Activity 2 – The Meissner Effect and BCS Theory

2 The Meissner Effect

In 1933 it was found that not only do superconductors show zero electrical resistance, but they also expel any magnetic field from their interiors below a critical field strength (known as $\mathbf{H_c}$) which is dependent on temperature, geometry and on the material that the superconductor is made from. This effect was discovered by Robert Ochsenfeld and Walter Meissner and is known as the Meissner effect, and is depicted in Figure 1. With this new discovery many theories attempted to explain the mechanism behind superconductivity, but it was not until 1957, some 46 years after the initial discovery, that a full theory of superconductivity emerged.

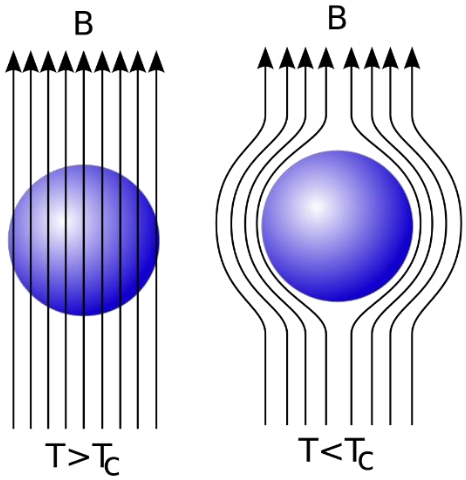
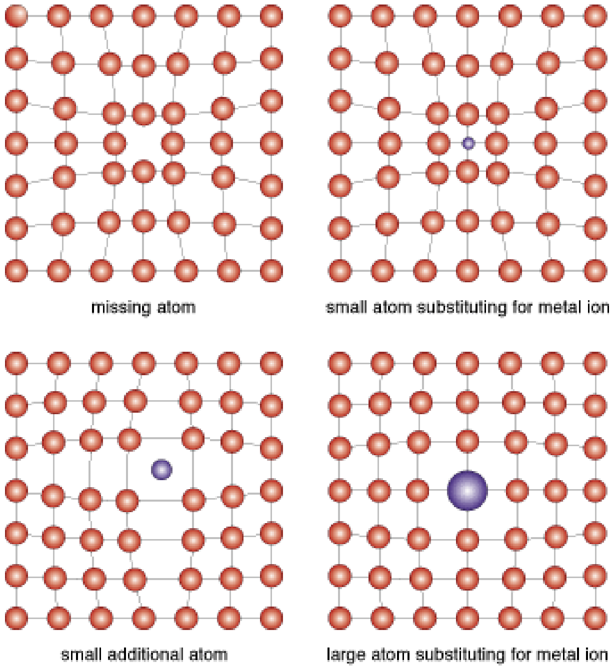


Figure 1: The Meissner effect. Below a critical temperature, magnetic field lines are excluded from a superconductor. (Obtained under a creative commons license via Wikipedia).

2.1 BCS Theory of Superconductivity

The theory, known as BCS theory, after its originators US physicists John Bardeen, Leon Cooper and John Schrieffer, explained how a so called supercurrent could flow without any resistance as well as explaining the Meissner effect. For their efforts the trio were jointly awarded the 1972 Nobel Prize in Physics.



missing atom

small atom substituting for metal ion

small additional atom

large atom substituting for metal ion

2.1.1 Conduction in a Normal Metal

To understand their theory, we first need to understand the origins of electrical resistance. In a metal, the electrical current is caused by the flow of free electrons through a lattice of positively charged ions. Resistance to the flow of current is caused by defects and impurities in this crystal lattice, as demonstrated in Figure 2. It is clear that resistance depends on the size of the sample you are measuring, (for example, a bigger sample will have more defects/impurities and so a bigger resistance). To make a meaningful comparison between different materials we must correct for this geometry factor by measuring the electrical resistivity ***ρ*** via:

$$\rho = R\frac{A}{l} \qquad (1)$$

Where **R** is the resistance, **A** is the cross sectional area of the sample and ***l*** is its length.

Figure 2: Defects and impurities in a crystal lattice cause resistance to the flow of electrical current. (Obtained under a creative commons license).

