G495: Field and Particle Pictures

Revision Notes

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Magnetic Fields

A-level Physics (Advancing Physics)/Flux

A coil of wire creates magnetic flux. The amount of magnetic flux created is dependant on three things: the number of coils in the wire, the amount of current flowing through the wire, and the permeance of the object through which the flux is flowing. So:

$$\Phi = \Lambda N I,$$

where Φ is flux (in webers, denoted Wb), Λ is permeance (in WbA^{-1}) and I is current (in A). This is the total flux induced. NI is the number of "current-turns", also known as the flux linkage. Permeance is related to permeability (a material property) by the following equation:

$$\Lambda = \frac{\mu A}{L},$$

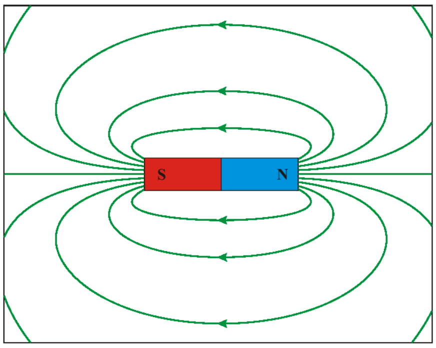
where μ is permeability, A is cross-sectional area, and L is length. A permanent magnet is just like a coil, except that a current does not need to be generated to maintain the flux. Over smaller areas, we need to know the flux density B. This is the amount of flux per. unit area:

$$B = \frac{\Phi}{A}$$

Therefore:

$$\Phi = AB$$

The flux around a coil of wire varies - ΛNI only gives the total flux, not the flux across a certain area. To show this, we use lines of flux. These obey the following rules:



Lines of flux around a permanent magnet.

1. Lines of flux go from the north pole of a permanent magnet to the south pole.

2. Lines of flux go clockwise about wires carrying current away from you.

3. Lines of flux never touch, intersect, or cross.

The direction of the flux is shown with an arrow. Flux is a bit like electricity in that it must have a complete circuit. The lines of flux always take the route of least permeance. An iron core has around 800 times as much permeability as some air. So, flux goes through the iron core, and not the air.

Questions

1. A circular steel core has a cross-sectional area of 9 cm^2, and a length of 0.5m. If the permeability of steel is 875 μNA^{-2}., what is the permeance of the core?

2. A coil of insulated wire is wrapped 60 times around the top of the core, and a 9A direct current is put through the coil. How much flux is induced?

3. Assuming that all the flux goes through the core, what is the flux density at any point in the core?

4. Draw a diagram showing the lines of flux within the core.

/Worked Solutions/

A-level Physics (Advancing Physics)/Induction

A magnetic field creates a current in a wire moving through it. This process is known as induction.

Flux Linkage

A magnetic field going through a coil of wire has a property known as flux linkage. This is the product of the flux Φ and the number of coils in the wire N.

Faraday's Law

Electric current is only induced in a coil of wire if the magnetic field is moving relative to the coil. Faraday's Law gives the electromotive force (emf) ε produced in a coil by a magnetic field:

$$\epsilon = -\frac{dN\Phi}{dt}$$

In other words, the emf (electric potential) induced in the coil is proportional to the rate of change of flux linkage. In practice, this means that if the coil is stationary relative to the magnetic field, no emf is induced. In order to induce emf, either the coil or the magnetic field must move. Alternatively, we may change the number of coils, for example, by crushing the coil, or pressing a switch which added more coils into the circuit, or moving more of the coils into the magnetic field.

Faraday's Law also works the other way. If we were to integrate both sides and rearrange the formula in terms of Φ, we would find that the flux depends on the integral of the voltage - not on its rate of change. If we put an emf across a coil, it produces a magnetic field - it induces a magnetic field. The flux does not depend on the rate of change of emf, but the emf does depend on the rate of change of the flux linkage.

Lenz's Law

Lenz's Law describes the direction of the current / emf induced by a change in magnetic flux. It states that current induced opposes the magnetic field. It does this by creating its own magnetic field. This explains the minus sign in Faraday's Law. This also means that the flux induced by a current (not a change in current) is proportional to the current, since the flux is produced in response to the current.

So, a change in flux induces a current and a voltage which is proportional to the rate of change of flux. This fits with Ohm's Law (V = IR). A current and a voltage in a coil induce a flux which is proportional to the current and the voltage.

Questions

1. What is the flux linkage of a 30cm coil of 0.5mm thick wire with a flux perpendicular to it of 10Wb?

2. If the above coil is crushed steadily over a period of 2s, what emf is maintained?

3. The flux in a flux circuit varies according to the equation Φ = sin ωt. What is the equation for the emf induced?

4. Using a constant k, what is the equation for a current which could induce the flux in the flux circuit above?

5. Draw a graph of the flux, flux linkage, emf and current as deduced in the previous two questions.

/Worked Solutions/

A-level Physics (Advancing Physics)/Force

Magnetic fields exert a force on a charge when the charge is moving. If the charge is stationary, no force is exerted. This force is given by:

$$\vec{F} = q(\vec{v} \times \vec{B}),$$

where q is the charge on the point charge, v is its velocity and B is the magnetic field strength. This involves a vector cross product, which you don't need to know about for A-level. However, you do need to know a simplified version of this. The magnitude of this force F is given by:

$$F = Bqv \sin\theta \, ,$$

where θ is the angle between the direction of motion of the point charge and the direction of the magnetic field. If the velocity and the magnetic field are in the same direction, the θ = 0, so sin θ = 0 and F = 0. If the velocity and the magnetic field are perpendicular to each other, θ = π, so sin &theta = 1. This means that, in the special case where velocity is perpendicular to the magnetic field:

$$F = Bqv$$

If q is negative (for example, for an electron), the force is in the opposite direction.

Current

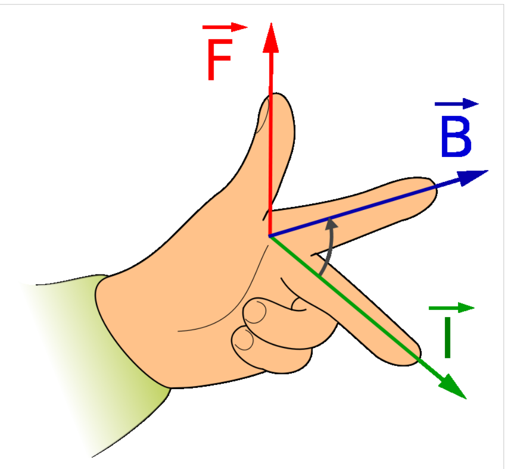
A current is just a flow of moving electrons, and so a magnetic field will exert a force on a wire with a current flowing through it. The case you need to know about is when the magnetic field is perpendicular to the wire. In this case, the magnitude of the force on the wire is given by:

$$F = BIl,$$

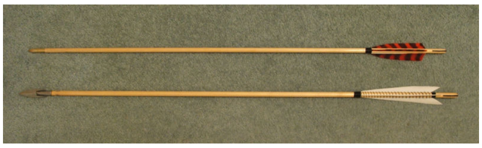
where I is current, and l is the length of the wire.

Direction

The direction of the force on either a point charge or on a wire can be worked out using Fleming's left-hand rule, as shown in the diagram on the right. The direction of the *th*umb is that of the force (or *th*rust), the direction of the *f*irst finger is that of the magnetic *f*ield, and the direction of the se*c*ond finger is that of the *c*urrent (or the motion of the point charge.



Fleming's left-hand rule


The point and fletchings of an arrow.

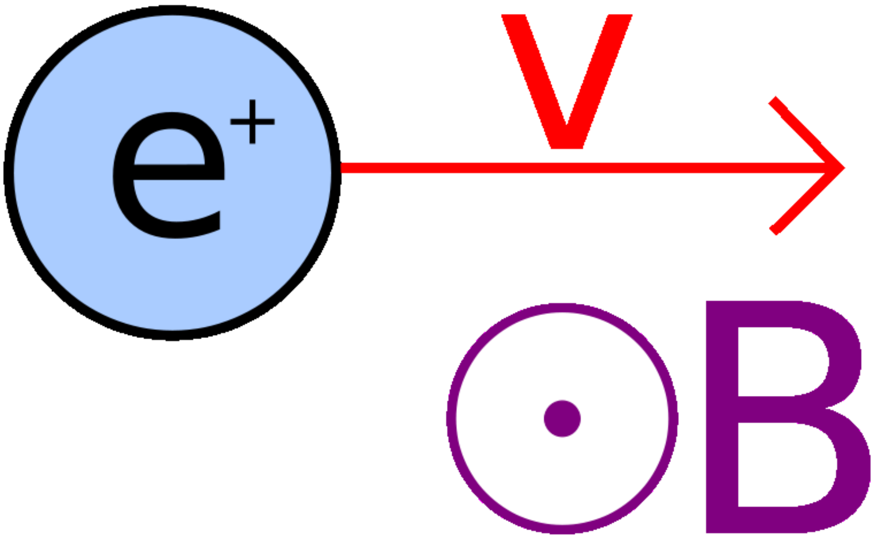
On a 2D diagram, the direction of a magnetic field is represented by one of two symbols, which resemble the point and fletchings of an arrow pointing in the direction of the magnetic field. The symbol $\odot$ means that the field is pointing towards you (just as the arrow would be, if you were looking at the point). The symbol $\otimes$ means that the field is pointing away from you (just as the arrow would be, if you were looking at the fletching).

Questions

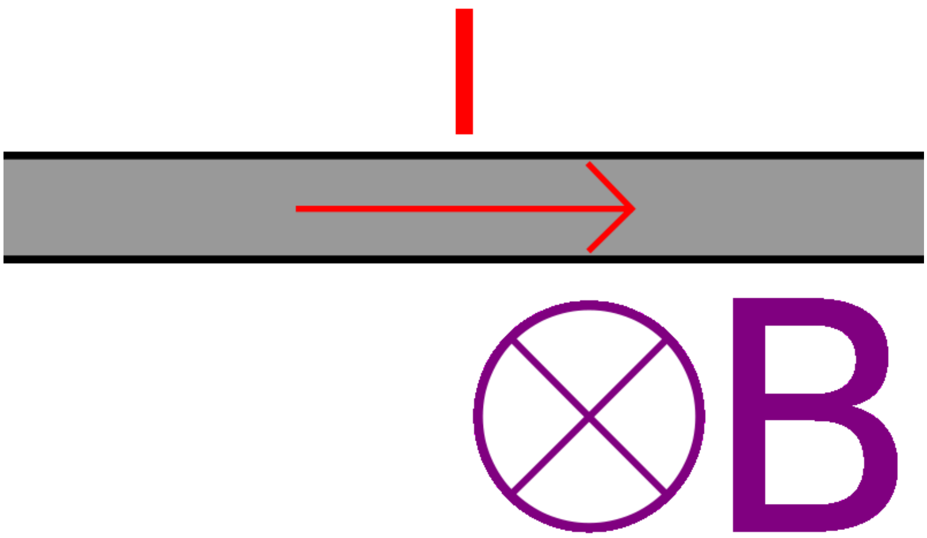
1. What force is exerted by a 1T magnetic field on an electron (of charge -1.6 x 10^{-19}C) moving at 5% of the speed of light (3 x 10^8 ms^{-1})?

2. What force is exerted by a 5mT magnetic field on a 20cm wire with resistance 1μΩ attached to a 9V battery?

3. The following diagram shows a positive charge moving through a magnetic field. Draw an arrow representing the direction of the force on the charge.



