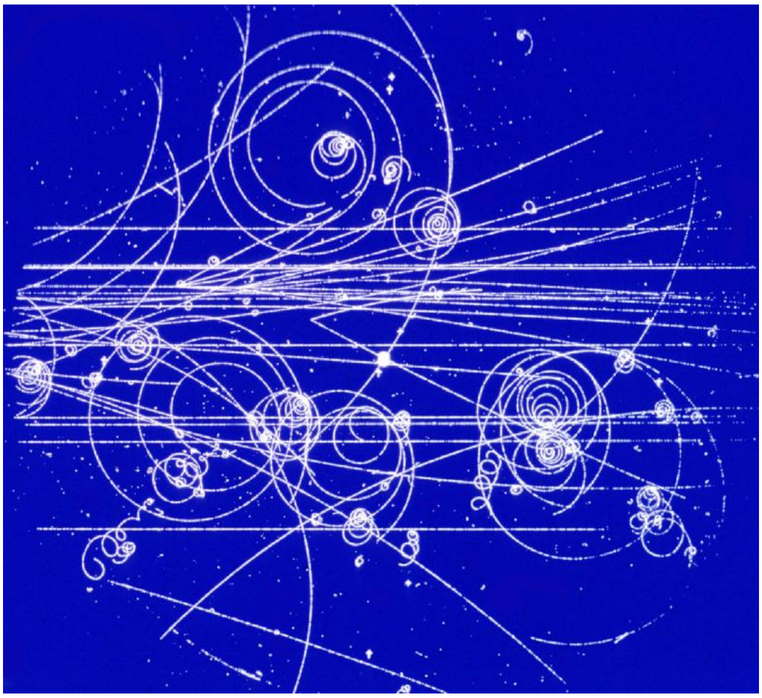
ANDERSON HIGH SCHOOL

Higher Physics
Particles and Waves
Notes



Teachers Booklet

Learning Outcomes – The standard model

This builds on information from Electricity and Energy

- Electrical charge carriers and electric fields

At the end of this section you should be able to

- Compare the orders of magnitude – the range of orders of magnitude of length from the very small (sub-nuclear) to the very large (distance to furthest known celestial objects)
    - Place different objects in order of size from smallest to largest.
- Describe what is meant by the standard model of fundamental particles and interactions.
- Provide evidence supporting the existence of sub-nuclear particles and the existence of antimatter.
- State that fermions, the matter particles, consist of quarks (six types) and leptons (electron, muon, tau, together with their neutrinos).
    - List the six types of quark
    - List the three types of lepton
    - List the three types of neutrino
- State that hadrons are composite particles made of quarks
    - List the quarks which make up a hadron
- State that baryons are made of three quarks
    - List the quarks which make up a baryon
- State that mesons are made up of quark-antiquark pairs.
    - List the quarks which make up a meson
- State that the force mediating particles are bosons (photons, W- and Z- bosons, and gluons).
- Describe beta decay as the first evidence for the neutrino.

The Atom Revisited

Orders of magnitude allow us to compare the relative size of objects, using scientific notation as the standard way to write very large and very small numbers.

Size	**Power of 10 (m)**	**Example**
	10^{-18}	Size of an electron/quark?
1 fm (femto)	10^{-15}	Size of a proton
	10^{-14}	Atomic Nucleus
	10^{-10}	Atom
1 nm (nano)	10^{-9}	Glucose molecule
	10^{-7}	Wavelength of visible light
1 μm(micro)	10^{-6}	Diameter of a mitochondria
1 mm (milli)	10^{-3}	Width of a credit card
1 cm (centi)	10^{-2}	Diameter of a pencil
1 m	10^{0}	Height of a door handle
	10^{1}	Width of a classroom
	10^{2}	Length of a football pitch
1 km (kilo)	10^{3}	Central span of the Forth Road Bridge
	10^{4}	Cruising altitude of airplane
	10^{5}	Height of the atmosphere
1 Mm(mega)	10^{6}	Length of Great Britain
	10^{7}	Diameter of Earth
1 Gm (giga)	10^{9}	Moon's orbit round Earth. Diameter of sun
	10^{11}	Orbit of Venus round sun
1 Tm (tera)	10^{12}	Orbit of Jupiter round sun
	10^{13}	The heliosphere - edge of our solar system?
	10^{16}	Light year. Distance to nearest star
	10^{21}	Diameter of our galaxy
	10^{23}	Distance to the Andromeda Galaxy
	10^{29}	Distance to the edge of the observable universe

Example 1

Which of the following lists the particles in order of size from smallest to largest?

A helium nucleus, electron, proton

B helium nucleus, proton, electron

C proton, helium nucleus, electron

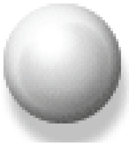
D electron, helium nucleus, proton

E electron, proton, helium nucleus

E

The Atom Revisited

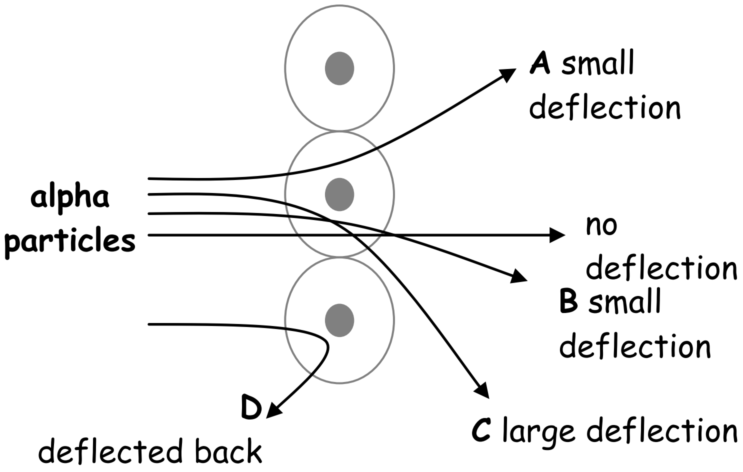
Original ideas about atoms regarded them as tiny spheres.



Current, simple descriptions of the structure of the atom have three types of particle – electron, proton and neutrons,

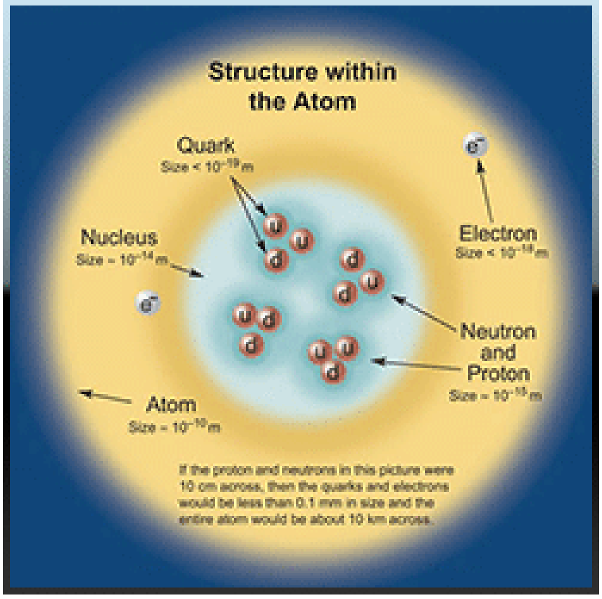
Electrons were discovered in 1897 by J.J. Thomson in a series of experiments. He suggested that they were charged particles, but thought that these were the only particles in an atom.

In 1914 Rutherford carried out an experiment firing alpha particles at a piece of gold leaf, then detecting where the alpha particles ended up.



These results suggested that most of the atom is empty space because the alpha particles passed straight through or are only slightly deflected (A and B). The large deflections at C and D suggest that the nucleus is also positively charged and has a large mass.
When the neutron was discovered in 1932 it explained how isotopes could exist.

The Atom Revisited

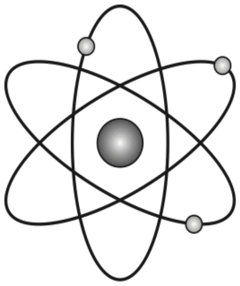


Protons and neutrons are made of even smaller particles called quarks.

In 1964 Gell-Mann suggested that protons and neutrons were made of smaller particles called quarks. Particle accelerators were used to smash up atoms to confirm the existence of quarks. The existence of second and third generation were predicted, but it took until 1995 to find the last quark in the set.

Example 2

A science textbook contains the following diagram of an atom. Use your knowledge of physics to comment on this diagram.



The diagram shows one type of particle in orbits around a central structure.

It does not give any indication of the relative sizes of each part or how far apart they are. Electrons are very small compared to nucleus and are far away from the nucleus.

The nucleus in the diagram appears to be one structure. We now know that this is made of neutrons and protons, which in turn are made from quarks.

The number of protons in the nucleus is not obvious – this should equal the number of electrons.

