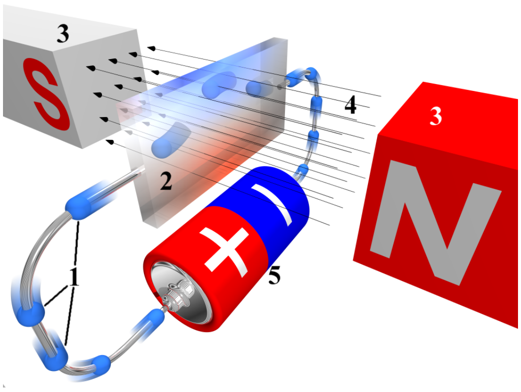
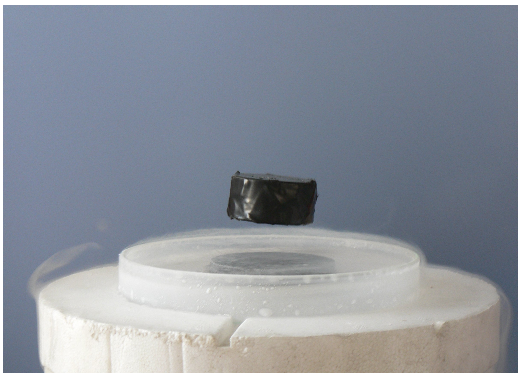
Lab II- Hall effect and superconductivity



(a) Hall Effect



(b) Superconductivity

Figure 1: Figure 1a shows how the Hall effect sets up a voltage difference between the top and bottom of the conducting material (2) because the charges are pushed towards one of the edges. It is the magnetic part of the Lorentz force that pushes the particles. Figure 1b shows a magnet hovering over a superconductor.

Motivation

We'll use the Hall Effect to detect a change in a magnetic field. The Hall Effect causes a voltage difference across a conductor placed in a magnetic field. By the Lorentz force, the electrons in the current is pushed towards one of the conductor's sides and causes a voltage difference to build up perpendicular to the current and the magnetic field. This voltage difference may be measured to detect the presence or absence of a magnetic field.

For a quick introduction on the Hall Effect, you should have a look at this video from Sixty Symbols[1].

History of the Hall effect

Many years before anyone was even talking about electrons, and less so about the Lorentz force, Edwin Hall discovered the effect which bears his name today in 1879. The effect magnetic fields has on currents had been discovered earlier through moving conductors in magnetic fields. This effect was discussed eagerly by Maxwell and others who thought that the force of the magnetic field acted on the conductor and not the current itself.

Hall, on the other hand found this 'contrary to the most natural supposition', noting that there was no effect without a present current and that the magnitude of the force was proportional to the strength of the current. He sought out to find the true explanation of the force and made a series of experiments. In the beginning he hoped to find an increased resistance in the conductor when a magnetic field was present. However, all experiments showed negative results.

Hall was determined that it should be possible to detect a deflection of the current to either side of the material. At the time, many viewed electric current as an incompressible fluid, so Hall figured it would be possible to detect stress in the conductor, with the current pressing against one side of the

[0] Images from http://commons.wikimedia.org/wiki/File:Hall_effect_A.png and http://en.wikipedia.org/wiki/File:Meissner_effect_p1390048.jpg

[1] http://www.youtube.com/watch?v=AcRCgyComEw

conductor. He repeated his experiment, this time by placing a galvanometer, an old version of our modern voltmeters, perpendicular to the current. In perfect agreement with Hall's assumptions, he detected a voltage difference, showing that in fact, the electrons were pressing against one side of the conductor.

Theoretical summary

Any charged particle traveling through a magnetic field is affected by the Lorentz force,

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1}$$

where $\mathbf{E}$ is the electric field, $\mathbf{v}$ is the velocity and $\mathbf{B}$ is the magnetic field. q is the charge of the particle.

We consider the situation where a current runs through a conductor. To begin with there is no electric field present, so the only force acting on the charges is the magnetic part of the Lortenz force,

$$\mathbf{F}_m = q\mathbf{v} \times \mathbf{B}. \tag{2}$$

When the magnetic field is perpendicular to the current, going from left to right in figure 1a, the electrons are pushed towards the upper side of the conductor (if you don't see why this is, you may have to read up on the right-hand rule - remember that the electron charge is negative!).