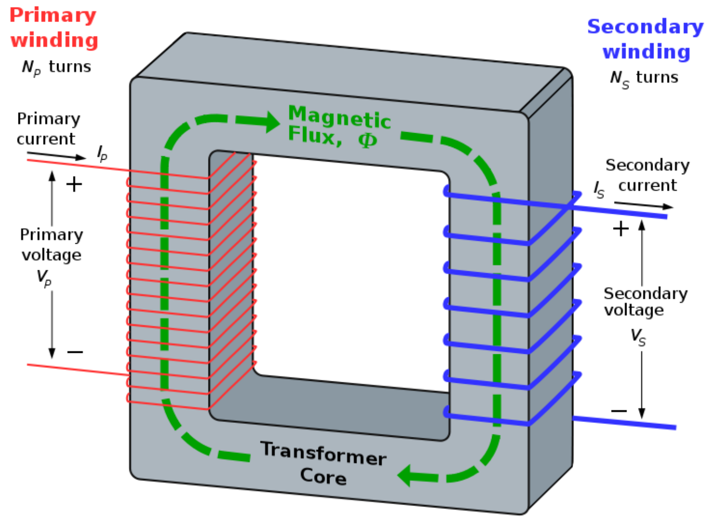
4. The following diagram shows a wire in a magnetic field. Draw an arrow representing the direction of the force on the wire.



/Worked Solutions/

A-level Physics (Advancing Physics)/Transformers

We have already seen that a change in flux induces an emf in a coil, given by Faraday's Law:



An ideal step-down transformer showing magnetic flux in the core.

$$\epsilon = -N\frac{d\phi}{dt}$$

We have also seen that a voltage in a coil induces a magnetic flux inside the coil. If we were to connect two coils with the same core, the flux, and the rate of change of flux, would be exactly the same inside both coils. We would have created a kind of flux circuit known as a transformer. The ratio between the voltage at the primary coil V_p and the voltage at the secondary coil V_s would have to be (since φ is constant):

$$\frac{V_p}{V_s} = \frac{-N_p\frac{d\phi}{dt}}{-N_s\frac{d\phi}{dt}} = \frac{N_p}{N_s},$$

where N_p and N_s are the numbers of coils in the primary and secondary coils respectively.

In other words, we can change the voltage of some electricity by varying the number of coils in each coil. In order for this to work, the current used must be an alternating current (AC). This means that the current and voltage are constantly changing sinusoidally, and so there is a sinusoidal change in flux. This means that an emf is induced in the secondary coil. If the flux did not change (ie. we were using direct current), then no emf would be induced, and the transformer would be useless except as a magnet (since it would still have a flux circuit in it).

Ideal Transformers

An ideal transformer is one in which all the electrical energy put into one coil comes out of the other coil. An ideal transformer does not exist, but, since it makes the maths easy, we like to pretend that it does. In this case, the power in must equal the power out:

$$P = P_p = P_s = I_p V_p = I_s V_s \, ,$$

where I_p and I_s are the currents in the primary and secondary coils, respectively. So:

$$V_p = \frac{P}{I_p} \text{and } V_s = \frac{P}{I_s}$$

By substitution into the transformer equation for voltage:

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} = \frac{\frac{P}{I_p}}{\frac{P}{I_s}} = \frac{\frac{1}{I_p}}{\frac{1}{I_s}} = \frac{I_s}{I_p}$$

So, in an ideal transformer, the ratio between the voltages is equal to the ratio between the numbers of coils, but the ratio between the currents is equal to the *reciprocal* of the ratio between the numbers of coils.

Eddy Currents

In reality, the electrical energy is not all conserved - a lot of it is converted into heat by eddy currents. In a transformer, the magnetic flux created by the primary coil induces a current in the core. This occurs in order to oppose the change that produced the magnetic flux (Lenz's Law). The currents flowing in the core are called eddy currents.

These currents produce heat, using up energy and so causing inefficiency. One way of minimising the effects of eddy currents is to make the core out of iron laminate. This is layers of iron separated by thin layers of an insulator such as varnish. The amplitude of the eddy currents produced is reduced as currents cannot flow through the layers of insulator. (Note: OCR B question papers tend to have a question on eddy currents.)

Questions

1. A step-down transformer has 300 coils on one coil, and 50 coils on the other. If 30 kV AC is put in, what voltage comes out?

2. A step-up transformer has 200 coils on one coil, and 980 coils on the other. If 25 kV AC comes out, what voltage was put in?

3. An ideal transformer transforms a 50A current into a 1A current. It has 40 coils on the primary coil. How many coils are in the secondary coil?

4. Transformers tend to vibrate. Why is this? What effect does this have on the efficiency of the transformer?

5. Air does have some permeability. What effect does this have on the efficiency of the transformer? Why?

/Worked Solutions/

A-level Physics (Advancing Physics)/Motors

Just as a moving magnetic field induces current in conductors, a changing current in a magnetic field induces motion. When this motion is used to ensure that the current keeps changing relative to the magnetic field, the motion will continue, and so we have an electric motor. There are several types of electric motor.

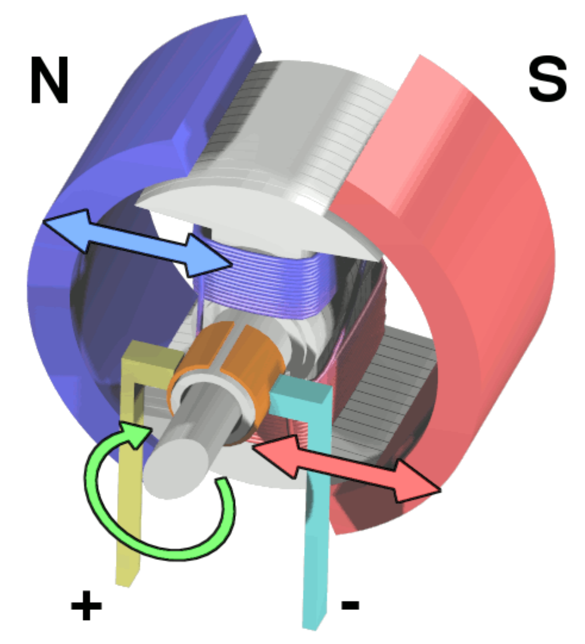
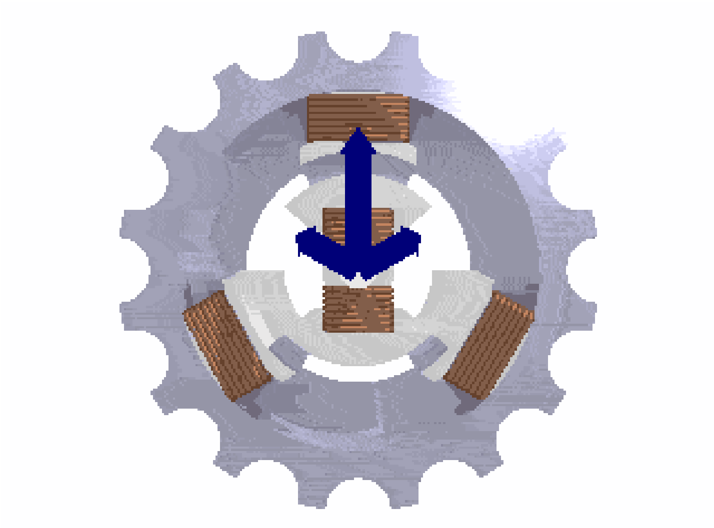


Diagram of a simple DC motor, showing the repulsion between the poles.

Simple DC Motor

When a coil is placed inside a stationary magnetic field, and a direct current is run through the coil, the coil tries to align itself with the field since it becomes an electromagnet. This would be useless as a motor, since it would always move to the same position when you turned it on, and then stop. If, however, we use a split-ring commutator which changes the direction of the current every half-rotation, then the coil would try to align itself in the opposite direction every half-rotation. This means that, once the rotor starts to move, it continues to move. This is a DC electric motor. The permanent magnets can be replaced with electromagnets as well. The main advantage of this type of motor is that the commutator works, regardless of the frequency of rotation.

Three-phase Motor

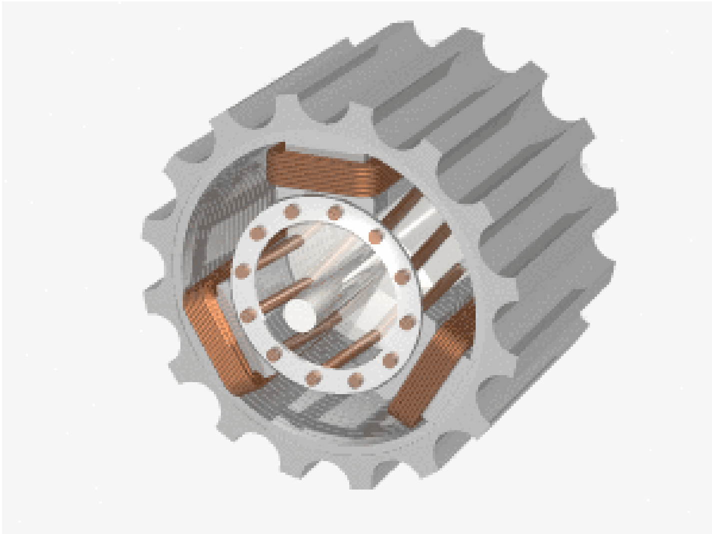

Animation of a three-phase motor with an electromagnet as the rotor.

The three-phase power produced by a three-phase generator may be used to power a motor. Each phase of power is connected to one of three coils. This creates a magnetic field which rotates once for each cycle of the power. If a permanent magnet is placed in the middle, at any given time, its north pole will be attracted to a south pole in one of the coils, and will be repelled by a north pole in one of the coils. The converse would be true for its south pole. This means that the rotating magnetic field drags the magnet around with it, causing the magnet to rotate with the same frequency as the magnetic field. The disadvantage of this type of motor is that it goes at one frequency only - the frequency of the current.

The permanent magnet can be replaced with a coil with direct current in it. This creates a magnetic field, the advantage being that there is no need for a permanent magnet which is expensive and heavy. The main disadvantages are that electricity must be used to power the electromagnet, and that a slip-ring commutator must be used to prevent the coil getting tangled up and stopping the motor from running.

Squirrel Cage Motor

A squirrel cage motor works on a similar principle, except that the rotor is no longer a permanent magnet. Instead, a series of metal rods run through the rotor, connected to each other at either ends. The rods run perpendicular to the rotating magnetic field. Once the rotor starts to rotate, an electric current is created in the rods - eddy currents. This creates a magnetic field which is perpendicular to the rotating magnetic at all times. As the rotating magnetic field created by the stator rotates, it pulls the induced magnetic field around after it, causing the rotor to continue to rotate.



Animation of a squirrel-cage AC motor

A squirrel cage motor relies on the fact that the two magnetic fields are rotating at different rates. If they were not, then there would be no change in flux in the rotor, and so no eddy currents would be induced.

Questions

1. How could you adapt the simple DC motor to use AC?

2. Why does a three-phase motor have a constant angular velocity?

3. What is the difference between a split-ring and a slip-ring commutator?

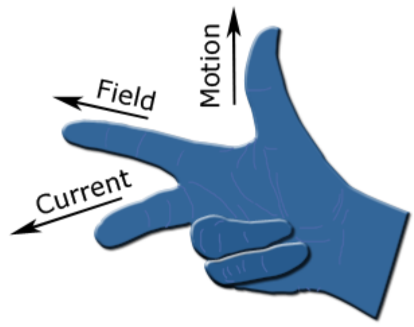
4. How could the angular velocity of a three-phase motor be increased?

