brought together to form a crystalline metal, the outermost electrons, i.e. those weakly bound to the atomic nucleus, become detached and are free to wander through the metal. These are the free or conduction electrons that are able to carry an electric current. A metal can then be pictured as a regular array (the crystal lattice) of positive ions surrounded by free electrons (figure 1). At a temperature different from absolute zero, the positive ions oscillate about their equilibrium positions, while the free electrons themselves undergo a random motion like molecules in a gas (figure 2).

Electric current

In the absence of a voltage source, the free electrons in a conducting wire exhibit disordered motion. Such a movement does not produce an electric current since the average displacement is zero. When the wire is subjected to a potential difference, each electron feels an electric force, which gives rise to a net drift. It is important to stress that the motion of the electrons is still disordered but now with a net drift in the direction of the applied electric field. This flow of electric charges produces an electric current.

Electrical resistivity

The electric current suffers opposition from two factors: the presence of impurities and imperfections in the crystal lattice, and thermal vibrations in which the positive ions oscillate about their equilibrium positions. These two effects destroy the perfect periodicity of the lattice and scatter the free electrons in different directions. This opposition to the electric current is called electrical resistivity (ρ) and it is responsible for the Joule effect—the heat generated as a current passes through the wire.

Temperature dependence of the electrical resistivity

The electrical resistivity of a metal decreases as the material is cooled. When the temperature is lowered, the electrons suffer less scattering since the ions' thermal vibrations diminish. The behaviour of the electrical resistivity of a perfect metal (without impurities and imperfections in the crystal lattice) with temperature is shown in figure 3.

We see that the resistivity tends to zero as the temperature approaches absolute zero. In this situation only thermal vibrations contribute to the material resistivity, and they have a minor effect in the vicinity of absolute zero. We will see in the next section that this curve does not characterize the phenomenon of superconductivity. Furthermore, real materials always exhibit impurities and imperfections, which give rise to a residual resistivity ρ_0 at absolute zero. The higher the content of impurities, the higher the residual resistivity.

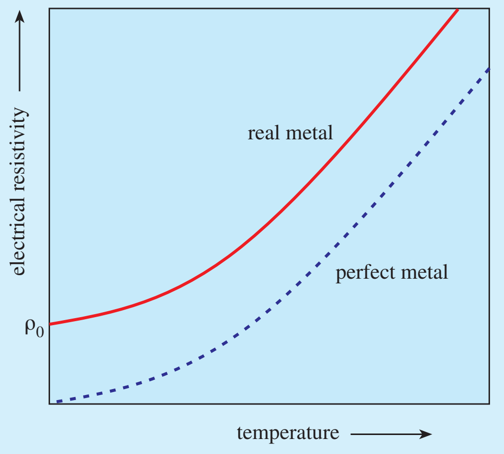

Figure 3. Temperature dependence of the electrical resistivity of a conductor.

Superconductivity

Zero electrical resistivity

The electrical behaviour of a metal in the vicinity of absolute zero (figure 3) was not known until 1908. The study of the electronic behaviour of materials at extremely low temperatures was possible only after the successful liquefaction of helium. This allows one to attain temperatures down to about 4.2 K. Such a technique first became available in 1908 at the Cryogenic Laboratory of the University of Leiden, at that time under the direction of the Dutch physicist Heike Kamerlingh Onnes. Onnes became one of the pioneers of low temperature physics. In 1911, while measuring the electrical resistance of pure mercury, he found that the resistance fell sharply at about 4.2 K, and below this temperature it suddenly dropped to zero. The curve obtained by Onnes is shown in figure 4.

Note that this curve differs from the usual behaviour of metals illustrated in figure 3. The material loses its resistance completely at a temperature called the critical temperature or transition temperature, written T_c in figure 4. Onnes called this new state of zero resistance 'superconductivity'. Following Onnes's discovery, many other elements, such as tin and aluminium, have been found to lose their resistivity abruptly at a temperature whose value varies from material to material. In fact, superconductivity occurs in a wide variety of materials, including simple elements, a number of metallic alloys and many other complex compounds. For his studies on the properties of matter

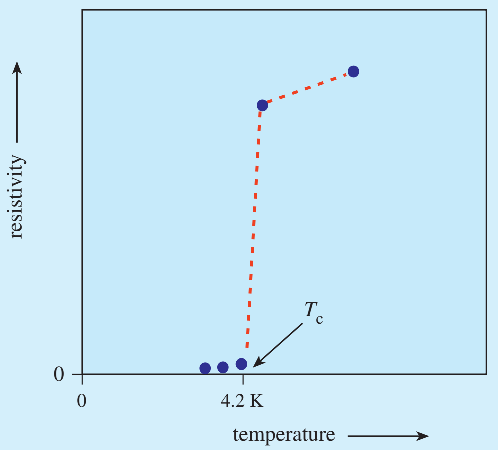

Figure 4. The electrical resistivity of mercury drops abruptly to zero at 4.2 K.

at low temperatures, Onnes was awarded the Nobel Prize in Physics in 1913.

