PHY331
Magnetism

Lecture 1

Overview

- Course syllabus / general information
- Quick revision of basic concepts
- Magnetization and susceptibility
- Using susceptibility to define magnetic materials
  - Diamagnetic
  - Paramagnetic
  - Ferromagnetic
- Summary

SYLLABUS

- Lecture 1: General introduction and revision, dipoles, magnetic materials, magnetisation, susceptibility.
- Lecture 2: Magnetic dipole moment of a circulating electron.
- Lecture 3: Langevin's theory of diamagnetism.
- Lecture 4: Classical treatment of paramagnetic susceptibility.
- Lecture 5: Magnetic dipole moment of an atom via Hund's Rules.
- Lecture 6: Quantum theory of paramagnetism.
- Lecture 7: Domain theory of ferromagnetism. Antiferromagnets.
- Lecture 8: Spontaneous magnetisation and the exchange interaction.
- Lecture 9: Weiss molecular field model of ferromagnetism.
- Lecture 10: Paramagnetic susceptibility of free electrons (Pauli paramagnetism).

What if we can't understand the lecture notes?

The material is covered in the two recommended text books,

"Introduction to Solid State Physics" Charles Kittel
7th Edition (John Wiley & sons)
Chapters 14 and 15

"Solid State Physics" J. R. Hook & H. E. Hall
2nd Edition (John Wiley & sons)
Chapters 7 and 8

All of these notes can be downloaded from PHY331 website. Can also get .pdf versions of the notes. These contain a little more 'background' information.

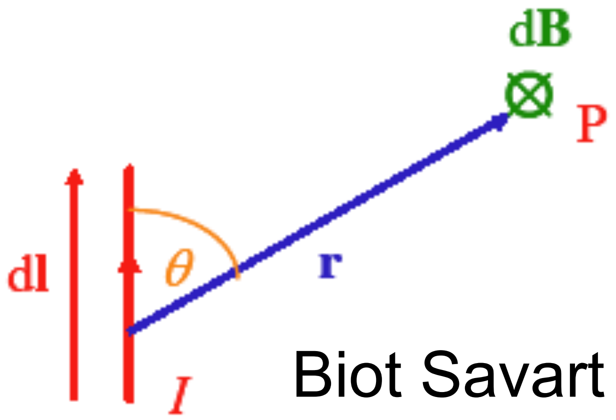
www.sheffield.ac.uk/physics/teaching/phy331/index.htm

Magnets - what's the big attraction?

- i) important physical state and
- ii) of considerable technological significance

  (all electrical motors and transformers, magnetic fields for all purposes, including medical, magnetic storage, sensors, security tags, etc etc)

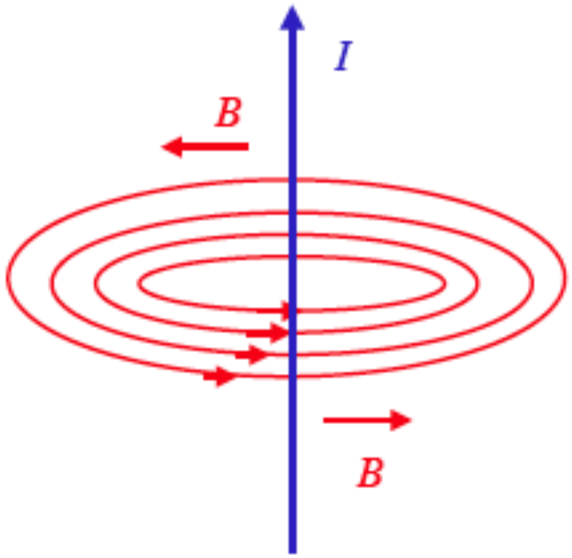
Magnetic fields from conduction currents (*i*)



Biot Savart Law

$$dB = \frac{\mu_0 i dL \sin\theta}{4\pi r^2}$$

The strength of the magnetic interaction is defined by μ_0 which is known as the permeability of free space. μ_0 has a value of 4 x 10^{-7} Hm^{-1}. The unit of B is the tesla (T).