5. A squirrel-cage motor relies on eddy currents running along the rotor to function. However, if eddy currents run across the rotor, then the force on the rotor is reduced. How may these eddy currents be reduced without reducing the desired eddy currents?

/Worked Solutions/

A-level Physics (Advancing Physics)/Generators

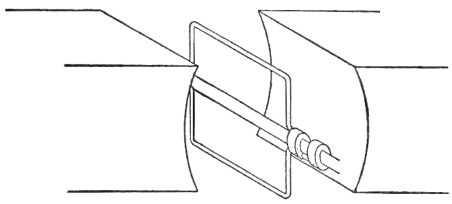
We have seen that a change in flux induces an electric current in a coil of wire. One way of changing the flux is to move the magnet. Alternatively, we can move the coil relative to the magnet. Generators work on this principle - a non-electrical source of energy is used to rotate something (known as the rotor), which induces an electric current in either the rotor or the stator (the stationary part of any electromagnetic machine). For a generator, the relationships between the directions of current, field and motion are given by Fleming's right-hand rule (right).



Fleming's right-hand rule

Moving Coil

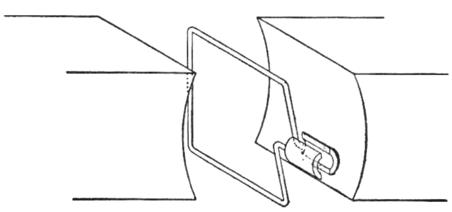
AC Generator


Attaching carbon brushes to a *slip*-ring commutator results in an AC generator.

If a coil of wire is placed in a magnetic field and rotated, an alternating (sinusoidal) current is induced. As it rotates, sometimes it is 'cutting' through lots of flux, and so lots of current is induced. At other times, it is moving parallel to the flux, and so no flux is cut, and no current is induced. In between, some current is induced. This creates an alternating current.

Either end of the coil can be connected to wires outside of the generator in order to use the current elsewhere. This would be fine for the first few rotations, but after this, the wires would get tangled up and the generator would be useless. To avoid this, we use a commutator. In an AC generator, this is a pair of rotating conducting 'slip rings' attached to either end of the coil. Carbon brushes bring these into contact with the outside world.

DC Generator


Attaching wires to a *split*-ring commutator results in an DC generator.

If we replace the slip-ring commutator in an AC generator with a pair of brushes which the ends of the coil rotate inside, the generator creates direct current (DC) instead. Halfway through the rotation, the brushes come into contact with the other end of the coil, and so the AC changes direction every half a rotation. This approximates to a direct current. This direct current is not perfect since it consists of a series of positive-voltage pulses. These pulses can be smoothed out using a capacitor or a complex system of commutators.

Moving Magnet

Simple AC Generator

An alternative method of generating an alternating current is to rotate a permanent magnet in a gap between two coils. This has the advantage of not requiring a commutator (the coil is the stator), but often a coil is lighter than a magnet, and so it is more efficient to use a rotating coil.

Three-Phase Generator

If we place three pairs of coils, evenly spaced, around the rotating magnet, then three different alternating currents, with three different phases, will be generated. This is a more efficient method of generating electricity, since current is always being generated. The sum of all three currents is zero, so three different cables must be used to transport the currents. Three-phase power is often used in motors with three coils in the stator.

Questions

1. Draw diagrams of an alternating current, the 'direct current' produced by a DC generator, and this current once it has been smoothed with a capacitor.
2. What is the phase difference (in radians) between the voltages produced by a three-phase generator?
3. According to Faraday's law, what three things will increase the amplitude of the emf created by a generator?
4. If an albatross touched two power cables carrying AC in phase, what would happen?
5. What would happen if the two cables carried three-phase power?

/Worked Solutions/

Electric Fields

A-level Physics (Advancing Physics)/Electric Force

Electric fields are caused by charge. This charge can be either positive or negative. Like charges repel each other, and opposite charges attract each other. If we have two point charges of charge Q and q respectively, and they are a distance r apart, the force on each of them is:

$$F_{electric} = \frac{kQq}{r^2} = \frac{Qq}{4\pi\epsilon_0 r^2},$$

where k and ε_0 are constants (k = 8.99 x 10^9 Nm^2C^{-2},ε_0 = 8.85 x $10^{-12}C^2N^{-1}m^{-2}$). This means that, twice as far away from the point charge, the force on another charge decreases by a factor of 4. Electric force around a point charge is very similar to gravitational force around a point mass.

An uniform electric field consists of two conducting plates. These plates are oppositely charged, and infinitely wide. Obviously, infinitely wide conducting plates do not exist, so uniform electric fields do not exist. However, fields which approximate uniform electric fields do exist, provided we look towards the middle of the plates, and the plates are not too far apart - at the ends, the formulae for uniform fields no longer apply.

The force on a charge in an uniform electric field is given by:

$$F_{electric} = \frac{qV}{d},$$

where V is the potential difference between the two plates, q is the charge of the point charge upon which the force is acting, and d is the distance between the two plates. This force remains constant as the charge travels within the electric field.

Questions

e = 1.6 x 10^{-19}C

1. A positron (charge +e) is 1 μm from a lithium nucleus (charge +3e). What is the magnitude of the force acting on each of the particles? In what direction is it acting?

2. An electron is 1mm from the positively charged plate in an uniform electric field. The potential difference between the plates is 20V, and the plates are 10cm apart. What force is acting on the electron? In what direction?

3. The acceleration due to gravity around a point mass is constant, irrespective of the mass of the objects it is acting on. The acceleration due to electricity around a point charge is not. Use Newton's Second Law (F=ma) to explain this.

4. An insulator contains charged particles, even though the overall charge on the insulator is 0. Why is the insulator attracted by a nearby charge?

5. Where in the charged conducting plates which create an uniform electric field would you expect to find the charge located? Why?

/Worked Solutions/

A-level Physics (Advancing Physics)/Electric Field

Electric field E is the force per. unit charge caused by an electric field:

$$E_{electric} = \frac{F_{electric}}{q}$$

The unit of electric field is NC^{-1} or Vm^{-1}.In general, the electric field is the rate of change of electric potential (voltage) with respect to distance:

$$E_{electric} = -\frac{dV_{electric}}{dx}$$

Special Cases

There are two different types of field which you need to know about. Uniform fields occur between two plates with opposite charges. Here, the electric field is simply:

$$E_{electric} = \frac{V_{electric}}{d}$$

A charged sphere also has an electric field. To gain a formula for this, we divide the formula for force around a charged sphere by q, so:

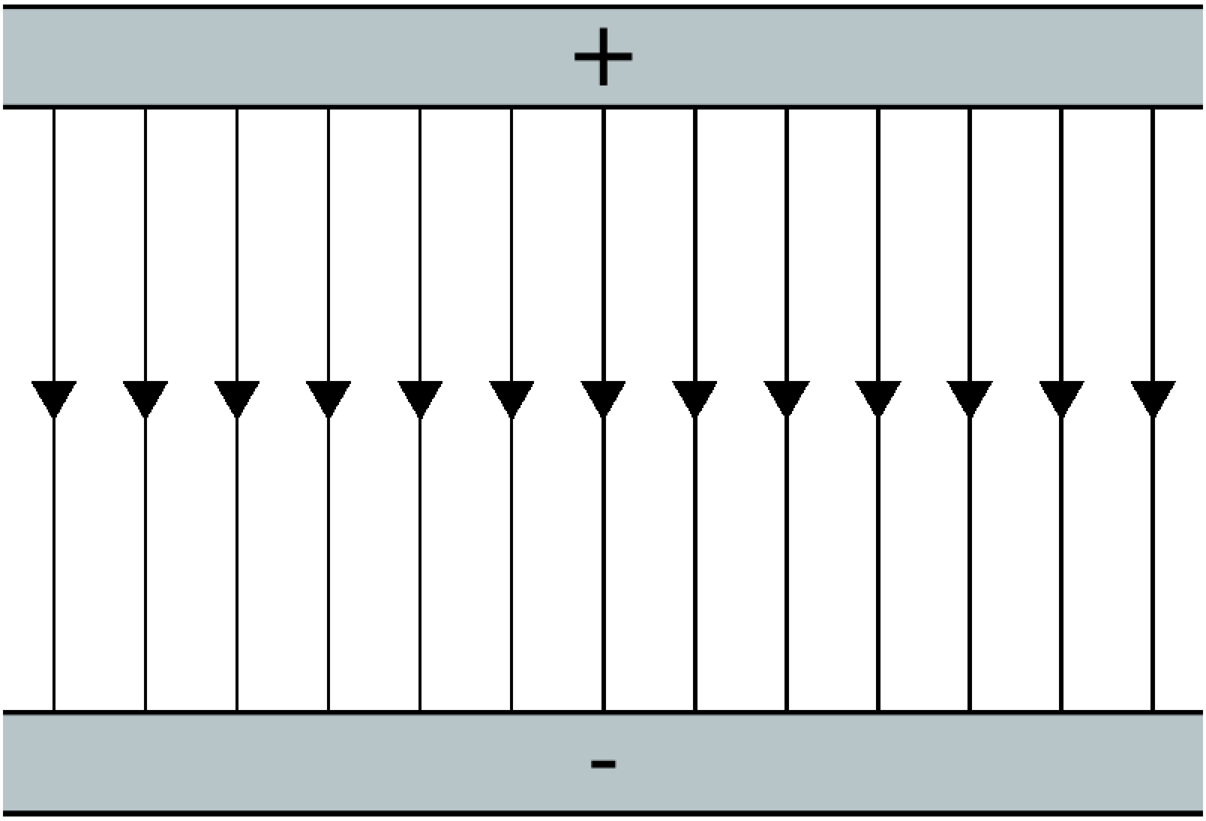
$$E_{electric} = \frac{Q}{4\pi\epsilon_0 r^2},$$

where $\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$.

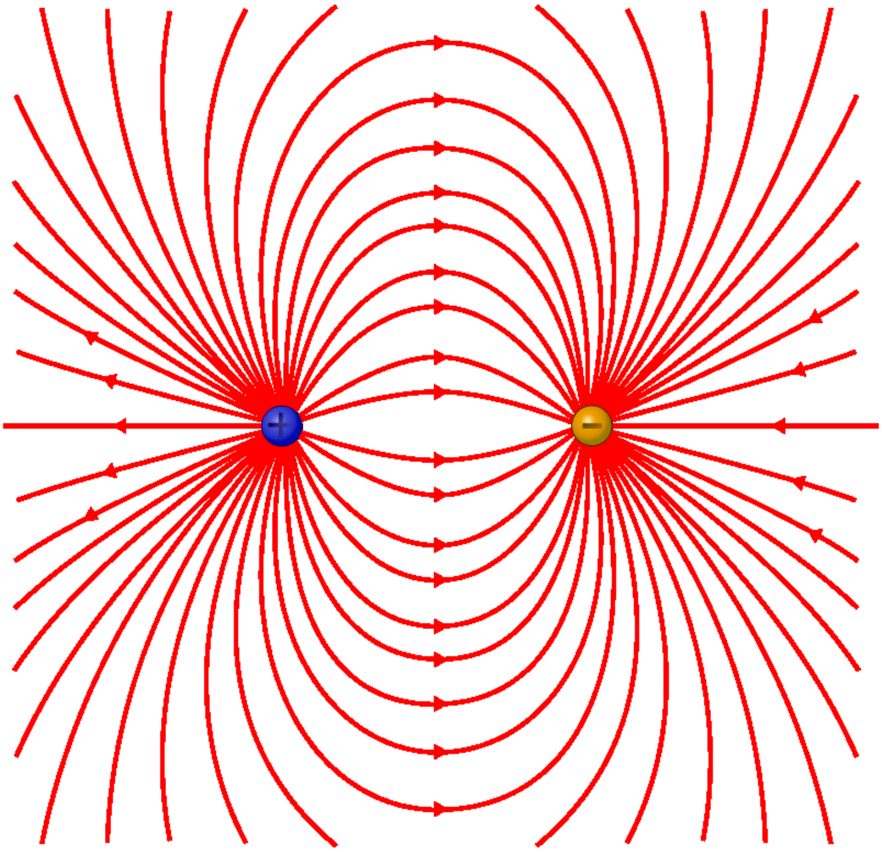
The electric field around a point charge is called a radial field. The field strength is highest at the centre and decreases as the distance from the centre increases. This is reflected in the above formula, which shows that $E_{electric}$ is proportional to $\frac{1}{r^2}$.