Nevertheless, the complete loss of electrical resistivity is but one of the basic properties of superconductors. As we will see in the following, they are more than perfect conducting materials.

Meissner effect

Until 1933, it was thought that infinite conductivity was the major property of a superconductor. In this year, however, the German physicists W Meissner and R Ochsenfeld found that superconductors exhibit a special magnetic behaviour that differs from what would be expected for a perfect conductor, i.e. a material with infinite conductivity.

Before proceeding to the finding of Meissner and Ochsenfeld, it would be helpful to consider certain points. As far as the magnetic behaviour of a material is concerned, it is important to distinguish between an applied magnetic field $\boldsymbol{H}$ and the response of the material to the field, the magnetization $\boldsymbol{M}$. The magnetic field $\boldsymbol{H}$ is generated by a permanent magnet or by electrical currents outside the material from either a solenoid or an electromagnet. Hence the magnetic field $\boldsymbol{H}$ can be controlled externally, while the magnetization $\boldsymbol{M}$ is a response that depends on the particular properties of the material. The vector sum of these two quantities gives rise to a net field $\boldsymbol{B}$, called the magnetic induction vector or magnetic flux density, which is given by the following relation (in the MKS system):

$$\boldsymbol{B} = \mu_0(\boldsymbol{M} + \boldsymbol{H}) \qquad (1)$$

where μ_0 is the magnetic permeability of vacuum, which is a universal constant.

It is also well known that the magnetic behaviour of a conductor follows the Faraday–Lenz law of electromagnetism. This means that a conductor reacts only to *changes* in the strength of the magnetic field. The variation of the field induces surface currents that flow in such a manner as to create a magnetic flux density that everywhere inside the material is exactly equal and opposite to the flux density due to the applied field. At ordinary temperatures, these currents decay almost instantaneously due to the finite resistivity of the conductor and, as a result, the external flux penetrates the bulk of the material.

Let us return now to the experiment of Meissner and Ochsenfeld. It is sketched on the left side of figure 5. They cooled specimens of lead and tin below their critical temperatures in the presence of a constant magnetic field $\boldsymbol{H}_a$. For temperatures higher than T_c (*a*), the specimen behaves as an ordinary conductor with finite resistivity. However, when cooling the superconductors below T_c in the external field (*b*), Meissner and Ochsenfeld observed that the previously established flux density was suddenly expelled at the transition temperature ($\boldsymbol{B} = 0$ inside the superconductor).

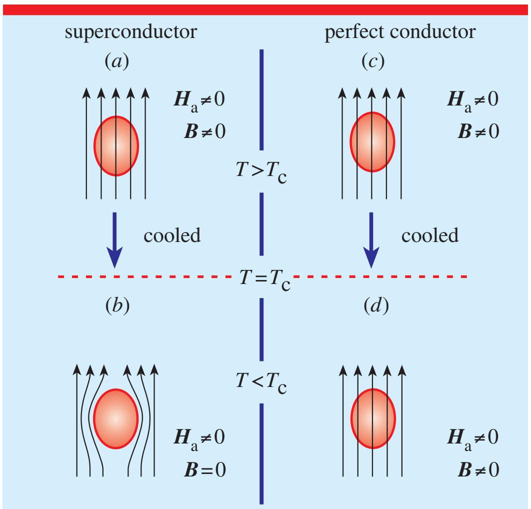

Figure 5. Magnetic behaviour of a superconductor and a perfect conductor in the presence of a constant magnetic field; the flux density $\boldsymbol{B}$ refers to the value inside the specimen. (*a*) and (*c*): the material is at a temperature $T > T_c$. Due to its finite resistivity, the flux lines penetrate the interior of the specimen. (*b*) and (*d*): for $T < T_c$, the superconductor excludes the magnetic flux from its interior, while the magnetic state of a perfect conductor does not change.

