

Superconductors – Lesson Outline

Syllabus References

- 9.4.4.2.6 - Discuss the BCS theory
- 9.4.4.2.7 - Discuss the advantages of using superconductors and identify limitations to their use
- 9.4.4.3.3 – Analyse information to explain why a magnet is able to hover above a superconducting material that has reached the temperature at which it is superconducting
- 9.4.4.3.4 - Gather and process information to describe how superconductors and the effects of magnetic fields have been applied to develop a maglev train

Resources

- Video: Meissner Effect
<http://www.hscphysics.edu.au/resource/Meissner.flv>
- Video: Superconductor Theory
<http://www.hscphysics.edu.au/resource/Supertheory.flv>
- Video: Superconductor Applications
<http://www.hscphysics.edu.au/resource/8n98w83hfv9356z>

Pre-video Activities

Split students into groups of four, hand out butcher's paper and markers. Students draw a concept map with the following words:

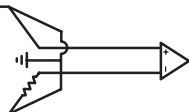
Metals Lattice Vibrations Electron
Resistance Temperature Conduction

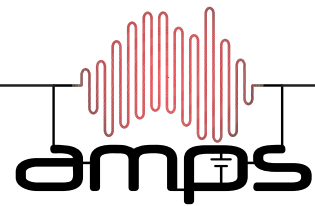
View Video

- Video: Meissner Effect
<http://www.hscphysics.edu.au/resource/Meissner.flv>

Activities

With students in the same groups of four, hand out blank butcher's paper. Students model what was happening in the video using physics principles they know. They then check if they were right in the following theory video.





View Video

Video: Superconductor Theory
<http://www.hscphysics.edu.au/resource/Supertheory.flv>

Activities

Students model the Meissner Effect again, this time using principles they learnt about in the video.

Students add to their concept map, using their own words.

In groups, students compare the model for the conduction of electricity in metals at room temperature with the model for conduction of electricity in superconductors below the critical temperature. Encourage the use of diagrams and tables.

Representatives present the group's responses to the rest of the class. Encourage class discussion and questioning.

Students then brainstorm potential applications of superconductivity. Then students watch a video with a physics researcher discussing applications.

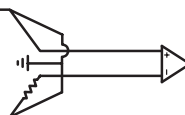
View Video

Video: Superconductor Applications
<http://www.hscphysics.edu.au/resource/8n98w83hfv9356z>

Post-video Activities

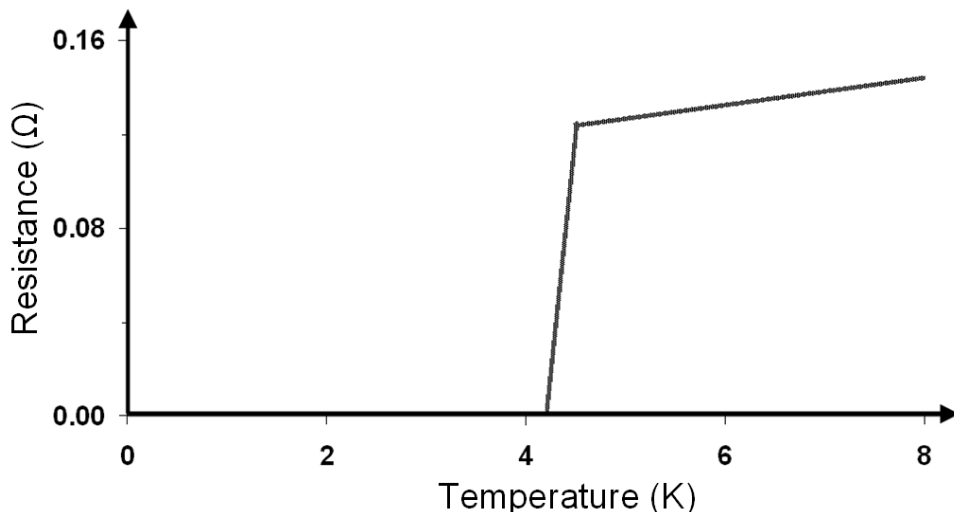
Post-video Activity: Concepts in Superconductivity quiz
Students complete the quiz individually.

Advanced students read through the discussion about different explanations for superconductors.