Field Lines

We can represent electric field using field lines. These go from positive charge to negative charge. They are more closely packed together when the electric field is stronger. In a uniform field, they look like the following:



Around two oppositely charged spheres (known as a dipole), they look like the following:



Questions

1. Two metal plates are connected to a 9V battery with negligible internal resistance. If the plates are 10cm apart, what is the electric field at either of the plates?

2. What is the electric field at the midpoint between the plates?

3. The charge on an electron is -1.6 x 10^{-19} C. What is the electric field 1μm from a hydrogen nucleus?

4. What is the direction of this field?

5. A 2C charge is placed 1m from a -1C charge. At what point will the electric field be 0?

/Worked Solutions/

A-level Physics (Advancing Physics)/Electric Potential

Relationship to Electric Potential Energy

You will probably remember from AS (or even GCSE) that the energy U which flows along a wire is given by:

$$U = Vq\,,$$

where V is the potential difference between either end of the wire, and q is the amount of charge which flows. A simple rearrangement shows that:

$$V = \frac{U}{q}$$

This potential difference is the same thing as electric potential. In a wire, the electric field is very simple. There are other electric fields, and in these fields as well, the electric potential is the electric potential energy per. unit charge. Electric potential energy between two point charges Q and q is given by:

$$U = \frac{Qq}{4\pi\epsilon_0 r}$$

So, the electric potential at a distance r from any point charge Q (ignoring other charges) is:

$$V = \frac{Q}{4\pi\epsilon_0 r}$$

Relationship to Electric Field Strength

Electric potential is also the integral of electric field strength. This is why it is often called potential difference - it is an integral between two limits (two points in space) with respect to distance. So, the potential difference between two points a and b is:

$$V_{ab} = \int_a^b E\,dx = \int_a^b \frac{Q}{4\pi\epsilon_0 x^2}\,dx = \left[-\frac{Q}{4\pi\epsilon_0 x}\right]_a^b$$

But, if we define b as infinity and a as r:

$$V = \left[-\frac{Q}{4\pi\epsilon_0 x}\right]_r^\infty = -\frac{Q}{4\pi\epsilon_0 \infty} - \left(-\frac{Q}{4\pi\epsilon_0 r}\right) = \frac{Q}{4\pi\epsilon_0 r}$$

So, the area under a graph of electric field strength against distance, between two points, is the potential difference between those two points.

For a uniform electric field, E is constant, so:

$$V = \int_r^\infty E\,dx = Er$$

In other words, V is proportional to r. If we double the distance between us and a point, the potential difference between us and that point will also double in a uniform electric field.

Equipotentials

Equipotentials are a bit like contours on a map. Contours are lines which join up all the points which have the same height. Equipotentials join up all the points which have the same electric potential. They always run perpendicular to electric field lines. As the field lines get closer together, the equipotentials get closer together.

Questions

$\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{Fm}^{-1}$

1. Draw a diagram of an uniform electric field between two plates, showing the field lines and the equipotentials.

2. Do the same for the electric field around a point charge.

3. The potential difference between two plates is 100V. What is the potential difference between a point halfway between the plates and one of the plates?

4. What is the electric potential at a point 0.2m from an alpha particle (charge on an electron = -1.6×10^{-19}C)?

5. What is the electric potential energy of an electron at the negative electrode of an electron gun if the potential difference between the electrodes is 10V?

/Worked Solutions/

A-level Physics (Advancing Physics)/Electric Potential Energy

Just as an object at a distance r from a sphere has gravitational potential energy, a charge at a distance r from another charge has electrical potential energy ε_{elec}. This is given by the formula:

$$\epsilon_{elec} = V_{elec} q\ ,$$

where V_{elec} is the potential difference between the two charges Q and q. In an uniform field, voltage is given by:

$$V_{elec} = E_{elec} d\ ,$$

where d is distance, and E_{elec} is electric field strength. Combining these two formulae, we get:

$$\epsilon_{elec} = qE_{elec}d$$

For the field around a point charge, the situation is different. By the same method, we get:

$$\epsilon_{elec} = \frac{-kQq}{r}$$

If a charge loses electric potential energy, it must gain some other sort of energy. You should also note that force is the rate of change of energy with respect to distance, and that, therefore:

$$\epsilon_{elec} = \int F\,dr$$

The Electronvolt

The electronvolt (eV) is a unit of energy equal to the charge of a proton or a positron. Its definition is the kinetic energy gained by an electron which has been accelerated through a potential difference of 1V:

1 eV = 1.6 x 10^{-19} J

For example: If a proton has an enerfy of 5MeV then in Joules it will be = 5 x 10^{6} x 1.6 x 10^{-19} = 8 x 10^{-13} J.

Using eV is an advantage when high energy particles are involved as in case of particle accelerators.

Summary of Electric Fields

You should now know (if you did the electric fields section in the right order) about four attributes of electric fields: force, field strength, potential energy and potential. These can be summarised by the following table:

Force $F_{elec} = \frac{-kQq}{r^2}$	→ *integrate* → *with respect to r*	**Potential Energy** $\epsilon_{elec} = \frac{-kQq}{r}$
↓ *per. unit charge* ↓		
Field Strength $E_{elec} = \frac{-kQ}{r^2}$	→ *integrate* → *with respect to r*	**Potential** $V_{elec} = \frac{-kQ}{r}$

This table is very similar to that for gravitational fields. The only difference is that field strength and potential are per. unit charge, instead of per. unit mass. This means that field strength is not the same as acceleration. Remember that integrate means 'find the area under the graph' and differentiate (the reverse process) means 'find the gradient of the graph'.

Questions

k = 8.99 x 10^{9} Nm^2C^{-2}

1. Convert 5 x 10^{-13} J to MeV.

2. Convert 0.9 GeV to J.

3. What is the potential energy of an electron at the negatively charged plate of an uniform electric field when the potential difference between the two plates is 100V?

4. What is the potential energy of a 2C charge 2cm from a 0.5C charge?

5. What is represented by the gradient of a graph of electric potential energy against distance from some charge?

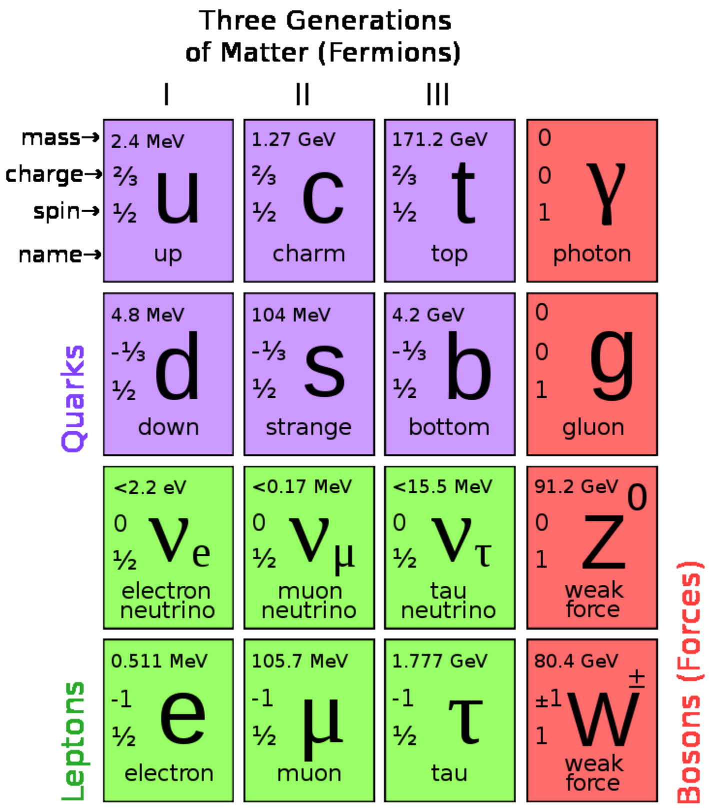
/Worked Solutions/

Particle Physics

A-level Physics (Advancing Physics)/The Standard Model

The standard model of particle physics attempts to explain everything in the universe in terms of fundamental particles. A fundamental particle is one which cannot be broken down into anything else. These fundamental particles are the building blocks of matter, and the things which hold matter together.

The standard model is usually represented by the following diagram:



The particles in the standard model can be put into two groups: fermions and bosons. Fermions are the building blocks of matter. They all obey the Pauli exclusion principle. Bosons are force-carriers. They carry the electromagnetic, strong, and weak forces between fermions.

Bosons

There are four bosons in the right-hand column of the standard model. The photon carries the electromagnetic force - photons are responsible for electromagnetic radiation, electric fields and magnetic fields. The gluon carries the strong nuclear force - they 'glue' quarks together to make up larger non-fundamental particles. The W^+, W^- and Z^0 bosons carry the weak nuclear force. When one quark changes into another quark, it gives off one of these bosons, which in turn decays into fermions.

Fermions

Fermions, in turn, can be put into two categories: quarks and leptons. Quarks make up, amongst other things, the protons and neutrons in the nucleus. Leptons include electrons and neutrinos. The difference between quarks and leptons is that quarks interact with the strong nuclear force, whereas leptons do not.

Generations

Fermions are also divided into three generations. The first generation contains the fermions which we are made of - electrons, the up and down quarks, and the neutrino. The first generation particles have less mass than the second, and the second generation particles have less mass than their respective third generation particles. The second generation (the μ generation) contains two leptons: the muon and the muon-neutrino. It also contains the charm and strange quarks. The third generation (the τ generation) contains another two leptons: the tau and the tau-neutrino. Its quarks are the top and bottom quarks.

Antiparticles

Every fermion has its antiparticle. An antiparticle has the same mass as a particle, but the opposite charge. So, the standard model contains 12 quarks, 12 leptons, and the bosons (which are even more complex).

Questions

1. The third generation top quark was the last quark in the Standard Model to have its existence proven experimentally (in 1995). It is also the most massive of the quarks. Why was it so difficult to observe a top quark?

2. What observable phenomena does the Standard Model not explain?

3. How much more massive is an up quark than an electron?

4. How many fermions are there in the Standard Model?

5. The antiparticle of the electron (e^-) is the positron. What is the charge and rest mass of a positron?

/Worked Solutions/

A-level Physics (Advancing Physics)/Quarks

Quarks (pronounced like 'orcs' with a 'qu' on the front) are a subset of the fermions - they make up part of matter, most notably the nuclei of atoms. Quarks interact with all four of the fundamental forces: gravity, electromagnetism, and the weak and strong nuclear forces.