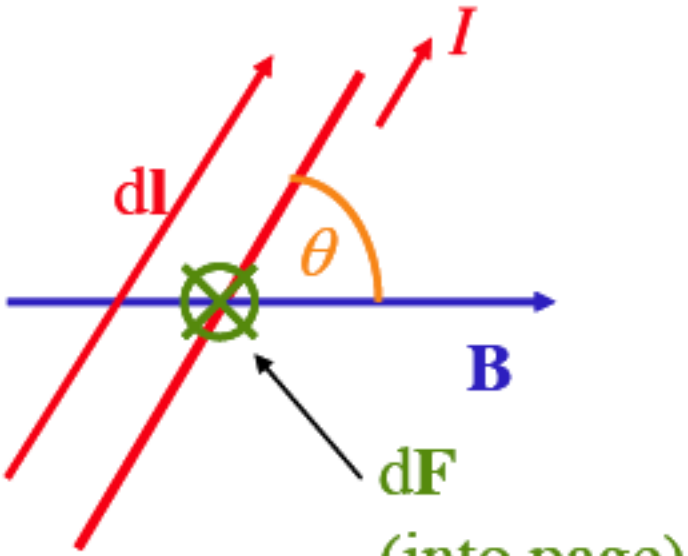


$$dB = \frac{\mu_0 i}{2\pi r}$$

For an infinitely long wire

See lecture 10 of 2nd year EM notes

Force on a current carrying element



Experimentally the magnetic force
d*F* acting
on a current element length d*L*
carrying a current i and placed
in a uniform field *B* is found to be

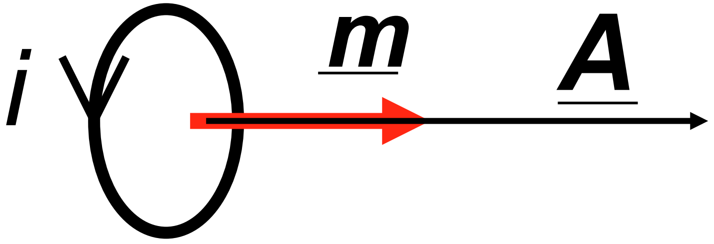
$$dF = BidL\sin\theta$$

The direction of the magnetic force
is normal to the plane
containing both *B* and d*L*. In vector
notation:

$$dF = idL \times B$$

Magnetic ‘dipoles’

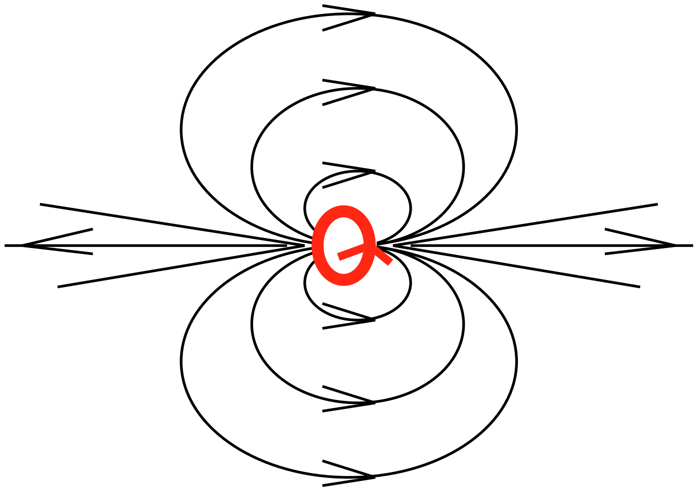
- Easiest way to think of a magnetic dipole is as a result of a current flowing in a miniature wire. Leads naturally to a picture of electron ‘currents’ in atoms.
- This results in a magnetic dipole moment ***m***, defined by a current *i*, and a vector area **A.** Arrow shows the sense of the vector area.