SQA Rev Higher 2013 Q27

Fundamental Particles

Our current understanding of matter is that there are 12 fundamental particles, which cannot be broken down into anything smaller, organised into three generations.

		Fermions		
		First Generation	Second Generation	Third Generation
Quarks	Symbol	u	c	t
	Name	**Up**	**Charm**	**Top**
	Charge	+2/3	+2/3	+2/3
	Symbol	d	s	b
	Name	**Down**	**Strange**	**Bottom**
	Charge	-1/3	-1/3	-1/3
Leptons	Symbol	e	μ	τ
	Name	**Electron**	**Muon**	**Tau**
	Charge	-1	-1	-1
	Symbol	ν_e	ν_μ	ν_τ
	Name	**Electron neutrino**	**Muon neutrino**	**Tau neutrino**
	Charge	0	0	0

First generation	particles which make up our normal universe.
Second/third generation	only found in high-energy collisions in particle accelerators or in naturally occurring cosmic rays.

Leptons are particles similar to electrons and neutrinos. Some of these second and third generation 'light particles' are heavier than protons.

Quarks have a fraction of the charge on an electron (1.6×10^{-19}C) and are never found alone.

Matter and Antimatter

Antiparticles have the same rest mass as the corresponding particle, but have the opposite charge. They have the same symbol as the particle, but with a bar over the top.

In 1928 Dirac found that the equations he was developing to describe electron interactions had two solutions. The solutions were identical other than the charge – one was negative as expected, the other was positive. This particle was named the **positron.** This is the only antiparticle with a special name.

It is believed that every particle has a corresponding antiparticle. If they come together they will annihilate one another, giving off energy.

Example 3

Three students each make a statement about antiparticles.

I An antiparticle has the same mass as its equivalent particle

II An antiparticle has the same charge as its equivalent particle

III Every elementary particle has a corresponding antiparticle.

Which of the statements is/are correct?

C

A I only

B II only

C I and III only

D II and III only

E I, II and III

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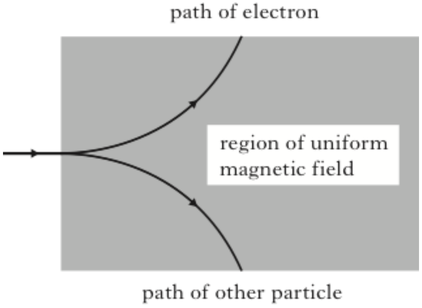
Example 4



An electron and another particle of identical mass pass through a uniform magnetic field. Their paths are shown in the diagram. This observation provides evidence for the existence of

A neutrinos

B antimatter

C quarks

D protons

E force mediating particles

B

SQA 2012 Revised H Q16

Hadrons

Hadrons 'heavy particles' are made up of groups of quarks.

Baryons are made up of three quarks.

A **proton** consists of two up quarks and one down quark.

Total charge = u + u + d = (2/3 + 2/3 + (-1/3)) = +1

A **neutron** consists of two down quarks and one up quark.

Total charge = d + d + u = (-1/3) + (-1/3) + 2/3 = 0

Mesons

Mesons are made up from 2 quarks. They always consist of a quark and an antiquark pair. Antiquarks are antiparticles.

An example of a meson is a negative pion (π^-). It is made up of an anti-up quark and a down quark.

Total charge = $\bar{u}$ + d = (-2/3) + (-1/3) = -1.

The Bosons.

Bosons are the exchange particles, which transmit the effects of a force, photons, W and Z bosons, gluons and the graviton (to be verified).
There are four fundamental forces – gravitational, electromagnetic, weak nuclear and strong nuclear.

Gravitational

Force particle	Range	Relative Strength
Graviton (not yet verified)	Infinite	1

This is the weakest of the four forces. It holds matter in planets, stars and galaxies together.

Electromagnetic

Force particle	Range	Relative Strength
Photon	Infinite	10^{36}

This is a combination of the electrostatic and magnetic forces. This holds electrons within atoms.

Weak Nuclear Force

Force particle	Range	Relative Strength
W and Z bosons	10^{-18}m	10^{25}

This is weak relative to the strong nuclear force. It is involved in radioactive beta decay and is experienced in quark and lepton interactions.

Strong Nuclear Force

Force particle	Range	Relative Strength
Gluon	10^{-15}m	10^{38}

This holds protons together in the nucleus of an atom – without this electrostatic theory predicts that they would fly apart. This is **only** experienced by **quarks**.

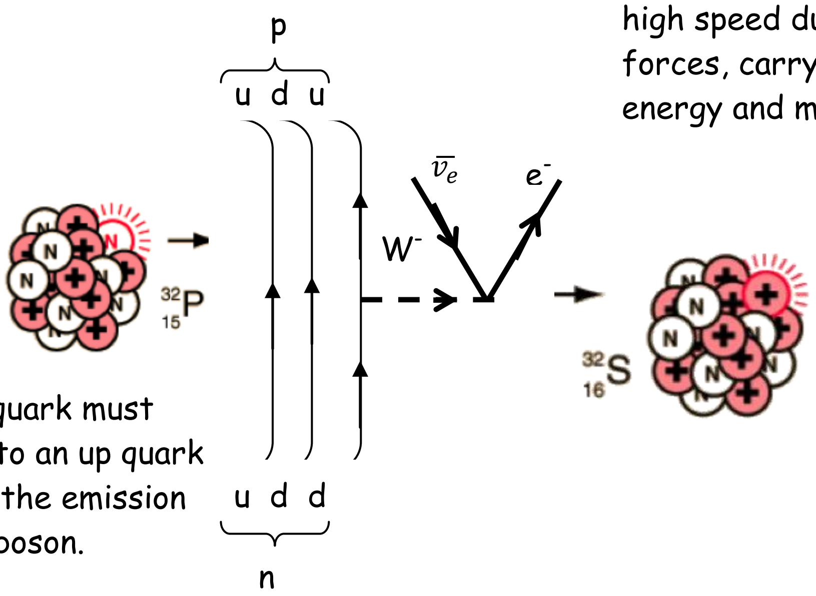
The Higgs boson is not involved in forces, but is what gives particles mass. This is not part of the Higher course.

The standard model

Beta decay - neutrinos

When there is beta decay a neutron decays into a proton.and an electron. The electron is emitted and the nucleus is left with a net positive charge, however, this does not follow the law of conservation of momentum.

The electron is forced out at high speed due to the nuclear forces, carrying away kinetic energy and momentum.



A down quark must decay into an up quark through the emission of a W^-boson.

Example 5

Physicists study subatomic particles using particle accelerators.

Pions are subatomic particles made up of two quarks.

There are two types of pion:

π^+ particles which have a charge of +1,

π^- particles which have a charge of -1,

and π^0 particles which have a zero charge.

The π^+particle is made up of an up quark and an anti-down quark.

a. Is a pion classified as a baryon or a meson?
Justify your answer.

b. The charge on an up quark is + 2/3.
Determine the charge on an anti-down quark.

c. The π^- particle is the antiparticle of the π^+particle.
State the names of the quarks that make up a π^- particle.

(a) Meson because it is made of two quarks.

(b) $\pi^+ = \mathrm{u} + \bar{\mathrm{d}}$

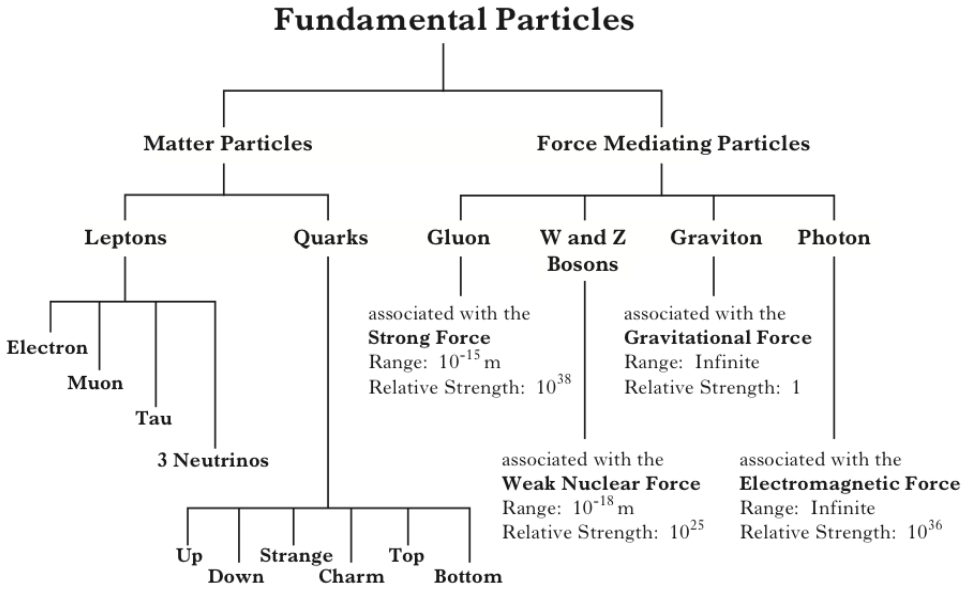
+1 = 2/3 + $\bar{\mathrm{d}}$

charge on anti-down = +1/3

(c) "anti-up" and "down"

The standard model

Example 6



a) Explain why particles such as leptons and quarks are known as *Fundamental particles.*

b) A particle called the sigma plus (Σ^+) has a charge of +1. It contains two different types of quark. It has two up quarks each having a charge of +2/3 and one strange quark. What is the charge on the strange quark?

c) Explain why the gluon cannot be the force mediating particle for the gravitational force.

a) These particles cannot be broken down (into other sub-particles)

b) For the sigma plus particle

$2 \times (+2/3) + q_s = +1$

$q_s = -1/3$

Charge on strange quark = -1/3

c) Strong force (associated with the gluon) acts over a very short distance. The gravitational force extends over very large/infinite distances.