Generations

There are four quarks in each of the three generations of fermions. The first contains the up quark (u), down quark (d), antiup quark ($\bar{u}$) and antidown quark ($\bar{d}$). The second generation contains the charm quark (c), strange quark (s), anticharm quark ($\bar{c}$) and antistrange quark ($\bar{s}$). The third generation contains the top quark (t), bottom quark (b), antitop quark ($\bar{t}$) and antibottom quark ($\bar{b}$).

Charge

The up, charm and top quarks have a charge of +⅔e, and so their respective antiparticles have a charge of -⅔e. The down, strange and bottom quarks have a charge of -⅓e, and so their respective antiparticles have a charge of +⅓e.

Hadrons

When quarks are combined, they form larger particles, which are not fundamental. These larger particles are known as hadrons and are held together by the strong nuclear force. There are two types of hadrons: baryons and mesons.

Baryons

Baryons are hadrons which are made up of three quarks. The two most common baryons are the proton and the neutron. Protons are made up of two up quarks and one down quark, giving them a total charge of +1e. Neutrons are made up of one up quark and two down quarks, giving them net charge of 0.

Mesons

Mesons are hadrons which are made up of a quark and an antiquark. For example, pions are made up of two first generation quarks - the π^0 is made up of either an up quark and an antiup quark, or a down quark and an antidown quark. The π^+ is made up of an up quark and an antidown quark (total charge +1e), and The π^- is made up of a down quark and an antiup quark (total charge -1e).

Questions

1. The Δ^{++} baryon is made up of up quarks. What is its total charge?

2. The Δ^- baryon has a total charge of -1e. Given that it is made up of only one type of first generation quark, what is this quark?

3. What is an antiproton made of? What is its charge?

4. A K+ meson is made of an up quark and an antistrange quark. What is its total charge?

5. Lambda (Λ) baryons are made up of an up quark, a down quark, and another quark (not an antiquark). The Λ^0 is neutral, and contains a second generation quark. What is this quark?

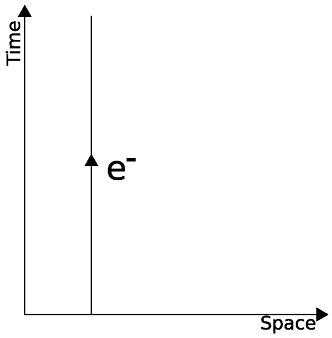
/Worked Solutions/

A-level Physics (Advancing Physics)/Bosons

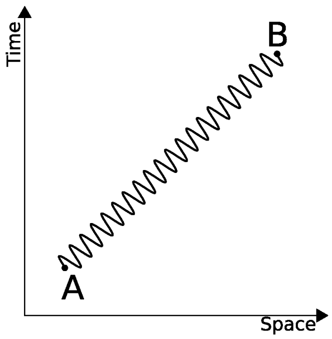
Bosons are particles which carry force. Different types of bosons carry different forces.

Feynman Diagrams

One way of representing these interactions is the Feynman diagram. This is a graph with time on the vertical axis, and space on the horizontal axis showing the paths of particles through space and time as lines. So, a stationary electron looks like this:



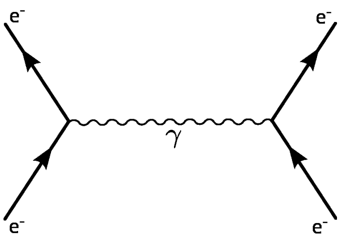
It is often useful to define our units of space and time in such a way that, if something is travelling at the speed of light, it makes a 45° angle. Bosons are virtual particles, so they are given wavy lines. So, a photon travelling at the speed of light from A to B looks like the following:



Different particles can, of course, interact with each other. These interactions must take place at a definite point in space-time. They can be represented by a certain point on a Feynman diagram, with lines coming in and out of the point representing the velocities of particles which take part in the interaction.

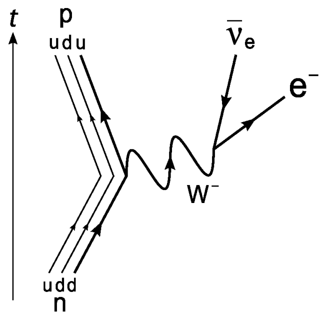
Photons

Photons carry the electromagnetic force. They are 'given off' by one particle, causing it to change its velocity. They are then 'received' by another particle, causing it too to change its velocity. This can be represented on a Feynman diagram in the following way:



W and Z Bosons

W and Z bosons carry the weak nuclear force between particles. This occurs, for example, in β decay, which actually takes place in two stages. First, a proton turns into a neutron (or vice versa), emitting a W boson. Then, the W boson 'turns into' an electron / positron and an (anti-) neutrino. This is shown in the following Feynman diagram:



Gluons

Gluons carry the color force between quarks, holding them together. Quarks have a property known as 'colour', as do gluons. The gluons carry colour between the quarks, mediating the color force. The strong force is the residual color force that holds hadrons together. You probably won't be asked about gluons in the exam.

Questions

1. A stationary light source emits single photons at regular intervals. Draw a Feynman diagram to represent this.

2. Write two equations (including a W^+ boson) which describe positron emission.

3. What is the charge on a W^- boson?

4. Read Richard Feynman's excellent book, "QED - the Strange Theory of Light and Matter", ISBN 978-0-140-12505-4.

/Worked Solutions/

A-level Physics (Advancing Physics)/Leptons

Leptons are particles which interact with all the fundamental forces except for the strong nuclear force. There are two types of leptons: electrons and neutrinos.

Electrons

Electrons are particles with a charge of -1.6 x 10^{-19}C. They are responsible, amongst other things, for the whole of chemistry since, as they occupy the quantum states around the nucleus. There are three types of electrons: the electron (e^-), the muon (μ^-), and the tauon(τ^-), one for each generation. These electrons have antiparticles, each with a charge of +1.6 x 10^{-19}C: the positron (e^+), the antimuon (μ^+), and the antitauon (τ^+), respectively.

Neutrinos

Neutrinos are chargeless, and almost massless. Loads of them travel around the universe and through you at speeds close to the speed of light. The symbol for a neutrino is the greek letter nu (ν), with its generation (e, μ or τ) in subscript. If it is an antineutrino, the symbol has a bar above it. So, the symbol for a muon-antineutrino is $\bar{\nu_\mu}$.

Lepton Number

All leptons have a lepton number of 1. All antileptons have a lepton number of -1. In a nuclear reaction, the lepton number before the reaction must equal the lepton number after the reaction. This necessitates the existence of neutrinos. When a nucleus gives of a beta particle (electron), the lepton number before the emission is 0. Without neutrinos, the lepton number after the emission would be 1, not 0. In reality, an electron-antineutrino is also emitted, with a lepton number of -1, and so the total lepton number both sides of the reaction is 0.

The situation is actually slightly more complicated, as the lepton number from each generation of particles must also be conserved. The lepton number from the beta particle cannot be balanced out by a tauon-antineutrino, since this is from a different generation.

Questions

1. An electron is produced by a nuclear reaction, but an electron-antineutrino is not produced. What other particle is produced?

2. Why do electrons not make up part of the nucleus?

3. Why did it take until the 1950s to detect the first antineutrino?

4. Complete the following equation for the emission of a beta particle from a nucleus:

$${}_0^1n \rightarrow_1^1 p + ? + ?$$

5. Complete the following equation for the emission of an antielectron from a nucleus:

$${}_1^1p \rightarrow_0^1 n + ? + ?$$

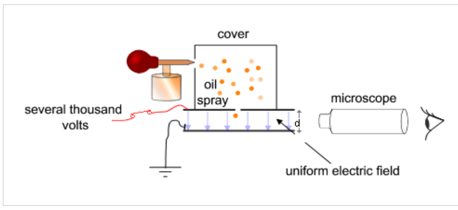
6. Complete the following equation for the capture of an electron by a nucleus:

$${}_1^1p + ? \rightarrow_0^1 n + ?$$

/Worked Solutions/

A-level Physics (Advancing Physics)/Millikan's Experiment

Electrons have a finite charge, which is approximately 1.6 x 10^{-19}C. This was first proven by Robert Millikan in 1909. Millikan sprayed drops of oil which were then charged (ionised) either by friction as they were sprayed, or with x-rays. They were then allowed to fall into an uniform electric field.



Once in the uniform electric field, the strength of the field was adjusted in order to keep an oil drop stationary. This was done by hand, looking through a microscope. In a stationary position, the gravitational force and the electric force were balanced - there was no net force on the oil drop. So, at this point:

$$\frac{qV}{d} = mg$$

The electric field strength was adjusted by changing the voltage between the two plates. The voltage at which the drops were stationary was measured. The charge on each drop was then calculated. Millikan found that these charges were all multiples of 1.6 x 10^{-19}C, thus showing that the charge of each drop was made up of smaller charges with a charge of 1.6 x 10^{-19}C.

Questions

h = 6.63 x 10^{-34} Js

c = 3 x 10^{8} ms^{-1}

g = 9.81 ms^{-2}

1. Rearrange the formula above in terms of q.

2. The mass of an oil drop cannot be measured easily. Express the mass of an oil drop in terms of its radius r and its density ρ, and, by substitution, find a more useful formula for q.

3. An oil droplet of density 885kgm^{-3} and radius 1μm is held stationary in between two plates which are 10cm apart. At what potential differences between the plates is this possible?

4. If the X-rays used to ionise the oil are of wavelength 1nm, how much energy do they give to the electrons? Why does this mean that the oil drops are ionised?

5. In reality, the oil drops are moving when they enter the uniform electric field. How can this be compensated for?

/Worked Solutions/

A-level Physics (Advancing Physics)/Pair Production and Annihilation

Pair Production

Sometimes, a photon turns into a particle and its antiparticle, for example, an electron and a positron. It could not turn into just an electron, since this would leave the lepton number unbalanced. The photon must have enough energy to create the masses of the two particles. The energy required to create one of the particles is given by:

$E = mc^2$,

where m is the mass of the particle, and c is the speed of light (3 x 10^8 ms^{-1}). However, two particles must be created. Since the two particles are each other's antiparticle, they have identical masses. So, the total energy required is:

$$E = 2mc^2$$

Annihilation

When a particle meets its antiparticle, the two annihilate each other to form a photon with energy equivalent to the total mass-energy of both particles.

Sometimes, a pair of particles annihilates, but then the photon produces another pair of particles. Also, a photon could produce a pair of particles which then annihilate each other.

Questions

h = 6.63 x 10^{-34} Js

1. The mass of an electron is 9.11 x 10-31 kg. What is the minimum amount of energy a photon must have to create an electron?

2. A 1.1 MeV electron annihilates with a 1.1 MeV positron. What is the total energy of the photon produced?

3. What is its frequency?

4. What is its wavelength?

5. What classical physical conditions might cause a newly produced electron-positron pair to annihilate almost immediately?

/Worked Solutions/

A-level Physics (Advancing Physics)/Particle Accelerators

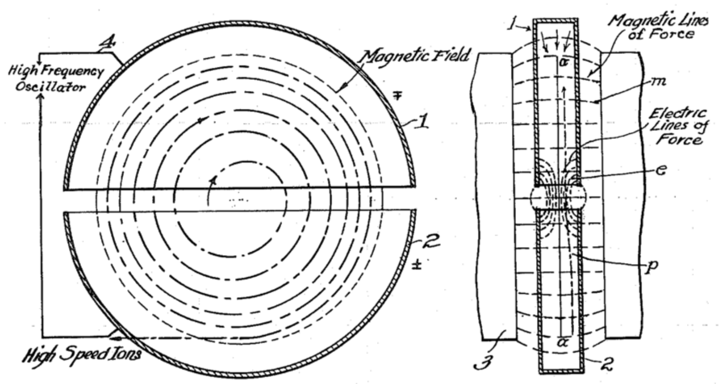
Modern experimental particle physics requires particles to be accelerated to very high energies. This is accomplished by passing them through an electric field multiple times, in a similar fashion to an electron gun. Types of particle accelerator include linear accelerators and cyclotrons.