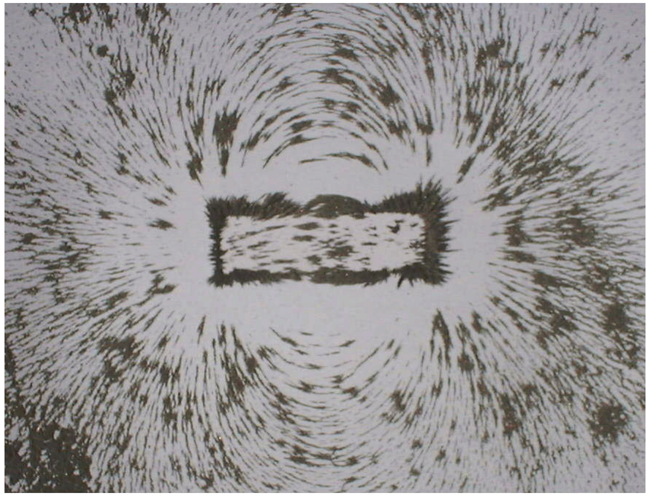
$$\underline{m} = i\underline{A}$$

Magnetic fields…

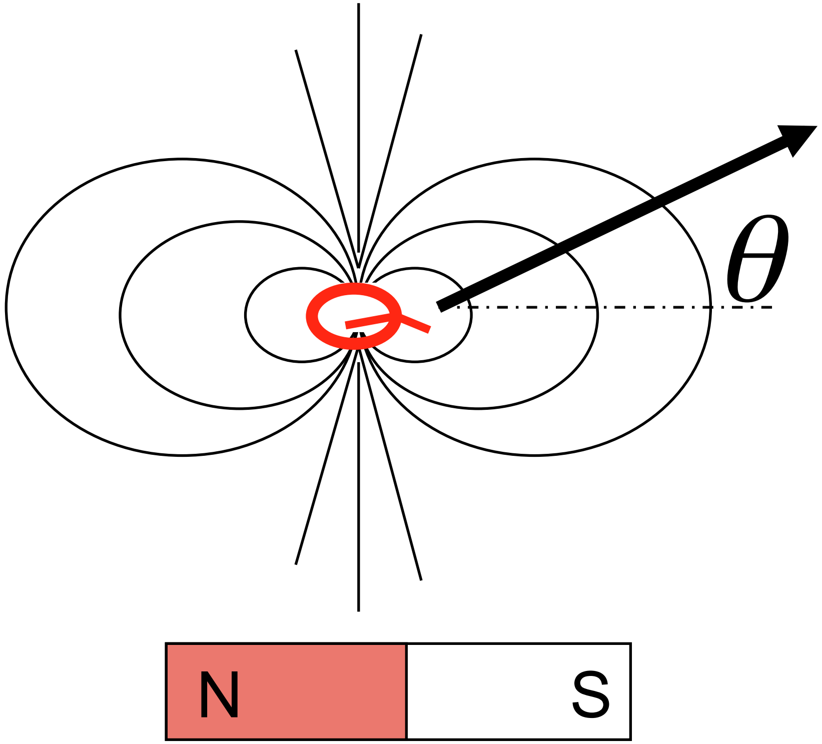
Magnetic induction field (B-field)



$$\underline{B} = -\nabla V_M$$



Potential (scalar) field



$$V_M = \frac{m\cos\theta}{4\pi r^2}$$

Placing a magnetic dipole in a B field

- The **energy** U of a magnetic dipole m in a uniform Magnetic Induction Field B

$$U = -\underline{m} \cdot \underline{B}$$

- The **torque** Γ on a magnetic dipole m in a uniform Magnetic Induction Field B (*Torque* is a measure of how much a force acting on an object causes that object to rotate)

$$\underline{\Gamma} = \underline{m} \times \underline{B}$$

- Scalar field can be used to 'generate' forces (which are usually vector fields). In general, the force $\underline{F}$ can be described by the gradient of a scalar field U, i.e.

$$\underline{F} = -\nabla U$$

- The **force** F on a magnetic dipole $\underline{m}$ in a non-uniform Magnetic Induction Field $\underline{B}$