Note that the observation made by Meissner and Ochsenfeld cannot be explained by the condition of zero resistivity. Consider a conductor subjected to the same conditions described above for a superconductor (right side of figure 5). Applying the same reasoning discussed previously, we can conclude that, for a temperature higher than T_c (*c*), the flux penetrates the material due to its non-zero resistance. But if the conductor becomes resistanceless at a temperature $T < T_c$ (*d*), the flux density inside our hypothetical perfect conductor remains the same since the external field has not been changed during the cooling procedure.

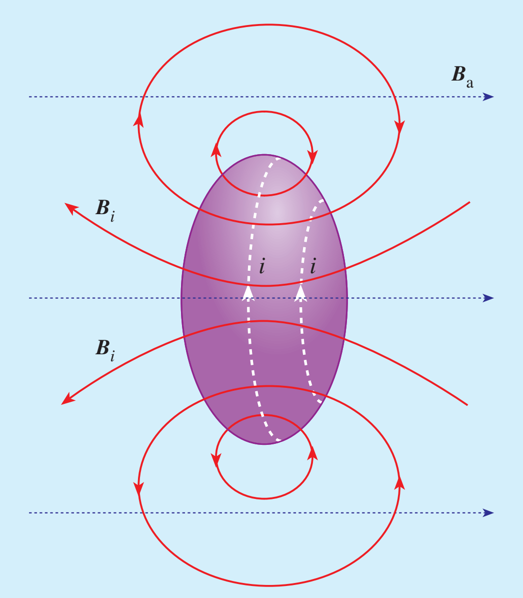

Figure 6. Magnetic flux distribution in a diamagnetic body such as a superconductor. When a magnetic field is applied to a superconductor, persistent currents i circulate in the surface of the material in such a manner as to produce a flux density $B_i = —B_a$, which exactly cancels the flux inside the superconductor due to the applied field.

The total exclusion of the magnetic flux density from the interior of a superconductor is known as the Meissner effect. Since $B = 0$, it follows from relation (1) that $M = -H_a$, and it is said that the superconductor is perfectly diamagnetic.

In figure 6 we see how a perfectly diamagnetic material behaves in the presence of an external magnetic field. Surface currents i generate a flux density B_i that exactly cancels out the flux density B_a of the applied magnetic field everywhere inside the material. At the boundary of the superconductor, the superposition of these two contributions gives rise to the net distribution of flux lines depicted in figure 7.

The famous demonstration of levitating a magnet above a superconducting disk is a manifestation of the Meissner effect. An interesting discussion on this demonstration can be found in Brown (2000). With the development of high temperature superconductors this appealing experiment is straightforward since it only requires the use of liquid nitrogen (figure 8).

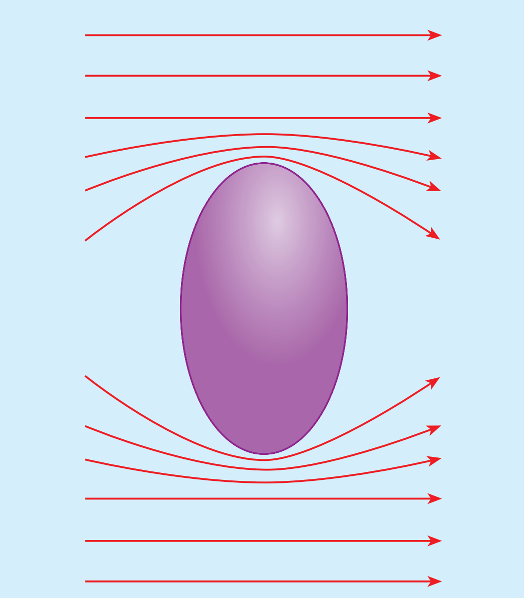

Figure 7. Net distribution of magnetic flux in the vicinity of a diamagnetic body.

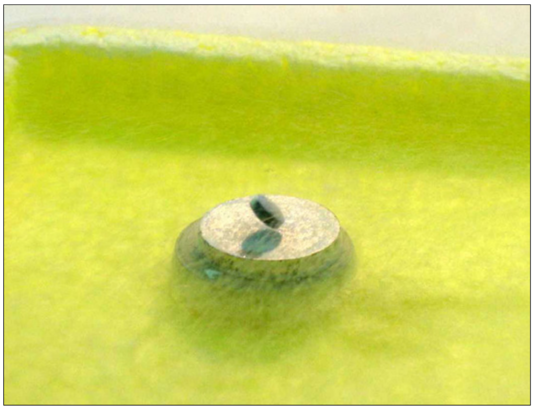

Figure 8. A small magnet levitates above a platelet of high temperature superconductor.