The negative charge that builds up on the upper side of the conductor will be canceled out by a positive charge on the other side. Eventually, the electric field that is set up becomes so strong that it will start working against the magnetic part of the Lorentz force. The reason why the current appears unaffected in a semiconductor placed in a magnetic field is because the electric and magnetic forces eventually cancel out each other.

1 Moving charges in magnetic field

The Lorentz force is given as

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}). \tag{3}$$

To test if this is true, we make use of an electric beam cannon. This is a device which is capable of firing off electrons with large speed, which are sent into a gas or onto a fluorescent screen. The electrons ionize the gas or the screen, which in turn emits light. This way we may observe the path of the electron beam - but remember that you don't actually see the electrons themselves!

We may calculate the magnetic field, by using the radius of the curvature of the beam and the velocity of the electrons:

$$qV = \frac{1}{2}mv^2 \tag{4}$$

which gives

$$v = \sqrt{\frac{2qV}{m}} \tag{5}$$

where V is the potential used to accelerate the electrons, q is the electron charge and m is the electron mass.

The radius of the curvature is related to the magnetic field through

$$R = \frac{mv}{qB} \tag{6}$$

which gives

$$B = \frac{mv}{qR} \tag{7}$$

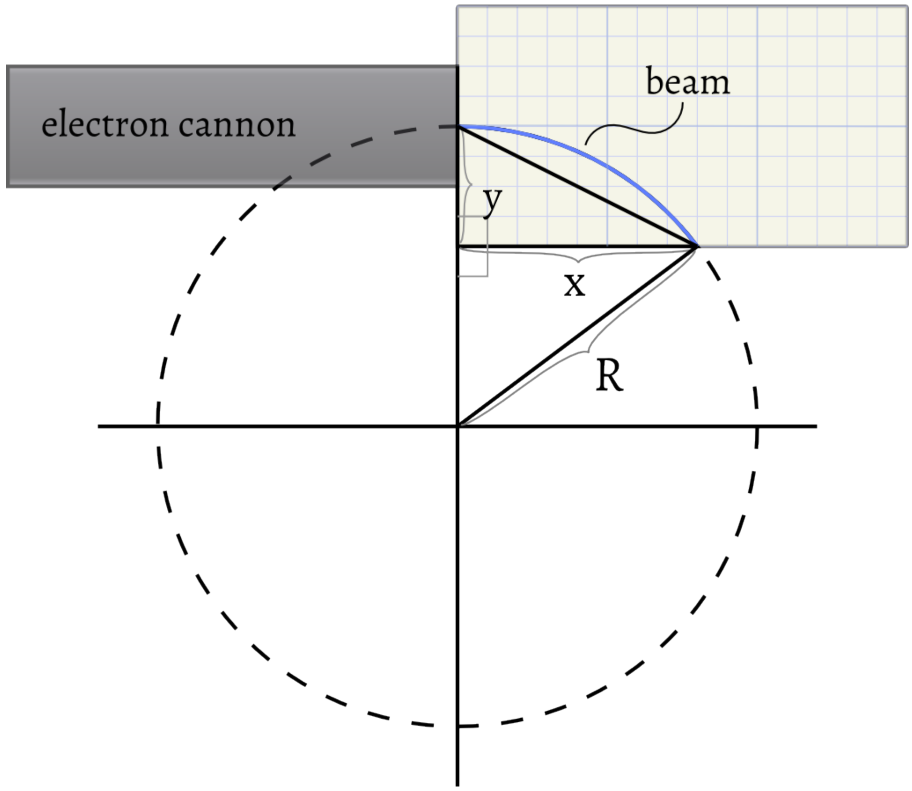


Figure 2: A sketch of the relations between the angles that enable us to find the curvature radius R.

under the assumption that the field is homogeneous. To find the radius we need to use some clever geometric relations shown in figure 2. The clever geometry is of course Pythagoras. From the figure we see that

$$(R-y)^2 + x^2 = R^2 \tag{8}$$

which gives

$$R = \frac{y^2 + x^2}{2y}. \tag{9}$$

The above equations are of course only useful if the electron moves with non-relativistic velocities. Otherwise we need to use relativistic relations between the curvature radius and the kinetic energy. We will not take this into account in this lab.

When the experiment is performed, remember to note x, y and the voltage.

1.1 Procedure

1. The equipment will be set up and demonstrated by a lab supervisor.
2. Observe the electron beam without any magnetic field present. Note the direction and curvature of the beam.
3. Introduce a strong magnet near the electron beam. Note what happens to the beam and note the curvature of the beam.