PW Problem booklet 1
P3 Q 1 - 7

Learning Outcomes – Forces on Charged Particles.

This builds on information from Electricity and Energy

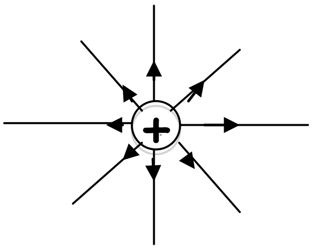
- Potential difference (voltage)

At the end of this unit you should be able to:

- State that charged particles experience a force in an electric field.
- State that forces exist round charged particles and between charged parallel plates
- Draw the field patterns for
  - single point charges
  - systems of two point charges
  - between two charged parallel plates.
- Describe the direction of movement of charged particles in an electric field
- Define the volt using the relationship between potential difference, work and charge.
- Carry out calculations using the relationship $W = QV$
- Use $W = QV$ and $E_K = \frac{1}{2} mv^2$ to solve problems involving the charge, mass, speed and energy of a charged particle in an electric field and the potential difference through which it moves. (Use conservation of energy to calculate the speed of a charged particle accelerated by an electric field)
- State that a moving charge produces a magnetic field.
- Determine the direction of the force on a charged particle moving in a magnetic field for both negative and positive charges (for example using the right hand rule for negative charges)
- Describe the basic operation of particle accelerators in terms of
  - acceleration of charged particles
  - deflection of charged particles
  - collision of charged particles.

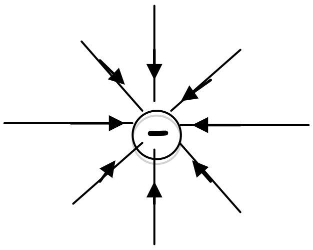
Electric Fields

An electric field exists around a charged object. We cannot see the field but we can see its effect on objects.



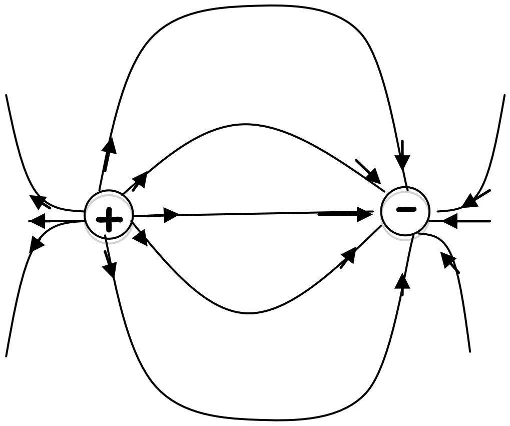
positive point charge

A positive test charge will move **away** from a positive point charge and **towards** a negative point charge.

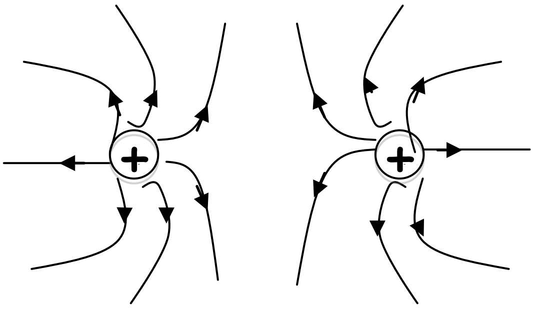


negative point charge

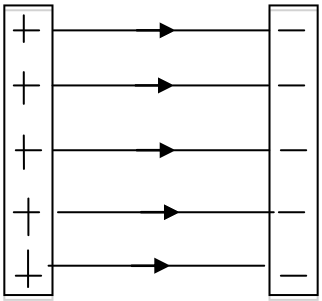
An electric field is three dimensional – but we draw it as two dimensional for simplicity. Where the field is stronger the lines are drawn closer together.



Two unlike charges – same size



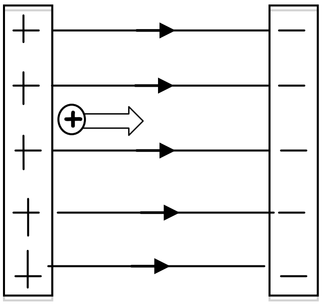
Two like charges – same size, just make sure the arrows are drawn in the correct direction.



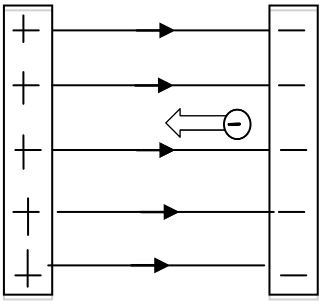
Uniform electric field.

- Use a ruler
- Space the lines evenly

Movement of Charged Particles



A positively charged particle, placed in a uniform electric field, will move towards the negative plate



A negatively charged particle, placed in a uniform electric field, will move towards the positive plate

An electric field exerts a force on a charged particle. When it is moving the energy can be calculated using $E_k = \frac{1}{2} mv^2$.

If the particle is moved against the direction of the force the energy is stored as electric potential energy.

$$E_w = QV$$

One volt = one joule per coulomb

Definition of the volt

The potential difference (p.d.) between two points is one volt if one joule of energy is used to move one coulomb of charge between those two points.

Example 7

A student writes the following statements about electric fields.

I There is a force on a charge in an electric field

II When an electric field is applied to a conductor, the free electric charges in the conductor move.

III Work is done when a charge is moved in an electric field.

Which of the above statements is true?

A I only

B II only

C I and II only

D I and III only

E I, II and III

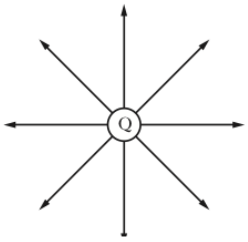
E

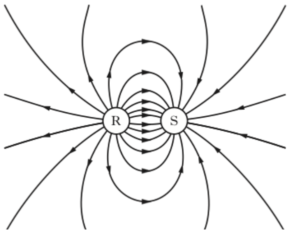
SQA 2004 Higher Q10

Movement of Charged Particles

Example 8

The electric field patterns around charged particles Q, R and S are shown. Identify the charge on each particle.





Q – positive
R – positive
S - negative

SQA revised H 2014
Q8 adapted

Example 9

An electron is accelerated from rest through a potential difference of 2.0 kV.

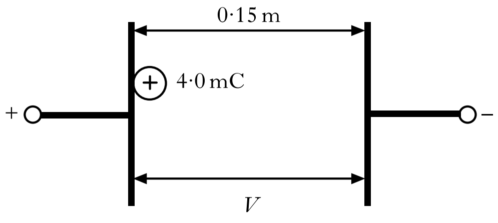
The kinetic energy gained by the electron is

A 8.0×10^{-23}J
B 8.0×10^{-20}J
C 3.2×10^{-19}J
D 1.6×10^{-16}J
E 3.2×10^{-16}J

E

Example 10

A potential difference, V, is applied between two metal plates. The plates are 0.15m apart. A charge of +4.0 mC is released from rest at the positively charged plate as shown.



The kinetic energy of the charge just before it hits the negative plate is 8.0 J.

The potential difference between the plates is .

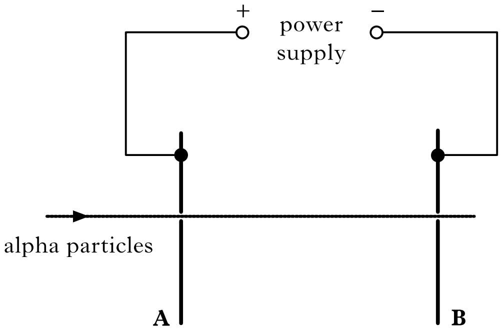
A 3.2×10^{-2}V
B 1.2 V
C 2.0 V
D 2.0×10^{3}V
E 4.0×10^{3}V

D

Movement of Charged Particles

Example 11

The apparatus shown in in the diagram is designed to accelerate alpha particles.