Electronic phase transition

One of the most interesting aspects of the superconducting state is that it is a phase transition. Phase transitions are a class of phenomena very common in nature. Examples of phase transitions are the transformation from ice to liquid and that from liquid to gas. Certain parameters control phase transitions. In the case of the solid–liquid–gas system, these parameters are the temperature T and pressure P. These two variables can be controlled in the laboratory and are called thermodynamic variables. Given values

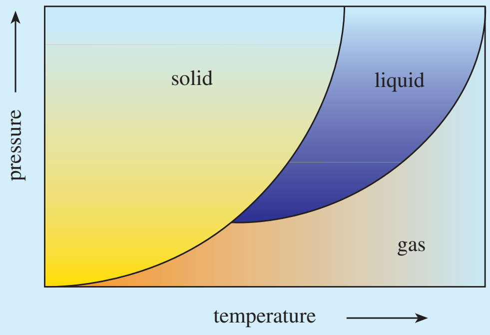

Figure 9. Phase diagram of the solid—liquid—gas system.

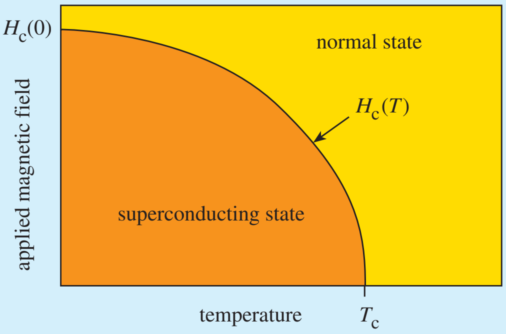

Figure 10. Phase diagram of a type-I superconductor.

of pressure and temperature determine the state of the system, giving rise to a phase diagram like the one shown in figure 9.

Well-defined phase boundaries separate one state from another. For a fixed pressure, the system can go from one state to another by a simple temperature change. At sea level, for example, water is found in the gas phase (steam) if the temperature is above 100 °C. With decreasing temperature the gas condenses into the liquid phase. A further decrease of temperature takes water to a solid phase (ice).

Each phase transition has its own thermodynamic parameters. In the superconducting transition the temperature is one of these parameters; the magnetic field is another. The superconducting state is stable up to a critical magnetic field H_c. For fields higher than the critical one, superconductivity is destroyed. This gives rise to a phase diagram like the one shown in figure 10. The curve is a boundary that separates the normal from the superconducting state. The critical temperature decreases as a function of the magnetic field. Superconducting materials that show a phase diagram like the one shown in figure 10 are known as type-I superconductors.

There are, however, some superconductors that have a more complicated phase diagram. In the case of type-II superconductors, there is also a third state called the mixed state, in which magnetic flux lines partially penetrate within the material while the bulk of the material remains in the superconducting state. The phase diagram for type-II superconductors is briefly discussed by Brown (2000). Actually, for technological purposes type-II superconductors are more interesting because they can sustain superconductivity in stronger magnetic fields. The extensively studied high temperature superconductors belong to this class of materials.

At the phase transition, there is a change in the degree of disorder. For example, in the case of a solid–liquid–gas system, the organization of the molecules determines in which state the system is found. The molecules in a gas do not interact with each other, forming a disordered state. As the temperature decreases, the disorder diminishes and the liquid is more ordered than the gas state. The solid state is so ordered that we can even know where its molecules are situated.

Let’s consider now the case of the superconducting transition. The absence of electrical resistivity is one of the main properties of superconducting materials. Since electrical conduction is due to charges (electrons) moving through the material, we can suppose that some change in the organization of the charges occurs when the material is brought from the normal to the superconducting state. Indeed the superconducting state is a manifestation of an ordered electronic state.

The electronic order in the superconducting state involves an attractive interaction between the electrons. In 1957, John Bardeen, Leon Cooper and Robert Schrieffer[1] proposed a microscopic theory of superconductivity, referred to as the BCS theory after the initials of their surnames. According to them, the electrons in a superconductor arrange themselves into

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[1] Joint winners of the 1972 Nobel Prize in Physics.

pairs called Cooper pairs. But the attraction between two electrons cannot be understood in the framework of classical physics. Only with the development of quantum mechanics could the microscopic theory emerge.

Clearly a discussion of the microscopic origin of superconductivity, as well as many other interesting features of this striking phenomenon, cannot be properly presented in this article. We refer the interested reader to the excellent books of Vidali (1993) and Ginzburg and Andryushin (1994).

