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Magnetism in the new GCSE AQ1

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AQ5 Abstract

AQ6 The new 9-1 GCSE courses in Physics include reference to both permanent and induced magnets. In this article I briefly examine the origin of ferromagnetism, diamagnetism and paramagnetism and suggest a number of helpful classroom demonstrations.

The elements iron, nickel, cobalt; some alloys of rare earth metals and minerals like lodestone are all ferromagnetic. These familiar materials are strongly attracted to a magnet and are also capable of being magnets themselves. Ferromagnetism arises from the spontaneous alignment of the magnetic moments of many electrons within the material with no need for an external magnetic field.

In classical electromagnetism a magnetic moment, $\boldsymbol{\mu}$, can be equated with a current loop: the electron moves around the nucleus with loop area $\mathrm{d}\mathbf{S}$, therefore $\boldsymbol{\mu} = \mathbf{I}\int \mathrm{d}\mathbf{S}$. However, magnetism has been regarded as a purely quantum mechanical effect (since the Bohr–van leeuwen theorem) which can not be explained by classical physics. The magnetic moment of the electron arises predominantly from the spin of the electron itself: the electron can spin in one of two 'directions' leading to the idea of 'up' spin and 'down' spin. It is these spins which give rise to a magnetic moment (think of them as tiny bar magnets) when they all align in the same direction. The magnetisation, **M**, of a material is defined as the magnetic moment per unit volume.

However diamagnetic and paramagnetic materials only gain their magnetism when they are subject to an external magnetic field which causes the spins to line up. If the spins of the electrons align in the same direction as an applied field the material is said to be paramagnetic: this leads to attraction. However if the spins align in the opposite direction to the applied field the material is said to be diamagnetic: this leads to repulsion.

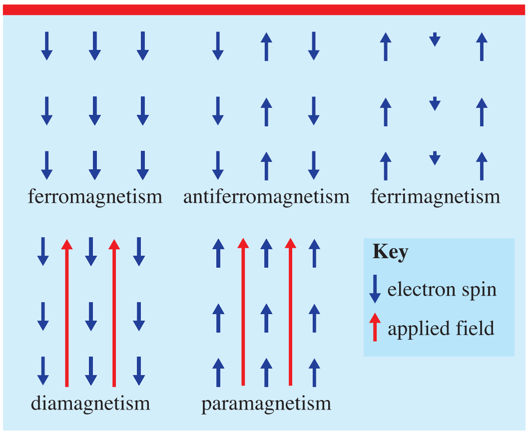

Figure 1. Types of magnetism.

There are also two further types of spontaneous magnetic order. Antiferromagnetism occurs where the spins align in an alternating pattern with neighbouring spins leading to absence of any overall magnetic moment. Ferrimagnetism is similar to antiferromagnetism, but where the alternating spins do not cancel each other out leading to an overall magnetic moment as in ferromagnetism. See figure 1.

In a vacuum there can be no magnetic moments and so there is no magnetisation. Therefore the magnetic field can be described by the either of the fields **B** and **H** which are are just

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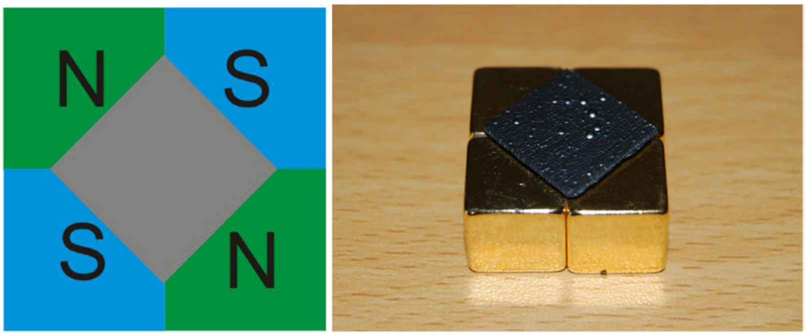

Figure 2. Graphite levitation.

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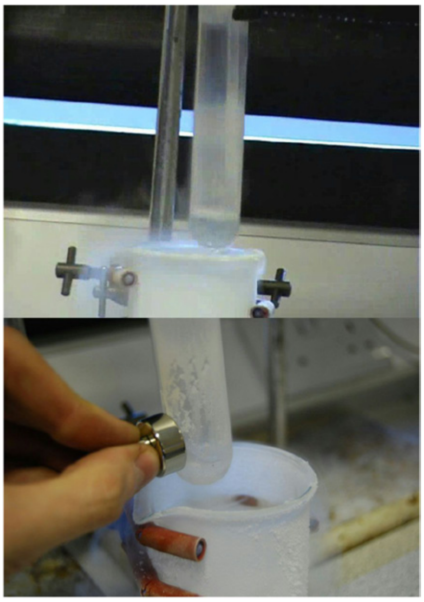

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Figure 3.

scaled versions of each other related by $\mathbf{B} = \mu_0 \mathbf{H}$, where μ_0 is the permeability of free space.

In a solid these two fields are related in a more complex way, in general this is $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$. In what is known as a linear material the magnetisation is linearly related to the magnetic field so that $\mathbf{M} = \chi \mathbf{H}$ where χ is the magnetic susceptibility thus $\mathbf{B} = \mu_0(\mathbf{H} + \chi \mathbf{H}) = \mu_0(1 + \chi)\mathbf{H}$. So χ represents the magnetic moment per unit volume induced (in the material) by an external magnetic field H. Since both M and H are measured in A m^{-1}, χ is a dimensionless quantity.