Linear Accelerators

In a linear accelerator, particles pass through a series of tubes. At either end of each tube are electrodes. An alternating current is used. This means that, when particles pass an electrode to which they are being attracted, the electrode switches charge, and starts to repel the particle. The distances between electrodes increase as you go along the accelerator, since, as the particles accelerate, they travel further per. oscillation of the current.

Aerial photo of the Stanford Linear Accelerator Center, with detector complex at the right (east) side

Cyclotrons



The original patent for a cyclotron.

A cyclotron is like a linear accelerator, except that, instead of using lots of different electrodes, it uses the same two over and over again. The particles move around in a circle due to a magnetic field. The radius of this circle depends on the velocity of the particles. The orbits of the particles are enclosed by two semi-cylindrical electrodes. An alternating current is used to accelerate the particles. When the particles enter one half of the cyclotron, they are pulled back to the other half. When they reach the other half, the current switches over, and they are pulled back to the first half. All the time, the magnetic field keeps them moving in circles. As they gain energy from the electric field, the radii of their orbits increase, and their velocities increase, until the radius is as large as the cyclotron.

Questions

1. Use the formula for centripetal force to show that the radius of motion depends on the speed of the moving object.

2. A cyclotron with a diameter of 1.5m is used to accelerate electrons (mass 9.11 x 10^{-31}kg). The maximum force exerted on an electron is 2.4 x 10^{-18}N. What is the maximum velocity of the electrons?

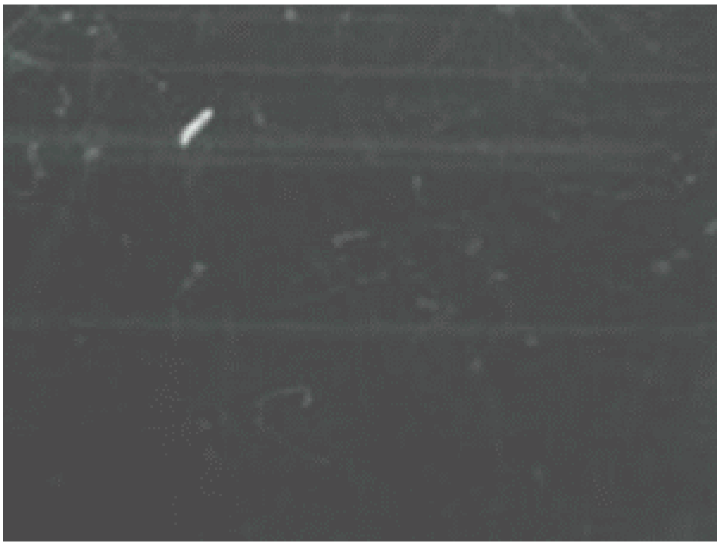
3. What are the problems involved in constructing a large cyclotron?

4. Why don't particles stick to the electrodes when passing through them?

/Worked Solutions/

A-level Physics (Advancing Physics)/Cloud Chambers and Mass Spectrometers

Cloud Chambers



A cloud chamber without a magnetic field, so the particles move in straight lines.

The magnitude of the magnetic force on a moving charged particle is given by:

$F = qvB$,

where B is the magnetic field strength, v is the speed of the particle and q is the charge on the particle. This force is exerted in a direction perpendicular to both the magnetic field and the direction of motion. If a charged particle enters an uniform magnetic field which is perpendicular to its velocity, then it will move in a circle, since there will be a force of constant magnitude acting on it in a direction perpendicular to its motion. Using the equation for centripetal force, we can derive a formula for the radius of this circle:

$$\frac{mv^2}{r} = qvB$$

$$\frac{mv}{r} = qB$$

$$r = \frac{mv}{qB} = \frac{p}{qB},$$

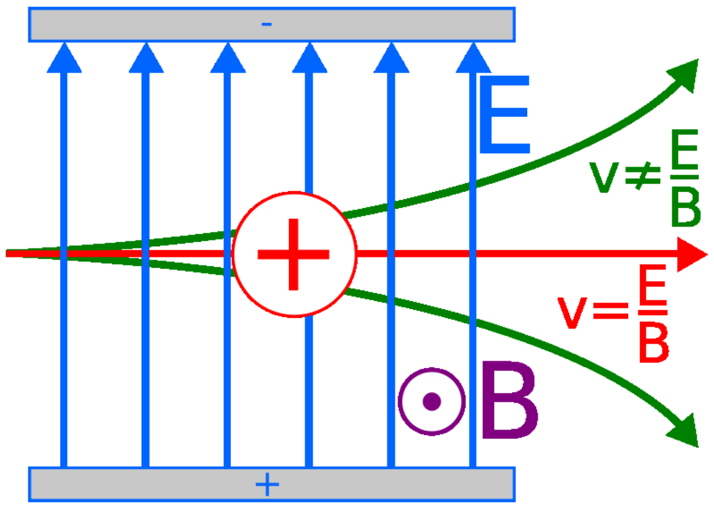
where p is the momentum of the particle, and m is the mass of the particle. This equation makes sense. If the particle has a higher momentum, then its circle of motion will have a larger radius. A stronger magnetic field strength, or a larger charge, will make the radius smaller.

In a cloud chamber, particles enter a magnetic field, and also a liquid which they ionise. This ionisation causes the paths of the particles to become visible. When the particle loses its charge, its track ceases. When the particle loses momentum, the radius of the circle decreases, and so, particles spiral inwards. The direction of this spiralling depends on the direction of the magnetic field. If the direction of the magnetic field causes a positively charged particle to spiral clockwise, then it will cause a negatively charged particle to spiral anticlockwise. Cloud chambers can, therefore, be used to identify particles by their charge and mass.

Mass Spectrometers

Mass spectrometers work on a similar principle. Particles to be identified (such as nuclei) are accelerated using an electric field. Then, a velocity selector is used to ensure all the nuclei are at a known velocity - all the rest are discarded. These nuclei enter an uniform magnetic field where they move in a circle. However, they are only allowed to move half a circle, since they are collected at this point, and the number of particles arriving at each point is measured.

Velocity Selector



A velocity selector

In the velocity selector, both an uniform electric field and an uniform magnetic field act on the particle. The only way a particle can travel through the velocity selector in a straight line is if the electric force on it is equal and opposite to the magnetic force on it. If this is not the case, the particle's path is bent, and so it does not get out of the velocity selector into the rest of the mass spectrometer. If we equate these two forces, we get:

$qE = qvB$,

where q is the charge on the particle, E is the strength of the uniform electric field, v is the velocity of the particle, and B is the strength of the uniform magnetic field. The charge may be eliminated from both sides:

$E = vB$

Therefore:

$$v = \frac{E}{B}$$

This means that, by adjusting the strengths of the electric and magnetic fields, we can choose the velocity at which particles emerge from the velocity selector.

Finding Mass

The particles them move at a speed v into another uniform magnetic field. Here, as in the cloud chamber, the radius of the circle in which the particle moves is given by:

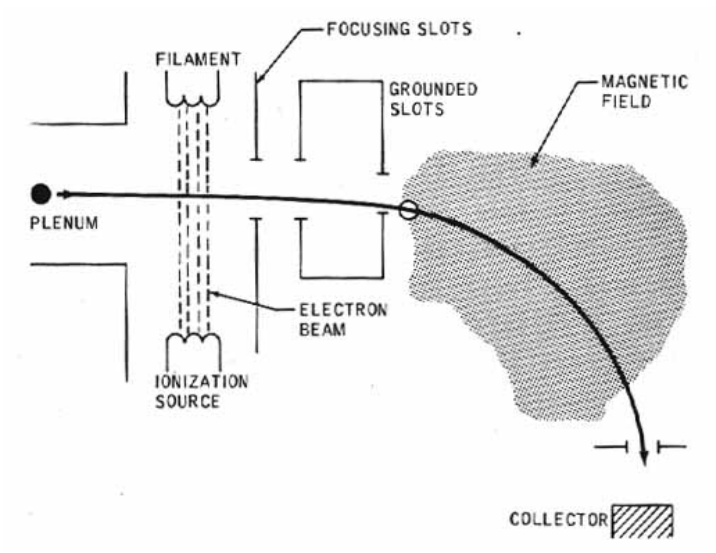


Diagram of the mass spectrometer which went to the moon on Apollo 16.

$$r = \frac{mv}{qB} = \frac{mE_{selector}}{qBB_{selector}}$$

If we know the charge on the particle (for example, we know what element it is), we can measure the radius of the circle, and find the mass of the particle (ie. what isotope it is, since neutrons have no charge) using the formula:

$$m = \frac{qBr}{v} = \frac{qrBB_{selector}}{E_{selector}}$$

If we do not know the charge, then we can find the mass to charge ratio:

$$\frac{m}{q} = \frac{rBB_{selector}}{E_{selector}}$$

Questions

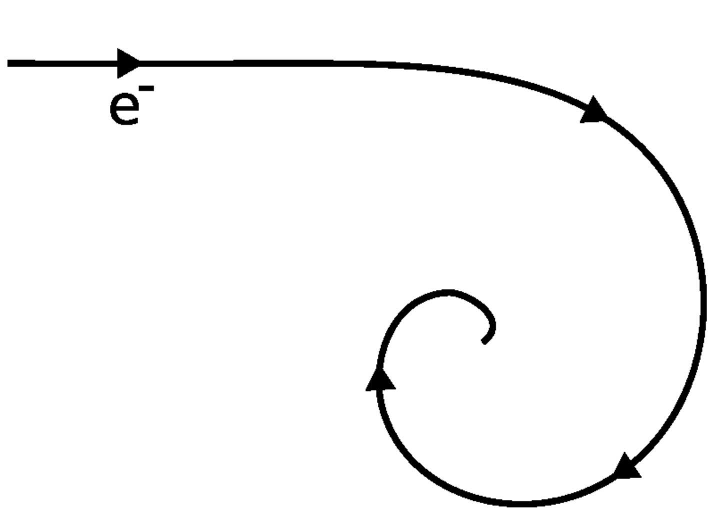
Charge of electron = -1.6 x 10^{-19}C

Mass of electron = 9.11 x 10^{-31}kg

u = 1.66 x 10^{-27}kg

1. An electron enters a cloud chamber, passing into a 0.1T magnetic field. The initial curvature (the reciprocal of its radius) of its path is 100m^{-1}. At what speed was it moving when it entered the magnetic field?

2. The electron spirals inwards in a clockwise direction, as show in the diagram on the right. What would the path of a positron, moving with an identical speed, look like?



3. Using a 2T magnetic field, what electric field strength must be used to get a velocity selector to select only particles which are moving at 100ms^{-1}?

4. Some uranium (atomic number 92) ions (charge +3e) of various isotopes are put through the velocity selector described in question 3. They then enter an 0.00002T uniform magnetic field. What radius of circular motion would uranium-235 have?

/Worked Solutions/

Nuclear Physics

A-level Physics (Advancing Physics)/Quantum Principles

There are two principles which you do not need to know for the exam, but may be helpful in understanding some of the concepts in the course.