$$\underline{F} = -\nabla \underline{m} \cdot \underline{B}$$

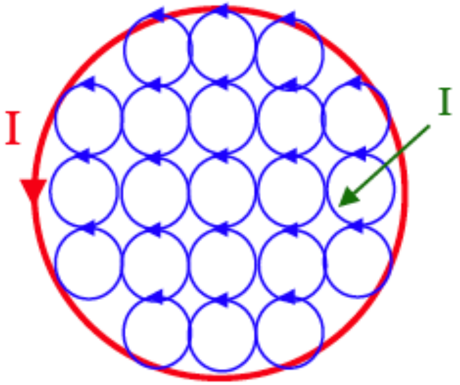
B-field and H-field

- Can view a magnetic material as being composed of many individual current-carrying loops - each with a magnetic dipole moment. If all loops are identical, then current flow in the material is zero.
- However the effects of the magnetic dipoles can be modelled by thinking of them resulting from a surface current termed an Amperian current (see L15, 2nd year EM course).
- Also have magnetic fields that result from the flow of ‘real’ conduction currents.
- **Both currents** (Amperian and conduction) **can contribute to the B-field**. However only conduction currents can contribute to the H-field.
- Can write B field in terms of the Magnetization of the material and the conduction currents that flow.

$$B = \mu_o(H + M)$$

From conduction currents

From magnetic material



Magnetization

- Each small volume $d\tau$ of a magnetized material will posses a magnetic dipole moment $d\underline{\boldsymbol{m}}$.

- Magnetization is defined as the magnetic dipole moment per unit volume $\mathbf{M} = d\underline{\boldsymbol{m}} \,/\, d\tau$ (units Am^{-1})

The magnetisation of materials

- In the presence of a magnetic material, there will be two contributions to the total ***Magnetic Induction Field*** B $B = B_{current\ elements} + B_{magnetic\ materials}$

Using our relation between B, H and M

$$B = \mu_0 H + \mu_0 M$$

We define the susceptibility (chi) as $\chi = M / H$

$$B = \mu_0 H + \mu_0 \chi H$$

so that,

$$B = \mu_0 (1 + \chi) H$$

and define,

so that,

$$\mu_r = (1 + \chi)$$

$$B = \mu_r \mu_0 H$$

- Here μ_r is the **relative** permeability of the **material**, which we use in place of, μ_0 the permeability of **free space**.

- All the equations used when there are **no** magnetic materials are simply modified by replacing,

$$\mu_0 \quad \text{with} \quad \mu_r\mu_0$$

when magnetic materials are present.

Units

- When M and H both have the (same) units of amperes / meter, then susceptibility (χ) is called the “volume magnetic susceptibility” and is dimensionless.
- There are however two other (SI) measures of susceptibility, the mass magnetic susceptibility (χ_{mass}), measured in $m^3\ kg^{-1}$ and the molar magnetic susceptibility (χ_{mol}) measured in $m^3 mol^{-1}$
- Can convert between these using ρ the density in $kg\ m^{-3}$ and M (molar mass) $kg\ mol^{-1}$.

$$\chi_{mass} = \chi / \rho$$

$$\chi_{mol} = M\chi_{mass} = M\chi / \rho$$

How do we classify magnetic materials?

Depending on χ, we class all materials as being

Diamagnetic,

Paramagnetic or

Ferromagnetic.

Diamagnetic materials

$\chi < 0$, *i.e* negative and $\mu_r < 1$ small negative magnetisation.

Examples	χ (per kg)
bismuth	-1.7×10^{-8}
copper	-0.107×10^{-8}
germanium	-0.15×10^{-8}
gold	-0.19×10^{-8}
hydrogen	-2.49×10^{-8}
helium	-0.59×10^{-8}

Discuss diamagnetism lecture 2 / 3

Diamagnetic levitation of a frog in a magnetic field

Paramagnets

Characterized by $\chi > 0$ and $\mu_r > 1$

Examples $\chi \times 10^{-6}$ (per kg)

aluminium	0.82
calcium	1.40
magnesium	0.69
platinum	1.65
tantalum	1.10

Discuss paramagnetism lecture 4 / 6 / 10

Ferromagnets

$$\chi > 0, \quad \text{and} \quad \mu_r >> 1$$

Large positive magnetisation

- **Examples** χ between 10^2 - 10^3 but only an in 'initial χ' is it is proportional to H
- **Examples** Iron, nickel, cobalt, NiFe, FeCo alloys *etc and other* amorphous alloys

- Discuss ferromagnetism in lectures 7 / 8 / 9

Summary

- Revised basic concepts (B and H-field, energy, torque and force in a magnetic field).
- Introduced magnetization, susceptability and relative permeability.
- Talked about different types of magnetic materials (diamagnetic, paramagnetic, ferromagnetic).