If χ is negative then the induced field acts in the opposite direction to the external field: we call this diamagnetism. On the other hand, if χ is positive then the induced field acts in the same direction as the external field: we call this paramagnetism. A perfect diamagnet (one in which the induced field completely opposes the applied field), would have $\chi = -1$. However, typical values for χ are small for most materials. Outliers and materials of interest are, for example: -9×10^{-6} for water, -170×10^{-6} for Bismuth and -260×10^{-6} for graphite meaning these are diamagnetic; 22×10^{-6} for Aluminium and 2640×10^{-6} for $MnSO_4 \cdot 4H_2O$ meaning these are paramagnetic. Iron, Nickel and Cobalt are ferromagnetic and so can have a spontaneous magnetisation with no applied magnetic field.

Classroom based demonstrations are possible for both diamagnetism and paramagnetism.

1. Levitation of graphite

This was previously explained by the author in [1]. A number of permanent magnets and a small square of the best diamagnet at room temperature: pyrolytic graphite are used. This graphite grows very slowly by a process called chemical vapour deposition, creating a highly ordered material where the carbon atoms form a layered hexagonal structure. Because of the low density of pyrolytic graphite a thin sheet will be repelled by a sufficiently strong neodymium magnet. A thick piece will be too heavy as the material above about a half of a millimetre does not contribute much to the lift. If the piece is thin enough, it will simply slide right off the side of a single magnet, and refuse to sit still on it. To get a piece of pyrolytic graphite to sit still above a magnet, we need to find a way to force it to the centre of a magnet. This can be achieved by using a set of four magnets (creating a magnetic potential well). The pole of each of the magnets (where the field is strongest) forces the graphite to

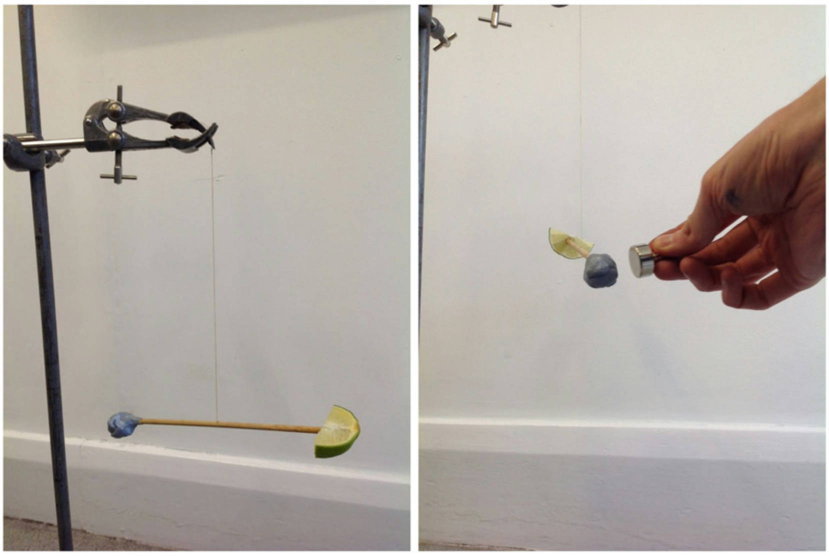

Figure 4.

the centre. This effectively pins the graphite above the magnets. The diagram in figure 2 shows the magnets coloured green and blue (with their north and south poles arranged as shown) and the pyrolytic graphite in grey in the centre. Note that the graphite sheet needs to be cleaved and cut slightly smaller than the size of a magnet. This creates a stable room temperature levitation demonstration where the graphite is levitated about 1 mm above the magnets. When pushed gently down, the graphite moves, but if the pressure is removed it levitates again. Although this demonstration is quite small (around 24 mm × 24 mm), it is available cheaply from [2]. Only four magnets are provided, but enough pyrolytic graphite is provided to make 8–10 units if additional magnets are purchased separately. This means around 5–8 can be used in each class allowing each student an opportunity to interact with them.

2. Levitation of small living things

This was achieved by a Michael Berry and the Nobel Prize winner Andre Geim inside a 32 mm diameter vertical bore of a solenoid in a magnetic field of about 16 T at the Nijmegen High Field Magnet Laboratory in Nijmegen in the Netherlands. They have released a detailed explanation of their calculations and results [3] and a more straightforward explanation [4] and around 10 videos suitable for the classroom [4].

3. Paramagnetic liquid oxygen

This was previously explained by the author in [5]. Oxygen boils at 90 K (−183 °C) and liquid nitrogen boils at 77 K (−196 °C), so we can use liquid nitrogen to liquify oxygen. The usual way to do this is to pass oxygen gas from a compressed gas cylinder through a coil of hollow copper pipe that is submerged in liquid nitrogen. The copper coil is a good conductor of heat and has a large surface area. Liquid oxygen is then collected in a thermos flask. If this is then decanted into a test tube (as well as appearing light blue in colour) a strong neodymium magnet can be used to drag the liquid up the side of the test tube: see figure 3. If the test tube is suspended from a retort stand by a fine piece of cotton the attractive force is enough to displace the test tube.

4. Paramagnetic blu-tac

The final example brings together both diamagnetism and paramagnetism in a single, simple, quick and cheap demonstration. A pencil is sharpened at both ends and a fine hole drilled through the centre of mass. The pencil is then suspended from a retort stand with a piece of fine cotton: see figure 4. On one side a small piece of fruit (such as apple, grape, lime etc) is skewered by the pencil. On the other side of the pencil an appropriate amount of blu-tac is placed to balance the pencil. A neodymium magnet is first brought up to the fruit with great care taken not to actually touch the fruit. Since the fruit is diamagnetic it repels from the magnet and the pencil begins to rotate. Follow the fruit around with the magnet. Next, bring the magnet up to the blu-tac, again taking great care that the blu-tac does not come into contact with the magnet. Since the blu-tac is paramagnetic it is attracted to the magnet and the pencil (previously rotating from earlier) begins to slow down, stop and then begin rotating in the opposite direction.

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