2 The magnetic field detector

Now that you know what happens to electrons moving through space, we will continue by exploring what happens to electrons moving as a current through a semiconductor. First of all, ask yourself what you expect would happen based on what you found in the previous experiment and the theory given above.

In this experiment we are using a small piece of a semiconductor on which we will measure the voltage in a perpendicular direction to the current. This means that we measure the voltage difference between the top and the bottom of the semiconductor pictured in figure 1a.

It is possible to find the exact magnetic field from a Hall effect sensor, but due to the limited time and resources in this lab, we will limit ourselves to detecting that a magnetic field is present or not.

2.1 Procedure

We want to measure the voltage across a semiconductor as a consequence of the Hall effect.

1. Connect the semiconductor to a current source.
2. Measure the voltage across the semiconductor perpendicular to the current.
3. Place the semiconductor in a magnetic field using the strong magnets in the lab. Measure the voltage again.

3 Superconductivity

Superconducting materials are able conducting current with zero resistance. Most materials become superconductors at extremely low temperatures, while others are superconducting at temperatures closer to what we are able to achieve in our lab.

One of these materials is $YBa_2Cu_3O_{7-x}$, also known as YBCO (Yttrium barium copper oxide). This material reaches superconductivity above the boiling point of liquid nitrogen, which is 77 K. This means that if we pour liquid nitrogen on top of a piece of YBCO, it will be cooled to a temperature below 77 K and become superconducting.

The piece we use has four contact points, C, C1, P and P1. See figure 3. We use the points P and P1 to measure the voltage difference, while we are sending current through C to C1.

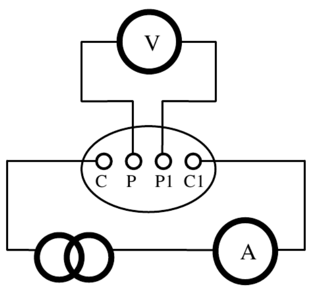


Figure 3: Setup for the superconductivity experiment

1. Connect the piece to a current source with an built-in ammeter and a voltmeter as shown in figure 3.
2. We put the piece in a bowl made of styrofoam.
3. The current is set to about 500 mA. The current should be constant (green light under CC (constant current) on the power source).

4. Cool the piece down with fluid nitrogen. (Use protective glasses and gloves.)
5. Notice how the potential difference between the points P and P1 varies.

4 Equipment list

- Electron cannon with power source and wires.
- Strong magnets.
- Semiconductors ready for Hall effect experiments.
- Wires
- Voltmeter
- Superconducting YBCO ready for experiment.
- Power source for YBCO experiment.

Prelab questions

- What happens to a current in a magnetic field?

  ☐ The current decrease.
  ☐ The current increase.
  ☐ The direction of the current will change.
  ☐ Nothing!

- Does the Hall effect influence the current running through a material?

  ☐ Yes.
  ☐ No.
  ☐ Sometimes.
  ☐ Depends on the material.

- What characterize a superconductor?

  ☐ They conduct electricity without resistance above a certain temperature.
  ☐ They conduct electricity without resistance at a certain temperature.
  ☐ They conduct electricity without resistance below a certain temperature.

- Did Edwin Hall receive a Nobel price in physics for his discovery of the Hall effect?

  ☐ Yes
  ☐ No

Lab journal: Hall effect **Name: .... Date:..................**

Moving charges in magnetic field

Questions:

1. What happens and why?

2. Use the relations from the lab text to calculate the approximate magnetic field B from the bar magnet. You may assume that the field is homogeneous. Is the speed realistic or should we actually have taken relativistic effects into account?

3. Use the force you found to calculate the magnetic field strength. Compare this to the field strength given on the magnet.

The magnet field detector

Questions:

4. Explain the Hall effect.

5. Can you explain why there is a difference when the magnetic field is present and when it is not?

6. How do you expect the voltage to vary with different amounts of current and with a stronger or weaker magnetic field (if you want to, you can do the measurements again to verify your assumptions.)

7. How can we use this device as a magnetic field detector?

8. Explain how our experiment shows the Hall effect.

Superconductivity

Questions:

9. Why does it make sense to measure the voltage difference between P and P1 while sending current through C and C1?

10. Why do we have to use a power source with a constant current? In other words, why does the power source have to limit its own current?

11. How did the potential difference between the points P and P1 vary?

12. Can you explain why it varies the way it does?