An alpha particle travelling at a speed of 2.60×10^{6} ms^{-1} passes through a hole in plate A. The mass of an alpha particle is 6.64×10^{-27} kg and its charge is 3.2×10^{-19}C.

(a) When the alpha particle reaches plate B, its kinetic energy has increased to 3.05×10^{-14} J.
Show that the work done on the alpha particle as it moves from plate A to plate B is 8.1×10^{-15}J

(b) Calculate the potential difference between plates A and B.

(c) The apparatus is now adapted to accelerate **electrons** from A to B through the same potential difference.
How does the increase in the kinetic energy of an electron compare with the increase in kinetic energy of the alpha particle in part (a)?
Justify your answer.

(a) At A, $E_k = \frac{1}{2} mv^2$

$= \frac{1}{2} \times 6.64 \times 10^{-27} \times (2.60 \times 10^{6})^2$

$= 2.24 \times 10^{-14}$J

Increase in E_k = work done between the plates

$= 3.05 \times 10^{-14} - 2.24 \times 10^{-14}$

$= 8.1 \times 10^{-15}$J

(b) $E_w = QV$

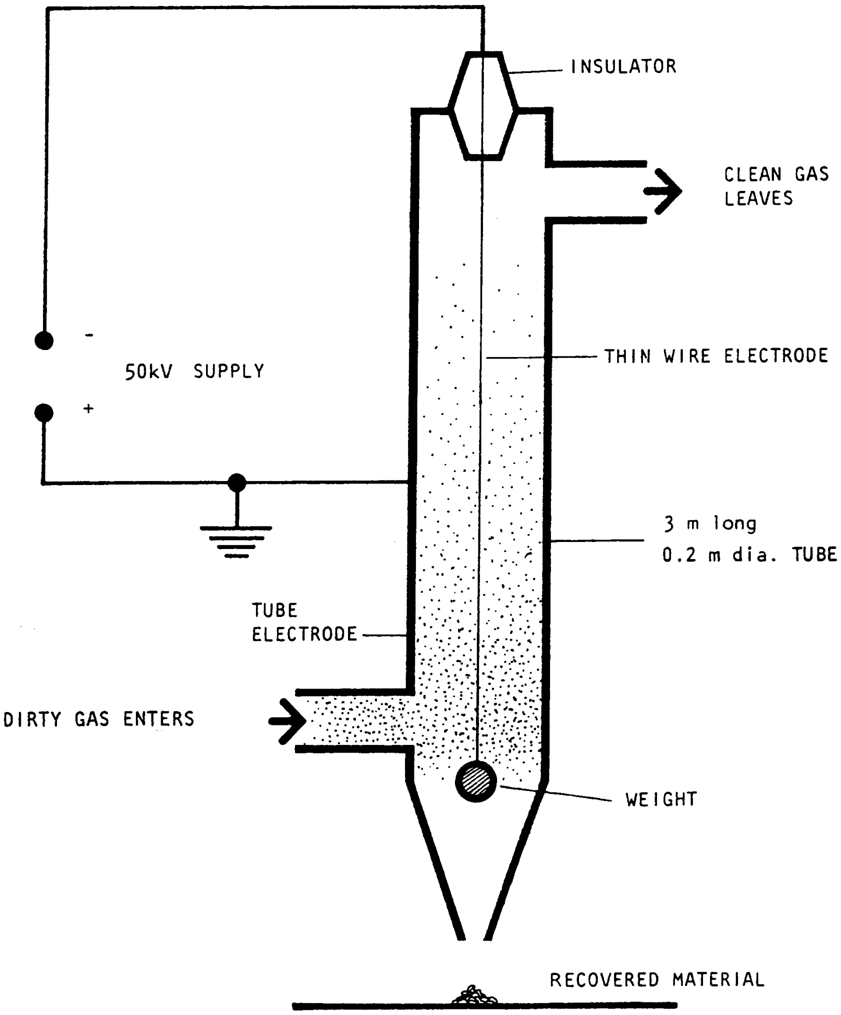
$$V = \frac{8.1 \times 10^{-15}}{3.2 \times 10^{-19}} = 2.5 \times 10^{4}\ V$$

(c) Same potential difference
But the charge is smaller.
So less work is done
So smaller (increase in) kinetic energy.

Practical Uses of Electrical Fields

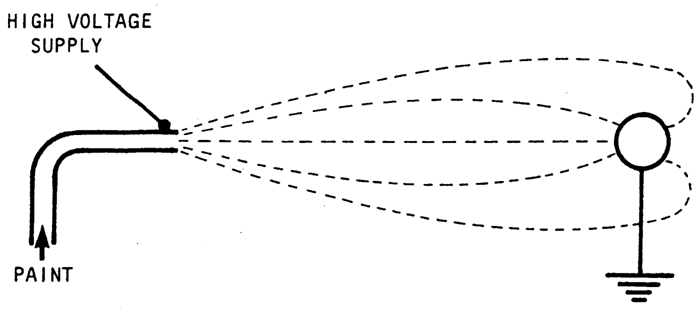
If an object is charged it can attract small particles - a charged plastic ruler can attract pieces of tissue paper. This can be put to practical use in cleaning ash from exhaust gases in power stations or in paint spraying.

Electrostatic precipitation



Ash particles are attracted to the wire and clump together, they then fall out the bottom where they can be removed. Clean air exits at the top.

Paint spraying



The object being painted is earthed. Paint particles are charged by the high voltage supply and are attracted to the object, even painting the back.

Practical Uses of Electrical Fields

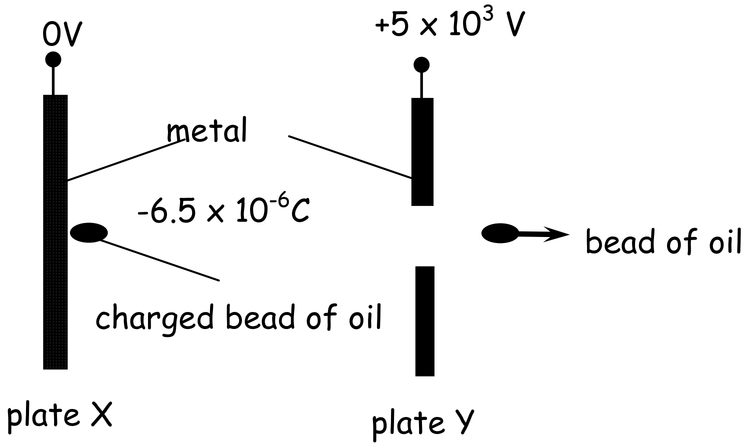
Example 12

A machine to help move threads in a modern weaving machine uses beads of oil and two metal plates X and Y.

The potential difference between these plates is 5.0×10^{3} V.

Each bead of oil has a mass of 4.0×10^{-5} kg and is given a negative charge of 6.5×10^{-6}C.

The bead accelerates from rest at plate X and passes through a hole in plate Y.



Neglecting air friction, calculating the speed of the bead at plateY.

$$E_w = QV$$
$$= 6.5 \times 10^{-6} \times 5 \times 10^{3}$$
$$= 3.25 \times 10^{-2}\ J$$
$$E_k = \tfrac{1}{2} mv^{2}$$
$$3.25 \times 10^{-2} = \tfrac{1}{2} \times 4.0 \times 10^{-5} \times v^{2}$$
$$v = 40.3\ ms^{-1}$$

SQA Higher 2001 Q23 (b)

Example 13

An electron is accelerated across a potential difference (p.d.) of 700V. Calculate the maximum speed the electron reaches.

Charge on an electron = 1.6×10^{-19} C

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

Assume all E_p is converted to E_k

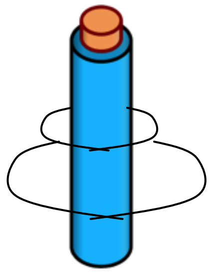
$$E_w = QV$$
$$= 1.6 \times 10^{-19} \times 700$$
$$= 1.12 \times 10^{-16}\ J$$

$$E_k = \tfrac{1}{2} mv^{2}$$
$$1.12 \times 10^{-16} = \tfrac{1}{2} \times 9.11 \times 10^{-31} \times v^{2}$$
$$v = \sqrt{\frac{2x\ 1.12\ x\ 10^{-16}}{9.11\ x\ 10^{-31}}}$$
$$= 1.6 \times 10^{7}\ ms^{-1}$$

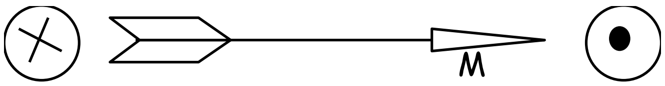
PW Problem booklet 1
P5 Q 1 - 9

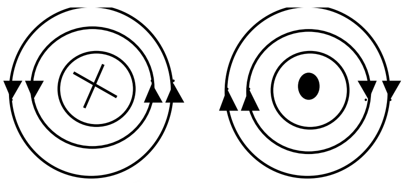
Moving Charge and Magnetic Fields – Predicting Motion

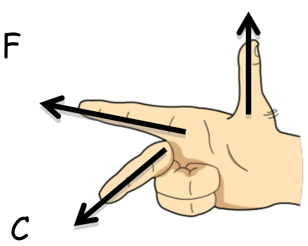
When current flows through a wire a magnetic field is produced around the wire.