Superconductors – Concepts

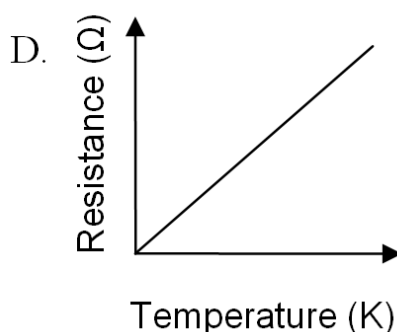
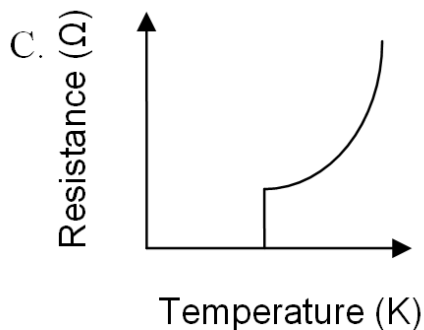
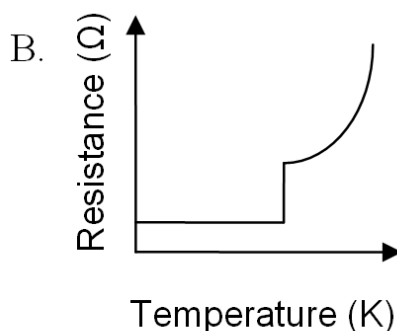
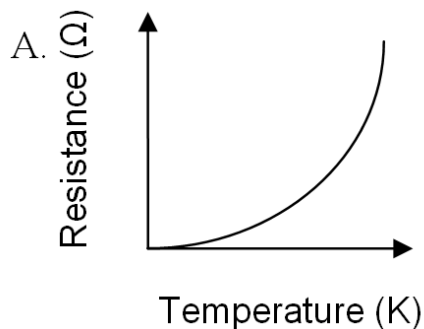
Q1. The resistance of mercury at various temperatures is shown in the graph.



Between which two temperatures does mercury always act as a superconductor?

- A. 0 K and 4.2 K
- B. 4.2 K and 4.5 K
- C. 4.5 K and 8.0 K
- D. 0K and 8.0 K

Q2. Which of the following graphs show the behaviour of a superconducting material?



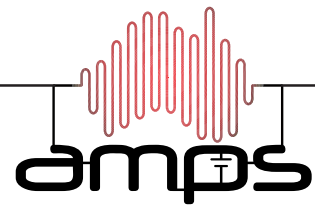
Extended Answer

Q3. The following image shows a magnet hovering above a superconducting disk.



Explain why the magnet is able to hover above the superconductor.

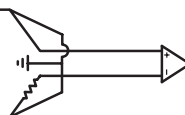
Q4. Some materials become superconductors when cooled to extremely low temperatures. Identify THREE properties of superconductors.

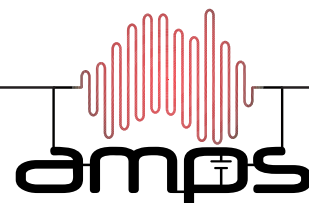


Q5. Explain how superconductivity can be modelled according to the BCS theory and the consequences for technology.

Q6. There are a few areas in which energy savings can be made by the use of superconductors. One of these is electricity generation and transmission. Discuss how energy savings can be achieved in this area.

Q7. Identify limitations of superconductors in technology.





Superconductors –

A discussion of different explanations

There are a number of explanations that can be given to students to help them visualize and understand superconductivity. This resource discusses a few of these explanations and is intended for teachers and advanced students.

Standard Explanation

Electrons are able to move through a conductor without feeling resistance because they form Cooper pairs. The lattice does not have enough thermal energy to scatter the pairs. The electrons form a Cooper pair through an interaction with the crystal lattice. As one electron moves through the lattice, the lattice ions are attracted to the electron and so move closer to the electron. This creates a region of excess positive charge. Another electron will be attracted to this region, and thus move towards the first electron. This attraction through the lattice forms the Cooper pair bond and the electrons then move through the lattice undisturbed.

However, there is a significant problem with this explanation in terms of conservation of momentum. There is another explanation that accounts for momentum.