Heisenberg Uncertainty Principle

The Heisenberg uncertainty principle states that the momentum and position of an object are limited. Within a certain uncertainty, when we measure a quantum's position, it does not have a definite momentum. When we measure its momentum, it ceases to have a definite position. If we try and measure both, the uncertainty in both will be limited. If we let the uncertainty in our knowledge of momentum be Δp, and the uncertainty in our knowledge of position be Δx:

$$\Delta x \Delta p = \frac{h}{4\pi},$$

where h is Planck's constant (6.63 x 10^{-34} Js). The Heisenberg uncertainty principle explains what happens when electrons occupy energy levels - within these levels, they are limited to a certain range of momentums and positions, but it is meaningless to say which exact momentum and position they occupy.

Pauli Exclusion Principle

The Pauli exclusion principle states that no two particles may occupy the same quantum state as each other. In layman's inaccurate terms, this means that, although two particles can be in the same place as each other, if they are, they will be moving at different velocities and so will shortly no longer be in the same place as each other.

This is why, for example, electrons appear to have 'shells' - there is only a limited number of quantum states that the electrons can occupy, so some have to occupy a different 'shell'. Also, without the Pauli exclusion principle, matter would collapse in on itself - the attractive forces between particles are greater than the repulsive forces. However, the moment they try and do this, then they must be moving at different velocities, and so no longer be collapsing in on each other.

A-level Physics (Advancing Physics)/Radioactive Emissions

'Radioactivity' is a catch-all term for several different emissions from the nuclei of 'radioactive' atoms. There are three main types of radiation: alpha (α), beta (β) and gamma (γ). When radiation occurs, four things must be conserved:

- Mass
- Charge
- Lepton Number
- Baryon Number

In formulae, mass and charge are shown next to the symbol of the particle. For example, a neutron with mass 1u and no charge is ${}^{1}_{0}n$. The charge on a nucleus is equal to the number of protons in the nucleus (electrons can be ignored). The lepton and baryon numbers may be obtained by counting the number of leptons and baryons on either side of the equation, remembering that antiparticles have negative lepton and baryon numbers.

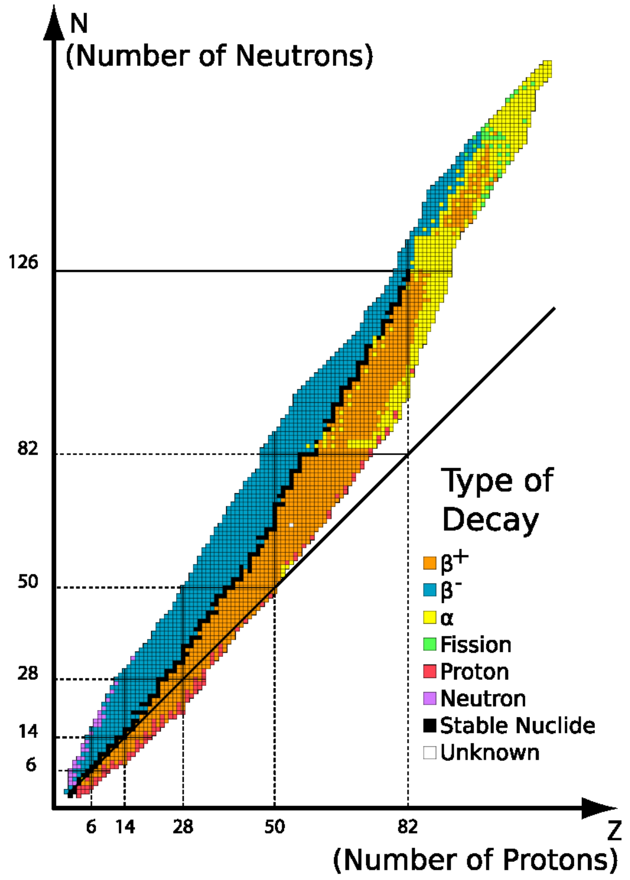


Table of the number of neutrons and protons in the nuclei of isotopes, showing their most common mode of decay.

α Radiation

Unstable nuclei with a mass greater than 82u emit α radiation. This consists of an Helium nucleus (${}^{4}_{2}He$). The alpha particle simply splits off from the nucleus. Since the particle has no electrons, it has a charge of +2e. This, combined with its relatively large mass, means that it reacts easily with other particles, ionising them, meaning that it cannot penetrate more than a few centimetres of air.

β Radiation

Unstable nuclei with a mass below 82u emit β radiation. There are two types of β radiation. β^- radiation consists of an electron (${}^{0}_{-1}e$). This is produced by nuclei with many more neutrons than protons. A neutron changes into a proton, emitting an electron and an antineutrino in order to balance the lepton number. β^+ radiation consists of an positron (${}^{0}_{1}e$). This is produced by nuclei with roughly the same number of neutrons as protons. A proton changes into a neutron, emitting a positron and a neutrino.

β particles also ionise particles, but since they have less charge and mass, they do this less easily, and so they travel further (on average). Both α and β radiation result in the nucleus which emitted them being changed into another element.

γ Radiation

The binding energies of nuclei are quantized - they can only take on certain values. When an electron jumps down an energy level, this energy has to go somewhere - it takes the form of a γ photon. The structure of the nucleus is not changed by γ radiation. γ radiation is ionising, but only at the right frequency - the resonant frequency of the things it ionises. γ radiation travels very far, and only a good thick layer of lead can stop it.

Questions

You will need a periodic table.

1. Americium-241 is an α emitter. What element, and what isotope, is produced by this decay?

2. Iodine-129 is a β^- emitter. What element, and what isotope, is produced by this decay?

3. Gamma rays are used to kill microbes in food. Why doesn't the food become radioactive?

4. Plutonium-244 decays by emitting an α particle. It does this twice, emits a β^- particle, and then emits a further two α particles. The nucleus becomes a different element each time. What element is produced at the end?

5. Carbon-11 changes into Boron-11 by a radioactive emission. What was emitted?

6. Uranium-236 decays, following the equation:

$$^{236}_{92}U \rightarrow \ ^{232}_{90}Th + \ X$$

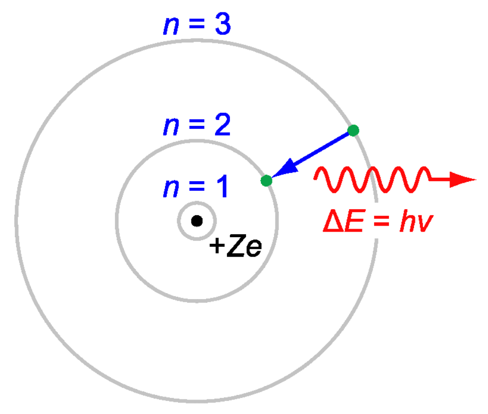
Identify the particle X in this equation.

/Worked Solutions/

A-level Physics (Advancing Physics)/Energy Levels

As an electron approaches a nucleus from infinity, it becomes 'bound' - it is attached to the nucleus, if you like. In this bound state, the electron occupies what is called an energy level. A nucleus has a discrete number of energy levels, and so electrons bound to a certain nucleus can only take on certain potential energies. These energies are negative by convention.

The lowest (most negative) energy level is denoted n=1, the next lowest n=2, and so on. The values of these can be found using formulae which you don't need to know about. Alternatively, they may be determined experimentally.



Energy levels in a hydrogen atom. The transition shown from the *n*=3 level to the *n*=2 level gives rise to visible light of wavelength 656 nm (red).

At random, electrons jump between energy levels. If they jump to a lower energy level (more negative), they release energy in the form of a photon. If they jump to a higher energy level, they must absorb a photon of the appropriate energy. The energies of these photons can be calculated using the following formulae, which you should already know from AS:

$$E = hf$$

$$c = \lambda f,$$

where E is energy, h is Planck's constant (6.63 x 10^{-34} J s), f is frequency, c is the speed of light, and λ is wavelength.

The energy levels of different nuclei are different. Evidence for these energy levels comes from the emission and absorption spectra of atoms. An emission spectrum can be obtained by heating a sample of an element. This gives the electrons energy, so they jump up the energy levels. At random, they then jump down again, giving off photons with measurable frequencies. The formulae above can be used to calculate the difference in energy between the levels between which the electrons have jumped.

An absorption spectrum can be found by passing light through (for example) a gas, and observing the frequencies of light which are absorbed. These frequencies correspond to jumps between energy levels which electrons have undergone when they absorb the photons, gaining energy.

It should be noted that electrons do not always jump to the next-door energy level - they can, in principle, jump to any energy level. They cannot jump to an energy which is not that of an energy level.

Questions

The following table gives the wavelengths of light given off when electrons change between the energy levels in hydrogen as described in the first row:

Transition of n	3→2	4→2	5→2	6→2	7→2	8→2	9→2	∞→2
Wavelength (nm)	656.3	486.1	434.1	410.2	397.0	388.9	383.5	364.6
Color	Red	Blue-green	Violet	Violet	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)

1. Calculate the potential energy of an electron at level n=2.

2. Calculate the difference in potential energy between levels n=2 and n=3.

3. What is the potential energy of an electron at level n=3?

4. If an electron were to jump from n=7 to n=5, what would the wavelength of the photon given off be?

/Worked Solutions/

A-level Physics (Advancing Physics)/Fission

Nuclear fission is the splitting of the nucleus of a massive atom into smaller nuclei. This is used to produce energy in power stations and nuclear bombs.

Chain Reaction

In order to start nuclear fission, one nucleus must be made to split apart. This is achieved by getting the nucleus to absorb a slow-moving neutron. When the nucleus splits, it releases energy, two components, and possibly some more neutrons. If at least one neutron is released, then a chain reaction occurs. This neutrons goes on to make another nucleus unstable, which splits, and produces more neutrons, and so on.

If this chain reaction is uncontrolled, a massive amount of energy is released very fast. This is an atomic explosion, which is used in nuclear bombs. In order to use nuclear fission in a power station, the number of neutrons released must be controlled by inserting a substance such as boron into the reactor, which absorbs the neutrons, preventing them from going on to make more nuclei split.

Binding Energy

The reason nuclear fission produces energy is that the binding energy of the original nucleus is greater than the binding energy of the products of the fission reaction. This difference in binding energy is the amount of energy released as photons (some of which are infra-red). This energy is used to heat up steam, pressurizing it, and enabling it to turn a turbine, producing electricity.

Neutron Moderator

Neutrons have to be moving slowly in order to cause a nucleus to become unstable and split. If they are moving too fast, then they simply bounce off. A neutron moderator (such as graphite or heavy water) is used to slow them down.

Questions

1. A neutron is fired at some Uranium-235. Barium-141 and Krypton-92 are produced:

$${}^1_0n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + N{}^1_0n$$

How many neutrons are produced (ie. what is the value of N)?

2. What proportion of the neutrons produced must be absorbed in order to make the reaction stable?

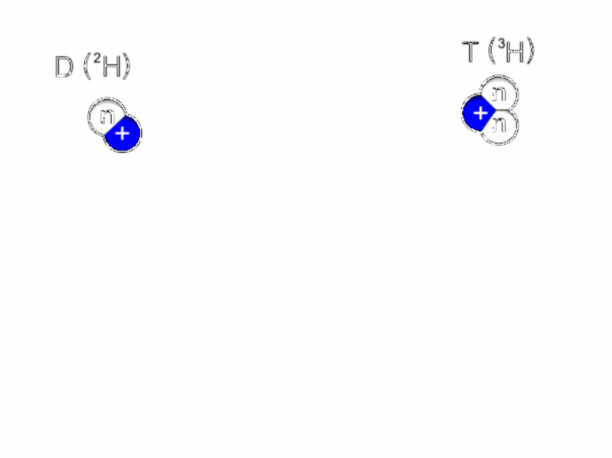
3. What would happen if too many neutrons were absorbed?