The direction current flows through a wire is represented by the tip or the flights of an arrow



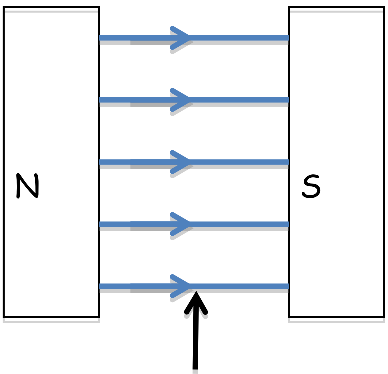




Right hand motor rule

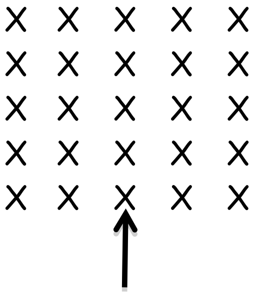
This is used to predict the direction of movement when there is a current in a magnetic field.

First finger = Field (N → S)
SeCond finger = Current (electron flow)
ThuMb = Movement



Electrons travelling up

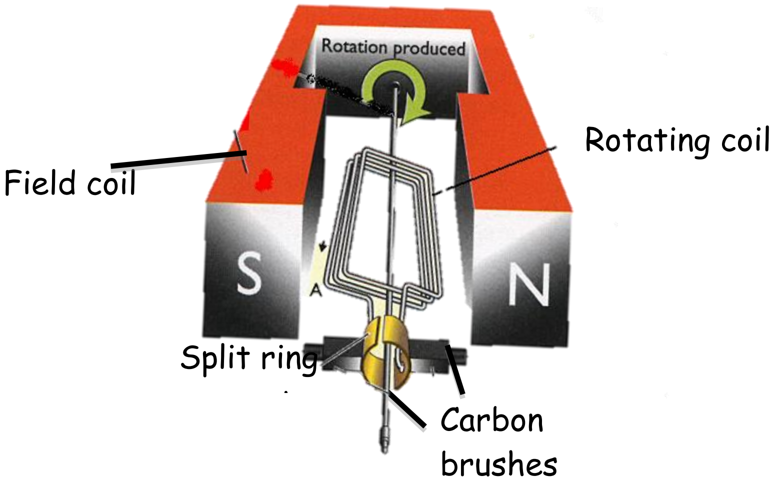
Magnetic field from left to right. Electrons will curve out of the page due to the field.



Electrons travelling up

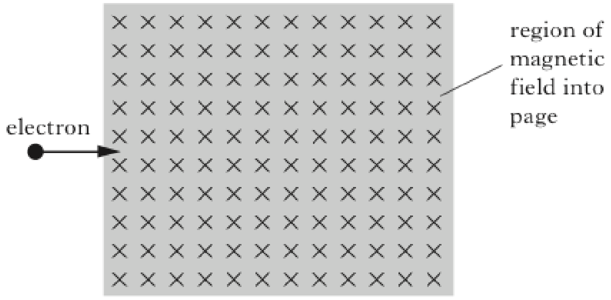
Magnetic field going into the page. Electrons will curve to the right due to the field.

Moving Charge and Magnetic Fields – Predicting Motion



A motor depends on the interaction between two magnetic fields. The coil in the centre of the motor is an electromagnet. When current flows through the rotating coil its magnetic field interacts with the field from the field magnet (which can be permanent or an electromagnet).
Where there are like poles the rotating coil is repelled. This makes it spin.
The commutator makes current flow in the correct direction to keep the motor spinning. The brushes allow the current to reach the commutator.

Example 14
An electron enters a region of magnetic field as shown.



The direction of the force exerted by the magnetic field on the electron as it enters the field is.....

Towards the bottom of the page.

SQA revised H 2014
Q9 adapted

PW Problem booklet 1
P7 Q 1 - 4

Particle Accelerators

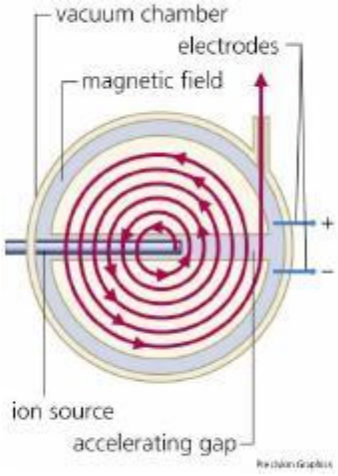
Particle accelerators are used to increase the velocity of particles so that when they are collided they break down into fundamental particles. They can also be used to treat cancer.

Linac – Linear Accelerator

As is suggested by the name charged particles are accelerated in a vacuum pipe through as series of electodes by an alternating voltage.

Advantage – simple acceleration
Disadvantage – must be very, very long to accelerate particles to high energy states.

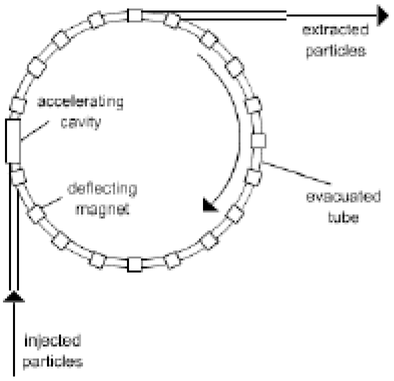
Cyclotron



Charged particles start off at the centre. Electrodes are shaped like the letter 'D' and are called 'dees'. A magnetic field causes the particle to move in a circular path. Each time the particle moves from one dee to another it accelerates and moves to a slightly larger orbit. When it spirals to the outer edge it is extracted for use.

Synchrotron

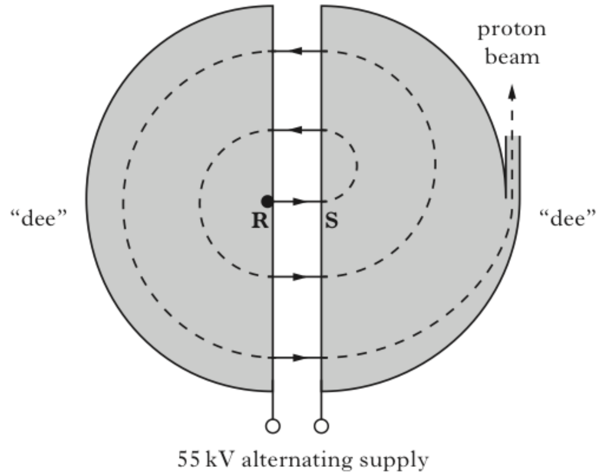
The synchrotron can be thought of as a circular linear accelerator. Magnets are used to keep the charged particles in the centre of the accelerator. The Large Hadron Collider at CERN is an example of a particle accelerator.



http://www.fi.edu/guide/jones/synchrotron.gif

Particle Accelerators

Example 15
A cyclotron is used in a hospital to accelerate protons that are then targeted to kill cancer cells.
The cyclotron consists of two D-shaped hollow metal structures called 'dees', placed in a vacuum. The diagram shows the cyclotron viewed from above.



Protons are released from rest at R and are accelerated across the gap between the 'dees' by a voltage of 55 kV.

(a) (i) Show that the work done on a proton as it accelerates from R to S is 8.8×10^{-15} J.
(ii) Calculate the speed of a proton as it reaches S.

(b) Inside the 'dees' a uniform magnetic field acts on the protons. Determine the direction of this field.

(c) Explain why an alternating voltage is used in the cyclotron.

(a) (i) $E = QV = 1.6 \times 10^{-19} \times 55000 = 8.8 \times 10^{-15}$ J
(ii) $E_k = \frac{1}{2} mv^2 = \frac{1}{2} \times 1.673 \times 10^{-27} \times v^2$
$v = 3.2 \times 10^6 \text{ms}^{-1}$

(b) Into the page or down/downwards but **not** down the page.