Advanced Explanation

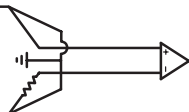
An electron is travelling along and collides with the lattice. The lattice absorbs some of the electron's momentum. This momentum propagates as a wave in the lattice called a phonon. A phonon is a quantised (local) lattice vibration. The phonon travels through the lattice until a while down the track it bumps into a second electron. The momentum is transferred to this second electron, which then experiences a push forward. As phonons are quantised particles, all the momentum must be transferred. The lattice is therefore facilitating the bond between the first and second electron. As the lattice does not end up keeping any of the momentum, the electron pair has not lost any energy to the lattice and therefore has not felt any resistance. This momentum exchange obeys the conservation of momentum argument.

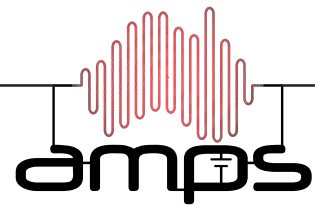
However, from this explanation, it is difficult to explain the origins of the critical temperature for the superconducting material. The inadequacy of this explanation is a result of the lack of considerations of quantum effects. These effects are discussed further in the technical explanation.

Analogy

Here is an analogy which better complies with the physics. In Naples, Italy there is an ingenious train called the funicular, which runs up and down a steep slope. Basically, a cable has the cars attached to it, and the cable runs on a loop around wheels at the top and bottom of the slope. As one car goes down, the other goes up, and the two exchange potential energy and form a pair with total momentum zero. This way, the motor driving the funicular does very little work.

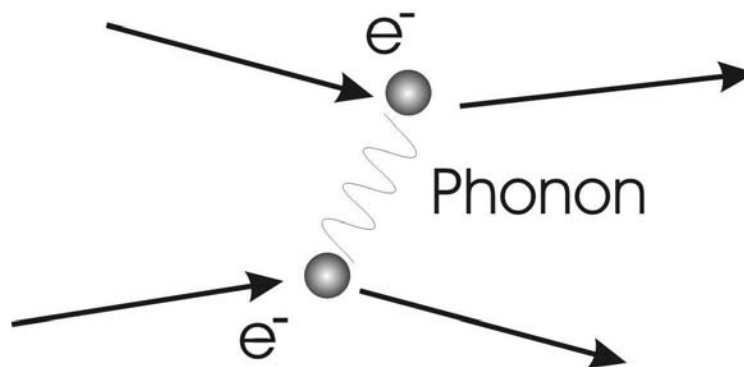
The Cooper pair is like a pair of cars on a funicular, in that each electron in the pair helps the other move more easily through the lattice. They have total momentum zero as well, but work better than the funicular in one way: no energy is expended as they move along, since they have too little momentum as a pair to lose energy by giving energy and momentum to the lattice in the form of phonons.





Technical Explanation

The technical explanation that best matches experimental evidence has been formulated using quantum physics. A key conceptual element in this theory is the pairing of electrons close to the Fermi level into Cooper pairs through interaction with the crystal lattice. This pairing results from a slight attraction between the electrons related to lattice vibrations; the coupling to the lattice is called a phonon interaction. The lattice absorbs and reemits momentum within the uncertainty time determined by Heisenberg's uncertainty principle, thus it can be considered a virtual phonon. This can happen over 100's of lattice spacings and the pairs are constantly breaking and reforming. However, as they are non-distinguishable, it is useful to think of a pair as constantly bound. Pairs of electrons can behave very differently from single electrons, which are fermions and must obey the Pauli exclusion principle. The pairs of electrons act more like bosons, which can condense into the same energy level. However, to form this boson pair, they must have opposite angular momentums or k-vectors due to the Pauli exclusion principle. The electron pairs have a slightly lower energy and leave an energy gap above them on the order of 0.001 eV, which inhibits the kind of collision interactions that lead to ordinary resistivity. For temperatures such that the thermal energy is less than the band gap, the material exhibits zero resistivity. The interaction is represented in the following diagram below (based on a Feynman diagram).



Key Points

- Electrons are linked indirectly by phonons
- They have the opposite momentum
- The paired electrons may be hundreds of lattice spacings apart.
- The pairs are constantly breaking and forming different pairs.
- The pairs of electrons act more like bosons, which can condense into the same energy level.
- The electron pairs have a slightly lower energy and leave an energy gap above them on the order of 0.001 eV, which inhibits the kind of collision interactions, which lead to ordinary resistivity.
- It is a quantum effect.