4. Alternatively, Uranium-235 can split into Xenon-140, two neutrons and another element. What is this element? (You will need to use a periodic table.)

/Worked Solutions/

A-level Physics (Advancing Physics)/Fusion

Nuclear fusion is the joining together of atomic nuclei to form a larger nucleus, and possibly some other products, including energy. It occurs naturally in stars, where hydrogen is fused together into larger isotopes of hydrogen and then into helium, releasing energy along the way.



Nuclear fusion of deuterium and tritium.

Forces

Nuclei repel each other due to the electromagnetic force, since they have the same charge. In order for two nuclei to fuse, they must be sufficiently close enough together that the attractive force between the baryons due to the strong nuclear force is greater than the repulsive force due to the electromagnetic force. If this is the case, then the two nuclei will become a new, larger, nucleus.

Uses

Nuclear fusion was used by humans for the first time in the hydrogen bomb, since the fusion of hydrogen produces more energy than nuclear fission. At the time of writing (2009), commercially viable fusion power has not yet been achieved. However, research is under way to bring a fusion reaction under control so that it can be used to generate electricity. This would have the advantage of minimal nuclear waste, since the main product would be non-radioactive helium, with some tritium, which has a relatively short 12-year half-life.

Binding Energy

The fusion of nuclei smaller than Iron-56 releases energy. This is because, if we were to take all the baryons of both the nuclei apart, and then stick them all back together as one, we would do less work than would be required to stick them together as the two separate nuclei. The difference in binding energy is the energy which is released by a fusion reaction. This energy might be given to the 'real' particles which are given off, or to a 'virtual' particle such as a photon.

Questions

$c = 3 \times 10^8 ms^{-1}$

1. In the Sun, two tritium nuclei (^3_1H) are fused to produce helium-4 (^4_2He). What else is produced, apart from energy?

2. In larger stars, carbon-12 ($^{12}_6C$) is fused with protium (^1_1H). What single nucleus does this produce?

3. In this reaction, 1.95MeV of energy is released. What difference in binding energy does this correspond to?

4. If all this energy was emitted as a photon, what would its frequency be?

5. In order to contain a fusion reaction, electromagnetism may be used. What other force could be used? Why is this not being used for fusion reactors on Earth?

/Worked Solutions/

A-level Physics (Advancing Physics)/Binding Energy

It takes energy to pull nuclei apart. The amount of work (energy) which must be done in order to pull all of the neutrons and protons in a nucleus infinitely far apart from each other is known as the binding energy of the nucleus. Practically, pulling them all apart far enough to stop them interacting will do.

If energy must be put in to a nucleus to break it apart, where does this energy go? The answer lies in the fact that if you add up the masses of all the protons and neutrons in a nucleus individually, it is a little bit more than the actual mass of the nucleus. The binding energy put in to break the nucleus apart has 'become' mass in the individual baryons. So, the binding energy of a nucleus can be calculated using the following formula:

$$E_b = (n_N m_N + n_Z m_Z - M)c^2,$$

where n_N and n_Z are the numbers of neutrons and protons in the nucleus, m_N and m_Z are the masses of neutrons and protons, M is the mass of the nucleus and c is the speed of light (3×10^8 ms^{-1}).

The Unified Atomic Mass Unit

The unified atomic mass unit, denoted u, is roughly equal to the mass of one proton or neutron. 1 u = $1.660538782 \times 10^{-27}$ kg. They are useful since 1 mole of atoms with a mass of 1 u each will weigh exactly 1 gram. However, when dealing with binding energy, you must **never** use atomic mass units in this way. The mass defect is so small that using atomic mass units will result in a completely wrong answer. If you want to use them with lots of decimal places, then you will save writing in standard form.

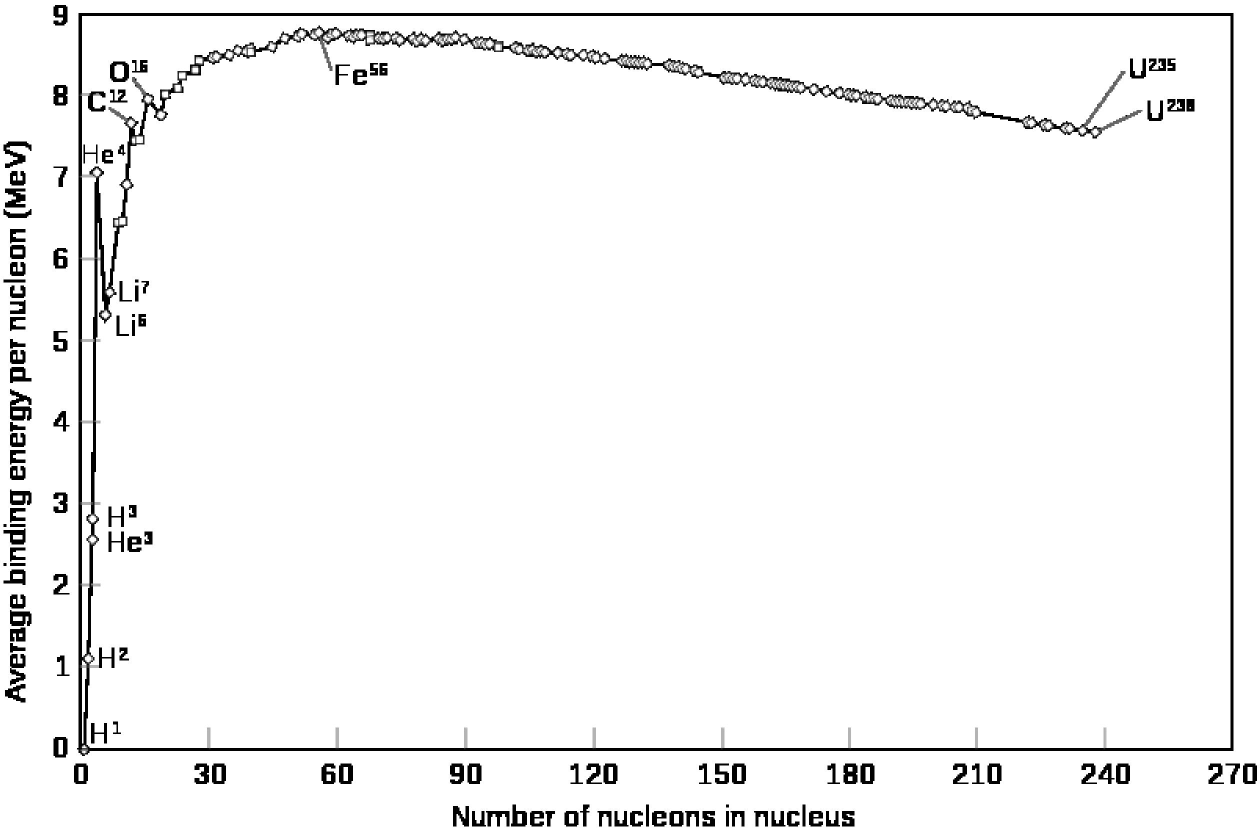
Data

The following table gives the masses in kg and u of the proton and the neutron:

Name	Mass (kg)	Mass (u)
Proton	$1.67262164 \times 10^{-27}$	1.00727647
Neutron	$1.67492729 \times 10^{-27}$	1.00866492

The Binding Energy Curve

Different nuclei have different binding energies. These are determined by the combination of protons and neutrons in the nucleus. These are shown in the following graph:



The position of Iron-56 at the top is important. If you take two nuclei completely apart, you do work. If you then put all the baryons back together again as one nucleus, you will get energy back out. Sometimes, the energy you get back out will be more than the work you had to do to take the nuclei apart. Overall, you release energy by fusing the nuclei together. This happens to nuclei which are smaller than Iron-56. Nuclei which are larger than Iron-56 will give out less energy when fused than you had to put in to take them apart into their constituent baryons in the first place. To the right of Iron-56, nuclear fusion, overall, requires energy.

If you take only one nucleus apart you still do work. If you stick its protons and neutrons back together, but this time in two lumps, you will get energy out. Again, sometimes this energy will be greater than the work you had to do to take them apart in the first place. Nuclear fission will be releasing energy. This occurs when the nucleus is larger than Iron-56. If the energy released is less than the initial work you put in, then nuclear fission, overall, requires energy. This happens when the nucleus is smaller than Iron-56.

This can be summarized in the following table:

Type of Nucleus	Nuclear Fusion	Nuclear Fission
smaller than Iron-56	releases energy	absorbs energy
Iron-56	≈ no energy change	≈ no energy change
Larger than Iron-56	absorbs energy	releases energy

Questions

1. Deuterium (an isotope of Hydrogen with an extra neutron) has a nuclear mass of 2.01355321270 u. What is its binding energy?

2. Uranium-235 has a nuclear mass of 235.0439299 u. It contains 92 protons. What is its binding energy?

3. How would you expect H-2 and U-235 to be used in nuclear reactors? Why?

/Worked Solutions/

A-level Physics (Advancing Physics)/Risks, Doses and Dose Equivalents

Risk

Radioactivity results in risk - this could be a risk of death, or a risk of developing cancer. In physics, risk is what you expect, on average, to happen:

$$\text{risk} = \text{probability} \times \text{consequence}$$

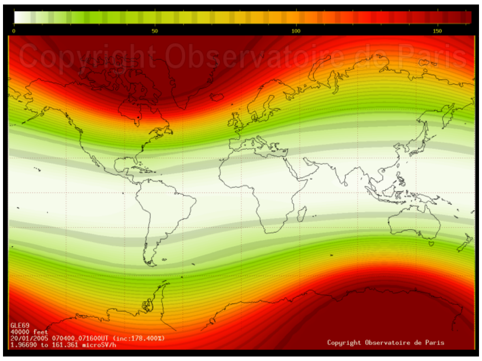
So, if there is a 1 in 500 chance that someone gets run over by a car when crossing the road, the risk involved in allowing 500 people to cross the road is one death.

Absorbed Dose

Absorbed dose is measured in grays, commonly denoted Gy. One gray is defined as one joule absorbed per. kilogram. You may be expected to use the equation $E = mc^2$to calculate absorbed dose in terms of numbers of particles with a given mass. If someone is exposed to a certain activity (particles per. second) over a period of time, the absorbed dose accumulates.

Dose Equivalent

Absorbed dose does not give a full picture of the potential harm radioactivity can do to you. Different types of radiation do different amounts of damage. Absorbed dose equivalent, measured in sieverts (denoted Sv) attempts to compensate. To calculate the dose equivalent, multiply the dose in grays by the quality factor of the particles absorbed. These quality factors are given in the table below.



Hourly dose equivalent due to cosmic rays per. hour in Sv, across the globe.

Radiation Type	Quality Factor
photons and leptons	1
neutrons with an energy > 10 MeV or < 10keV, protons	5
neutrons with an energy between 10 and 100 keV, or between 2 and 20 MeV	10
neutrons with an energy between 100 keV and 2 MeV and atomic nuclei	20

Questions

1. A mobile phone emits electromagnetic radiation. 1.2 watts of power are absorbed per. kilogram. Assuming that the radiation is absorbed uniformly across a 5kg head, what dose of radiation would be delivered to the head when making a 10-minute telephone call?

2. What dose equivalent does this correspond to?

3. How many nuclei are there in 1 mg of Americium-241?

4. A ham sandwich becomes contaminated with 1 μg of Americium-241, and is eaten by an 80kg person. The half-life of Americium-241 is 432 years. Given that Americium-241 gives off 5.638 MeV alpha particles, how long would it be before a dose equivalent of 6 Sv is absorbed, making death certain?

5. What assumptions have you made?

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