(c) A.c. voltage used to chage the direction of the force on protons/polarity of the dees/electric field across the gap.
OR
Electric field must change direction to accelerate the protons because the direction the protons cross the gap changes/keeps changing

SQA revised H 2013 Q 26

Particle Accelerators

Example 16

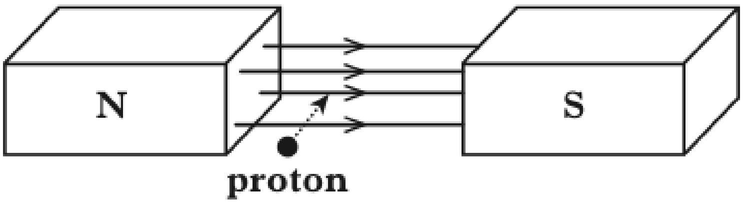
The electron volt (eV) is a unit of energy. It represents the change in potential energy of an electron that moves through a potential difference of 1V (the size of the charge on an electron is 1.6×10^{-19}C. What is the equivalent energy of 1eV in joules?

$$\begin{aligned} E_w &= QV \\ &= 1.6 \times 10^{-19} \times 1 \\ &= 1.6 \times 10^{-19}\ \text{J} \end{aligned}$$

Example 17

(a) In the Large Hadron Collider (LHC) beams of hadrons travel in opposite directions inside a circular accelerator and then collide. The accelerating particles are guided around the collider using strong magnetic fields.

(i) The diagram shows a proton entering a magnetic field



In which direction is this proton deflected?

(ii) The neutron is classified as a hadron.
Explain why neutrons are **not** used for collision experiments at the LHC.

(b) Explain how particle accelerators, such as the LHC at CERN are able to

(i) accelerate charged particles

(ii) deflect charged particles.

(a) (i) deflected downwards (**not South)**

(ii) neutrons don't carry/have charge, so cannot be accelerated/guided/deflected by **magnetic** fields

(b) (i) electric field (to accelerate)

(ii) magnetic field (to deflect)

SQA revised H 2012 Q26 (d), 2014 Q26 (b)

PW Problem booklet 1
P9 Q 1 - 11

Nuclear Reactions – Learning Outcomes

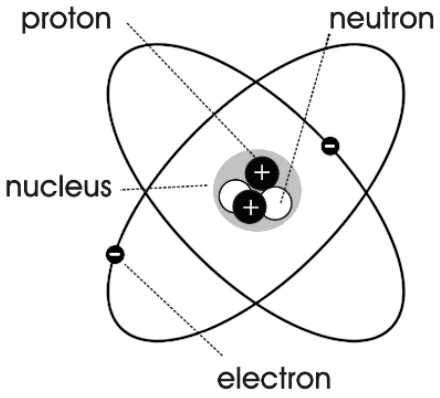
This builds on information from Waves and Radiation

- Nuclear radiation

At the end of this section you should be able to

- Write nuclear reactions to describe radioactive decay for
    - Alpha radioactive decay
    - Beta radioactive decay
    - Gamma radioactive decay
- Use nuclear equations to calculate the original element which has undergone a series of radioactive decays
- Use nuclear equations to predict the element produced by a series of radioactive decays
- Identify spontaneous fission, induced fission and fusion reaction from a nuclear equation
- Calculate the mass loss in a nuclear reaction
- Use $E = mc^2$ to calculate the energy released by a nuclear reaction by calculating the mass loss in both fission and fusion reactions
- Explain, in words, what happens when fission and fusion reactions take place.
- Describe what is meant by coolant and containment issues in nuclear fusion reactors.

Model of the atom



The nucleus of the atom contains both protons and neutrons. It has an overall positive charge. Most of the mass of the atom is concentrated at the centre of the atom.
Electrons are around the outside of the atom.

Mass number =
Number of protons +
number of neutrons

A - Mass number

$${}^{238}_{92}U$$

Chemical
symbol

Z - Atomic number

Uranium

Atomic number =
Number of protons

To find the number of neutrons in an atom
Mass number – atomic number
238 – 92 = 146

Atoms which have the same atomic number but different mass numbers are called **isotoPes.**

Alpha Decay

$${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Uranium Thorium

Alpha decay is when an alpha particle (2 protons and 2 neutrons, equivalent to a Helium nucleus) is lost from an atom.

Beta Decay

$${}^{234}_{91}Pa \rightarrow {}^{234}_{92}U + {}^{0}_{-1}e$$

Protactinium Uranium

Beta decay is where a neutron changes into a proton and electron. The proton stays in the atom, but the electron and an antineutrino is emitted.

Gamma Decay
Gamma rays are photons of electromagnetic radiation, not particles. When gamma rays are emitted from an atom this does not change the mass number of atomic number of the atom.

Nuclear Reactions – emitting radiation

It is possible to predict the type of radiation emitted during a radioactive decay by looking at the mass number and the atomic number

1. If the mass number goes down by 4 and the atomic number goes down by 2 it is **alpha radiation.**
2. If the mass number stays the same and the atomic number goes up by 1 it is **beta radiation.**
3. If the mass number stays the same and the atomic number stays the same it is possible that **gamma radiation** has been emitted, but there is no way to tell, so the picture is incomplete.

Example 18
Identify the missing particles or nuclides represented by the letters A, B, C and D.

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$

Radium Radon

$${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

Thorium Proactinium

$${}^{234}_{91}Pa \rightarrow {}^{234}_{92}U + {}^{0}_{-1}e$$

Proactinium Uranium

$${}^{212}_{83}Bi \rightarrow {}^{208}_{81}Tl + {}^{4}_{2}He$$

Bismuth Thallium

Reactions can follow on from one another in a radioactive 'daisy chain' as shown below.

Example 19
Identify the type of radiation released at each stage of the following radioactive chain reaction.

$${}^{238}_{92}U \xrightarrow{{}^{4}_{2}He} {}^{234}_{90}Th \xrightarrow{{}^{0}_{-1}e} {}^{234}_{91}Pa \xrightarrow{{}^{0}_{-1}e} {}^{234}_{92}U$$

Uranium Thorium Protactinium Uranium

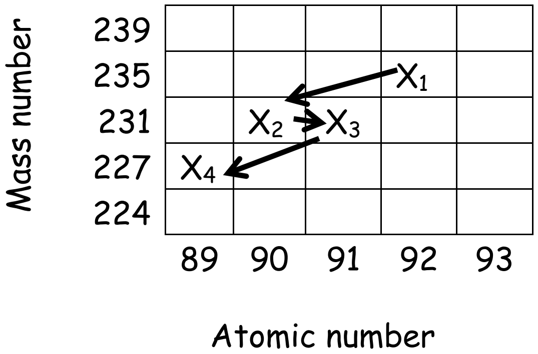
Using the information about which type of radiation was emitted, identify the element at the start of the reaction (including mass and atomic numbers).

$${}^{212}_{83}Bi \xrightarrow{{}^{0}_{-1}e} {}^{212}_{84}Po \xrightarrow{{}^{4}_{2}He} {}^{208}_{82}Pb$$

Bismuth Polonium Lead

Nuclear Fission Calculations

A series of nuclear reactions can also be represented in a grid



This could also be written as

$$^{235}_{92}U \rightarrow {}^{231}_{90}Th \rightarrow {}^{231}_{91}Pa \rightarrow {}^{227}_{89}Ac$$

Uranium Thorium Protactinium Actinium

where an alpha particle is emitted going from X_1 to X_2 and from X_3 to X_4 , and a beta particle is emitted going from X_2 to X_3.
It isn't possible to tell whether gamma radiation is emitted or not from the diagram.

Nuclear Fission (break apart)
Nuclear fission can either be spontaneous or stimulated.

a) Spontaneous nuclear fission
A large atomic nucleus splits into two nuclei of smaller mass number plus several free neutrons, releasing energy.

$$^{256}_{100}Fm \rightarrow {}^{140}_{54}Xe + {}^{112}_{46}Pd + 4\,{}^{1}_{0}n + energy$$

Fermium Xenon Palladium neutrons

b) Stimulated nuclear fission
A large atomic nucleus is induced by bombarding it with neutrons, it splits into two nuclei of smaller mass number plus several free neutrons, releasing energy.

$$^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + energy$$

Neutron Uranium Barium Krypton neutrons

Nuclear Fusion
In nuclear fusion, two small atomic nuclei combine to form a larger nucleus, releasing energy. Other small particles such as neutrons may also be formed.

$$^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + energy$$

Hydrogen Hydrogen Helium neutron

Nuclear Fission Calculations

In nuclear fission reactions – both spontaneous and stimulated - mass is **always** lost during the reaction. This 'lost mass' is converted into kinetic energy of the products using Einstein's famous equation

$E = mc^2$ where

E = energy (J)
m = mass (kg)
c = speed of light (3×10^8 ms^{-1})

Example 20

A nuclear fission reaction is represented by the following statement.

$$^{235}_{92}U + \,^{1}_{0}n \rightarrow \,^{137}_{r}Cs + \,^{s}_{37}T + 4\,^{1}_{0}n$$

(i) Is this a spontaneous or an induced reaction ? You must justify your answer.

(ii) Determine the numbers represented by the letters **r** and **s** in the above reaction.

(iii) Use the periodic table to identify the element represented by T.

(iv) The masses of the nuclei and particles in the reaction are given below

	Mass (kg)
$^{235}_{92}U$	390.219×10^{-27}
$^{137}_{r}Cs$	227.292×10^{-27}
$^{s}_{37}T$	157.562×10^{-27}
$^{1}_{0}n$	1.675×10^{-27}

Calculate the energy released in the reaction.