Exercise 1: Elemental lead (Pb) has a superconducting transition at 7.2 K. A cuboid sample of Pb has dimensions (l × w × h) of (4 × 0.5 × 0.5) mm. At 7.5 K the voltage across two contacts (V^+ and V^-) was measured to be 3.52 nV when a current of 1 mA was applied across two other contacts (I^+ and I^-) as shown in Figure 3.

i. Work out the resistivity of the sample and compare it to the literature value of ρ = 25 nΩ.cm at 7.5 K. If your value is different, why do you think this is? (Hint: think about the geometry factor A/l in the diagram and where the contacts are located). [*note: n*Ω *=* 10^{-9} Ω]

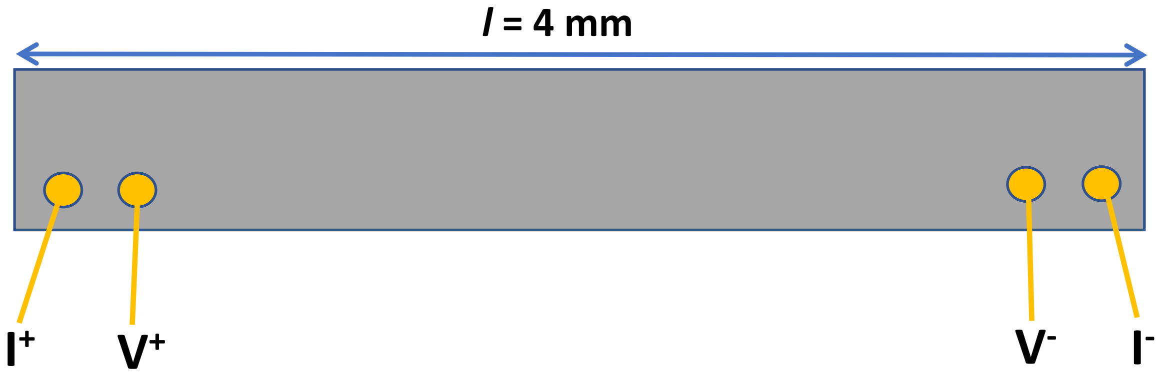


Figure 3: Sample of Pb with four contacts.

ii. The Pb sample is then cooled below 7.2 K and the voltage across V^+ and V^- is again measured for the same applied current of 1mA. The new voltage was recorded as 0.4 pV, what resistivity does this correspond to? What has happened to the sample of Pb? [*note: pV =* 10^{-12} *V*].

iii. Why do you think it is important to use four contacts to measure the resistance and not two?

2.1.2 Conduction in a Superconductor

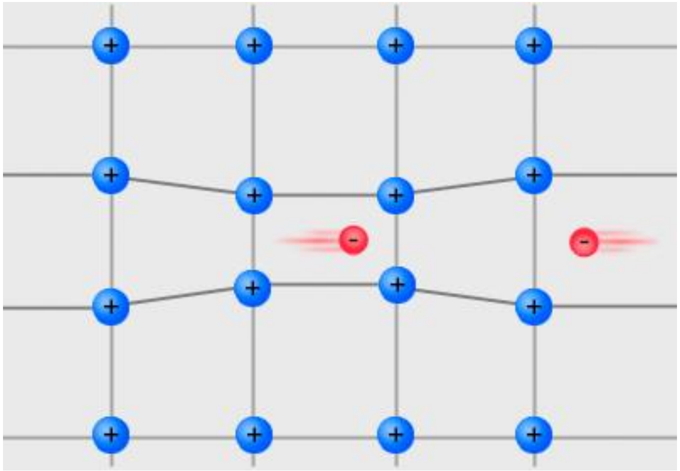


Figure 4: The formation of a Cooper pair of electrons in the crystal lattice of a superconductor. The second electron (right) feels the effects of the first electron (middle) as it passes through the crystal lattice. (Obtained under a creative commons license via Wikipedia).

So how is a superconductor different to a normal metal? The answer, as put forward by Leon Cooper, is that the supercurrent is not carried by electrons but by bound pairs of electrons known as Cooper Pairs. The idea is that there is an attraction between two electrons, which is contrary to what you would expect as two like charges would normally repel each other.

The mechanism for the attraction between electrons is demonstrated in Figure 4. As one electron (red) passes the lattice of positively charged ions (blue), the ions are attracted to the negatively charged electron. When a second electron passes through the same region some time later, it ‘feels’ the effect of the first electron via the distortion in the crystal lattice left from the first electron, thus creating a pair of bound electrons. So, the attractive interaction of two electrons is allowed via a lattice distortion. This interaction is known as an exchange of a phonon. Much like the photon, the quantised particle of light, the phonon is a quantised unit of lattice distortion, or more precisely, lattice vibration.

The Cooper pairs overlap strongly with each other as the temperature is further lowered below the critical temperature and a quantum state called a condensate is formed. The energy required to break a Cooper pair back into two electrons is then related to the energy of all the Cooper pairs (not just one) and so the superconducting state remains and is stable below the critical temperature. Above the critical temperature there is enough energy to break up the Cooper pairs, and so the superconducting state is destroyed. The condensate state also allows the Cooper pairs to flow as one entity which is not affected by lattice defects (which gave rise to resistance in a normal metal), allowing the supercurrent of Cooper pairs to flow without any resistance.

Useful Links

Meissner Effect

BCS Theory