Superconducting materials

Superconductivity is not a rare phenomenon. About half of the metallic elements and also a large number of alloys and intermetallic compounds have been found to superconduct at low temperatures. Currently there are 29 simple elements that exhibit superconductivity at normal pressure with critical temperatures varying between 0.0003 K for rhodium (Rh) and 9.25 K for niobium (Nb). Many other elements, such as Si and Ge, become superconductors when subjected to very high pressures. From a technological point of view, the alloy Nb–Ti ($T_c = 10$ K) and the intermetallic compound Nb_3Ge ($T_c = 18$ K) are particularly important. Most wires and commercially available superconductor devices are manufactured from these materials.

The low temperature required to maintain the material in the superconducting state is a limiting factor that has prevented many technological applications of superconductivity. The handling of liquid helium is a complex and expensive task that requires some technical skill. A great deal of effort has been directed towards finding new superconductors with higher critical temperatures. The chronological evolution of the critical temperature of superconductor materials can be seen in figure 11. Until the mid-1980s the intermetallic compound Nb_3Ge held the record high T_c ($\sim$23 K), which still required liquid helium as a coolant. The remarkable year of 1986 opened a new age in the study of superconductivity. In this year, K A Müller and J G Bednorz, researchers at the IBM Research Laboratory in Switzerland, synthesized a ceramic material composed by lanthanum, barium, copper and oxygen with a T_c of 30 K. This discovery stimulated new research concerning copper oxide compounds (or cuprates), and similar materials with higher critical temperatures were soon discovered. One important development was the discovery of the cuprate $YBa_2Cu_3O_7$ in 1987. With a critical temperature of 92 K, the YBCO compound surpassed for the first time the technological obstacle represented by the boiling point of liquid nitrogen (77 K). The use of liquid nitrogen as a refrigerant is far safer and much less expensive than liquid helium, which justifies the great enthusiasm caused by the discovery. The search for new materials in this class of superconductors culminated with the discovery of the mercury-based cuprate $HgBa_2Ca_2Cu_3O_{8-\delta}$, which exhibits the highest known critical temperature ($T_c \sim 133$ K) at ambient pressure. In recognition of their important breakthrough in the discovery of ceramic superconductors, Bednorz and Müller were awarded the 1987 Nobel Prize in Physics.

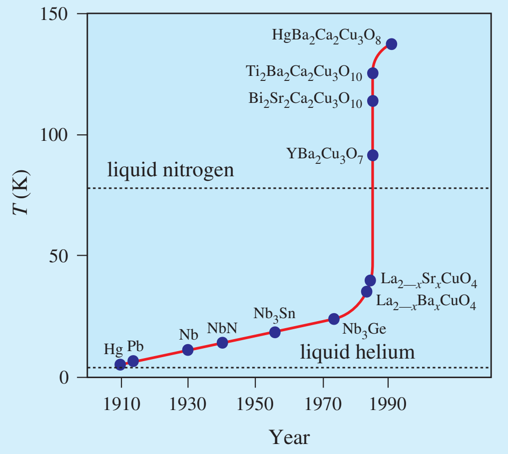

Figure 11. Evolution of the record superconducting critical temperature.

Superconductivity also occurs in exotic systems composed of organic molecules. Critical temperatures of the order of 10 K have been observed in systems of this kind. An interesting example of an organic superconductor is made of fullerenes containing alkaline atoms. The fullerene molecule, C_{60}, has the shape of a soccer ball in which carbon atoms are arranged at the vertices of regularly distributed hexagons and pentagons. High critical temperatures were found in these systems: for example, a critical temperature of 29 K has been observed in the case of Rb_3C_{60}.

Final remarks

Technology based on superconductivity is already present in many commercially available products including powerful superconducting magnets for application in medical magnetic resonance imaging and in high energy physics.

Nearly 100 years have passed since the first observation of superconductivity in 1911. It is worth mentioning that on four occasions the Nobel Prize in Physics has been awarded for work on superconductivity. Despite the scientific and technical achievements made since then, it is still an active field of research. Every year new superconductors are being discovered. Understanding their properties and, more importantly, the way superconductivity occurs in these materials can help to show how we can manufacture superconductors suitable for many more applications.

We hope the didactic approach proposed in this article will contribute towards the updating of the physics curriculum in high schools, exploring a theme of current scientific research in a way that is accessible to physics teachers. We believe that a detailed discussion of the fundamental properties of superconductors helps to reinforce concepts usually discussed in high school physics classes, and also provides the opportunity to introduce new ones.

Acknowledgments

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