(i) Induced – a neutron is added to the left hand side.

(ii) r = 55 s = 95

(iii) Element T = Rubidium

(iv)

Left hand side

$$\begin{array}{r} 390.219 \\ +\quad 1.675 \\ \hline 391.894 \times 10^{-27}\text{kg} \end{array}$$

Right hand side

$$\begin{array}{r} 227.292 \\ 157.562 \\ +\ (4 \times 1.675) \\ \hline 391.554 \times 10^{-27}\text{kg} \end{array}$$

Loss in mass

$$\begin{array}{r} 391.894 \\ -\ 391.554 \\ \hline 0.34 \times 10^{-27}\text{kg} \end{array}$$

$E = mc^2$

$= 0.34 \times 10^{-27} \times (3 \times 10^8)^2$

$= 3.06 \times 10^{-11}$ J

SQA H 2006 Q 29 (b)

Nuclear Fusion Calculations

In nuclear fusion reactions mass is **always** lost during the reaction. This 'lost mass' is converted into kinetic energy of the products using Einstein's famous equation

$E = mc^2$ where E = energy (J)

m = mass (kg)

c = speed of light (3×10^8 ms^{-1})

Example 21

The sun releases its energy through vast numbers of hydrogen nuclei fusing into helium every second. Calculate the energy released by one of these reactions, shown below.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + energy$$

Deuterium + tritium → α particle + neutron

	Mass (kg)
$^{2}_{1}H$	3.345×10^{-27}
$^{3}_{1}H$	5.008×10^{-27}
$^{4}_{2}He$	6.647×10^{-27}
$^{1}_{0}n$	1.675×10^{-27}

Left hand side

$$\begin{array}{r} 3.345 \times 10^{-27} \\ \underline{+\ 5.008 \times 10^{-27}} \\ 8.353 \times 10^{-27}\ kg \end{array}$$

Right hand side

$$\begin{array}{r} 6.647 \times 10^{-27} \\ \underline{+\ 1.675 \times 10^{-27}} \\ 8.322 \times 10^{-27}\ kg \end{array}$$

Mass difference

$$\begin{array}{r} 8.353 \times 10^{-27} \\ \underline{-\ 8.322 \times 10^{-27}} \\ 0.031 \times 10^{-27} kg \end{array}$$

Energy released

$E = mc^2$

$= 0.031 \times 10^{-27} \times (3 \times 10^8)^2$

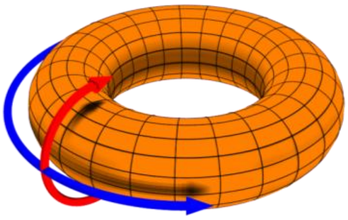
$= 2.8 \times 10^{-12} J$

Nuclear Fusion – the fuel of the future?

The hydrogen bomb is an example of an uncontrolled nuclear fusion reaction.

To use fusion as an energy source the reaction needs to be controlled. To sustain fusion there are three conditions, which must be met simultaneously

- Plasma temperature must be 100 – 200 million Kelvin. At this temperature the molecules of a gas will lose electrons to become positively charged ions.
- A stable reaction lasting at least 5 seconds called the Energy Confinement Time 4 – 6 seconds
- A precise value for the density of plasma 1-2 particles m^{-3} (approximately 1mg m^{-3} i.e. one millionth the density of air)



Containing the extremely hot plasma is done using magnetic fields in the shape of a torus (doughnut). Two magnetic fields are needed – the toroidal direction is the circumference of the doughnut, the poloidal direction is the circumference of a slice of the doughnut

It takes a lot of energy to raise the temperature of the plasma to a high enough temperature for the reaction to take place.
Plasma is a conductor, so it can be heated by passing a current through it in the same way as the wire in an electric light bulb is heated (ohmic heating). This can take the temperature to 20-30 million degrees Celsius. To go above this other methods are needed.
Rapidly moving atoms injected into the plasma become ionised and are trapped by the magnetic field. The high-energy ions transfer energy through collisions with the plasma particles. (Neutral beam injection)
High-frequency electromagnetic waves can also help heat the plasma.

Cooling
Fusion reactions produce large amounts of high energy neutrons. These are not contained by the magnetic field and continue until they are stopped by the inside wall – this yields enough energy to melt the walls of the reactor. Ceramic plates and a cryogenic system operating superconducting magnets using liquid helium and liquid nitrogen are designed to combat this problem.

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Photoelectric Effect – Learning Outcomes

At the end of this section you should be able to

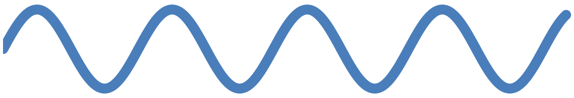
- State that the photoelectric effect is evidence for the particulate nature of light
- State that photons of sufficient energy can eject electrons from the surface of materials
- Use $E = hf$ to solve problems involving frequency and energy of a photon.
- State that the threshold frequency is the minimum frequency of a photon required for photoemission
- State that the work function of the material is the minimum energy required to cause photoemission
- Use $E = hf_0$ to calculate the work function of a material
- Use $Ek = hf - hf_0$ to solve problems involving the maximum kinetic energy of a photoelectrons, the threshold frequency of the material and the frequency of the photon.

Photoelectric Effect - background

Classical Wave Theory

Light is part of the electromagnetic spectrum. Everything on the electromagnetic spectrum observes the properties of a wave

- Reflection
- Refraction
- Diffraction
- Interference.



This suggests that light is a continuous wave.

Quantum Theory

Max Planck suggested that light could be delivered as packets of energy, called quanta or photons. Einstein related this to the photoelectric effect and was awarded the Nobel prize for this work in 1921.

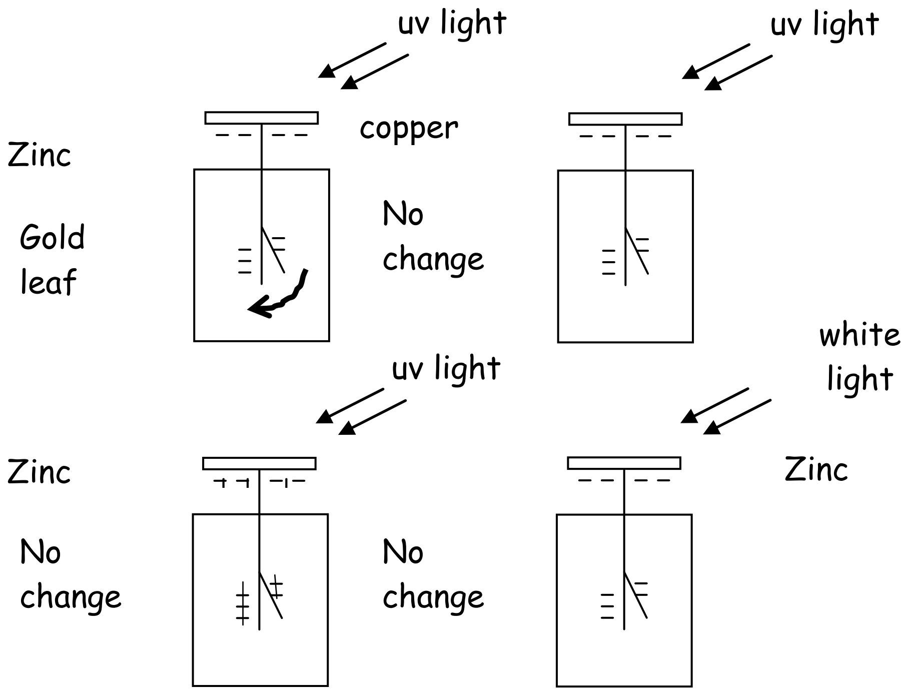
From http://universe-physics.blogspot.co.uk/

The equation $v = f\lambda$ where v = velocity (3×10^8 ms^{-1})
f = frequency (Hz)
λ = wavelength (m)
also applies to photons of light, however the energy of a photon does not depend on amplitude but is directly proportional to frequency.

This gives the equation
$E = hf$ where E = Energy (J)
h = Planck's constant(6.63×10^{-34}Js)
f = frequency (Hz)

Classical theory says light behaves like a wave, quantum theory says light behaves like a particle. This is referred to as 'wave-particle duality' and is a key concept.

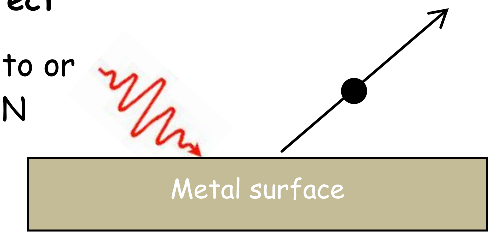
Photoelectric Effect – practical demonstration



The gold leaf electroscope is only discharged when all three criteria are met

- it is negatively charged
- it is ultraviolet light
- it is a zinc plate

This is the **photoelectric effect**



ONE photon with energy equal to or greater than WORK FUNCTION strikes metal surface

ONE electron emitted from surface

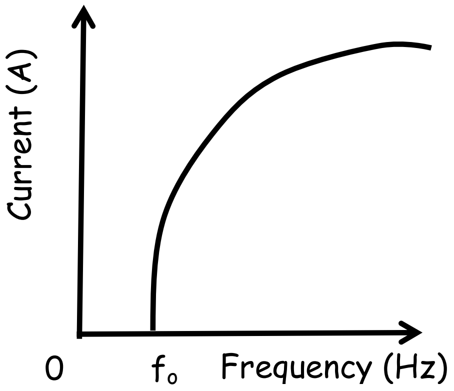
The photoelectric effect supports quantum theory because electrons within the metal are being given enough energy to come to the surface and be released from the surface of the metal.

- If the electroscope is negatively charged an electron released from the surface of the metal will be repelled. The opposite will happen if the electroscope is positively charged.
- Ultraviolet light has a higher frequency than white light - using E = hf shows it has a higher energy too.
- Zinc is a more reactive metal than copper so it is easier to free electrons from its surface.

Photoelectric Effect – Calculating Energy

Threshold frequency (f_o)

Each metal has a minimum frequency of electromagnetic radiation required in order to eject electrons from the surface.
This is called the threshold frequency, f_o.



The minimum energy required to release an electron from the surface of a metal is called the **work function**, E_o, of the material

$$E_o = hf_o$$

E = Energy (J)
h = Planck's constant(6.63×10^{-34}Js)
f = frequency (Hz)

If an electron is given this amount of energy it will escape from the surface of the metal but will have no kinetic energy.

Example 22
If the work function of a metal is 8.0×10^{-19}J, can light of frequency 6.7×10^{14} Hz cause electrons to be emitted? Justify your answer.
$E = hf = 6.63 \times 10^{-34} \times 6.7 \times 10^{14} = 4.44 \times 10^{-19}$ J
No – this is below the work function.

If the energy supplied to the metal is greater than the work function the additional energy will appear as kinetic energy of the electrons.
This can be written as

$$E_k = E - E_o$$

Using the equation this can be re-written as

$$E_k = hf - hf_o$$

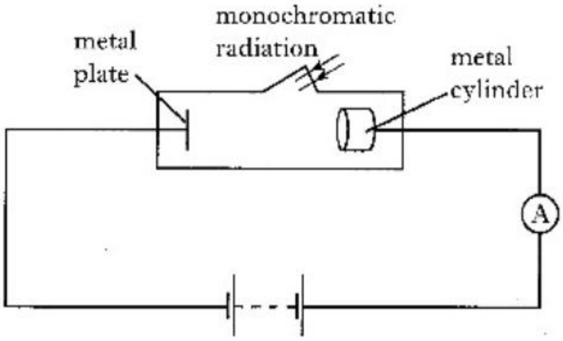
So

$$\frac{1}{2} mv^2 = hf - hf_o$$

E_k = kinetic energy (J)
E = energy (J)
E_o= work function (J)
h = Planck's constant
f = frequency (Hz)
m = mass (kg)
v = velocity (ms^{-1})

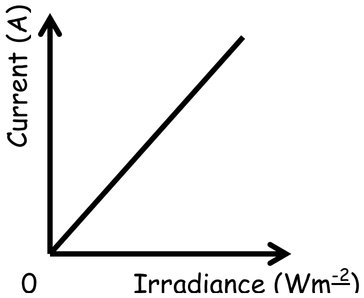
Example 23

In 1902, P. Lenard set up an experiment similar to the one shown below.



There is a constant potential difference between the metal plate and the metal cylinder. Monochromatic radiation is directed onto the plate. Photoelectrons produced at the plate are collected by the cylinder. The frequency and the irradiance of the radiation can be altered independently. The frequency of the radiation is set at a value above the threshold frequency.

a) The irradiance of the radiation is slowly increased. Sketch a graph of the current against the intensity of radiation



As more photons hit the surface more electrons are released.

b) The battery connections are now reversed. Explain why there could still be a reading on the ammeter.
Some electrons may have enough (kinetic) energy to travel from the (metal) plate to the (metal) cylinder.

c) What would happen if the light source was moved closer to the metal plate?
The electron discharge rate increases.

SQA Higher 2005 Q29 adapted

Photoelectric Effect – Calculating Energy

Example 24

The metal of the plate has a work function of 3.11×10^{-19}J. The wavelength of the radiation is 400nm.

Calculate the maximum kinetic energy of a photoelectron.

$v = f\lambda \Rightarrow 3 \times 10^{8} = f \times 400 \times 10^{-9}$

$f = 7.5 \times 10^{14}$ Hz

$E = hf = 6.63 \times 10^{-34} \times 7.5 \times 10^{14}$

$= 4.97 \times 10^{-19}$J

$E_k = E - E_o = 4.97 \times 10^{-19} - 3.11 \times 10^{-19}$

$= 1.86 \times 10^{-19}$J

SQA Higher 2005 Q29 adapted

Example 25

Ultraviolet radiation is incident on a clean zinc plate. Photoelectrons are ejected.

The clean zinc plate is replaced by a different metal, which has a lower work function. The same irradiance of ultraviolet radiationis incident on this metal.

Compared to the zinc plate, which of the following statements is/are true for the new metal?

I. The maximum speed of the photoelectrons is greater
II. The maximum kinetic energy of the photo electrons is greater
III. There are more photoelectrons ejected per second

A I only
B II only
C III only
D I and II only
E I, II and III

D

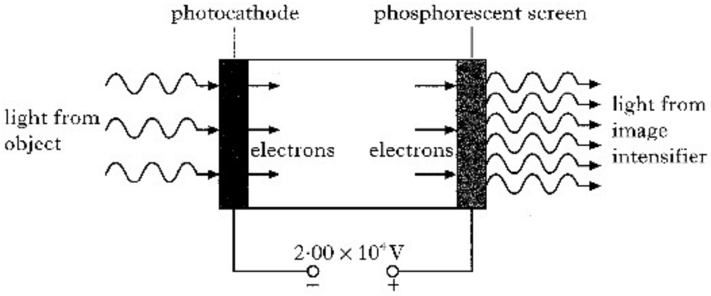
SQA Higher 2004 Q 14

Photoelectric Effect – Calculating Energy

Example 26

An image intensifier is used to improve night vision. It does this by amplifying the light from an object.

Light incident on a photocathode causes the emission of photoelectrons. These electrons are accelerated by an electric field and strike a phosphorescent screen causing it to emit light. This emitted light is of a greater irradiance than the light that was incident on the photocathode.



The voltage between the photocathode and the phosphorescent screen is 2.00×10^4V.

The minimum frequency of the incident light that allows photoemission to take place is 3.33×10^{14}Hz.

a) Show that the work function of the photocathode material is $2.2.1 \times 10^{-19}$ J.

b) Light of frequency 5.66×10^{14} Hz is incident on the photocathode. Calclate the maximum kinetic energy of an electron emitted from the photocathode.

a) $E = hf$

$= 6.63 \times 10^{-34} \times 3.33 \times 10^{14}$

$= 2.21 \times 10^{-19}$ J

b) $E = hf$

$= 6.63 \times 10^{-34} \times 5.66 \times 10^{14}$

$= 3.75 \times 10^{-19}$ J

Maximum kinetic energy of emitted electron

$= 3.75 \times 10^{-19} - 2.21 \times 10^{-19}$

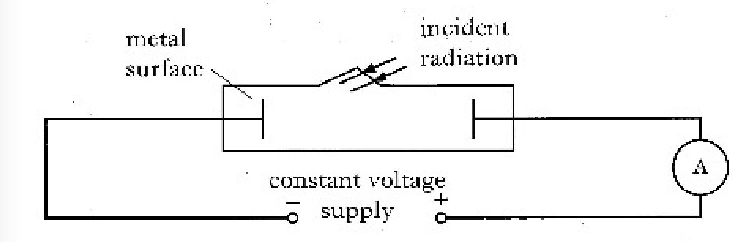
$= 1.54 \times 10^{-19}$J

SQA Higher 2002 Q28 adapted

Photoelectric Effect – Calculating Energy

Example 27

The apparatus shown below is used to investigate photoelectric emission from a metal surface when electromagnetic radiation is shone on the surface. The intensity and frequency of the incident radiation can be varied as required



a) Explain what is meant by *photoelectric emission* from a metal
b) What is the name given to the minimum frequency of the radiation that produces a current in the circuit?
c) A particular source of radiation produces a current in the circuit.
   Explain why current in the circuit increases as the intensity of the incident radiation increases.

a) Electrons are emitted from a metal surface when exposed to electromagnetic radiation/light.
b) Threshold frequency
c) More photons are incident on surface per second, so more electrons are ejected per second.