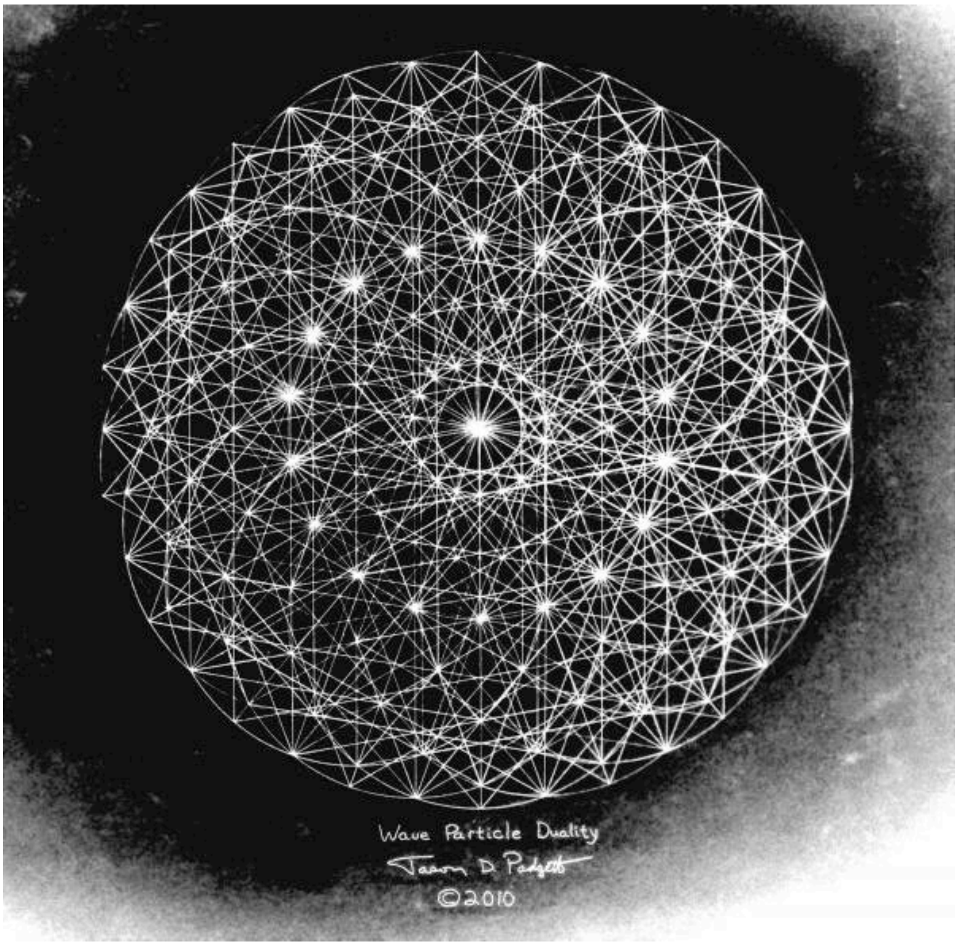
HIGHER PHYSICS

Particles and waves



http://images.fineartamerica.com/images-medium/wave-particle-duality-ii-jason-padgett.jpg

Part 1 - Particles

HIGHER PHYSICS

1) THE STANDARD MODEL

Can you talk about:

a) 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).

b) The Standard Model of Fundamental Particles and Interactions

- The evidence for the sub-nuclear particles and the existence of antimatter.
- Fermions, the matter particles, consist of:
  - **Quarks** (6 types)
  - **Leptons** (**Electron**, **Muon** and **Tau**, together with their neutrinos).
- **Hadrons** are composite particles made of **Quarks**.
- **Baryons** are made of three **Quarks**
- **Mesons** are made of two **Quarks**.
- The force mediating particles are bosons:

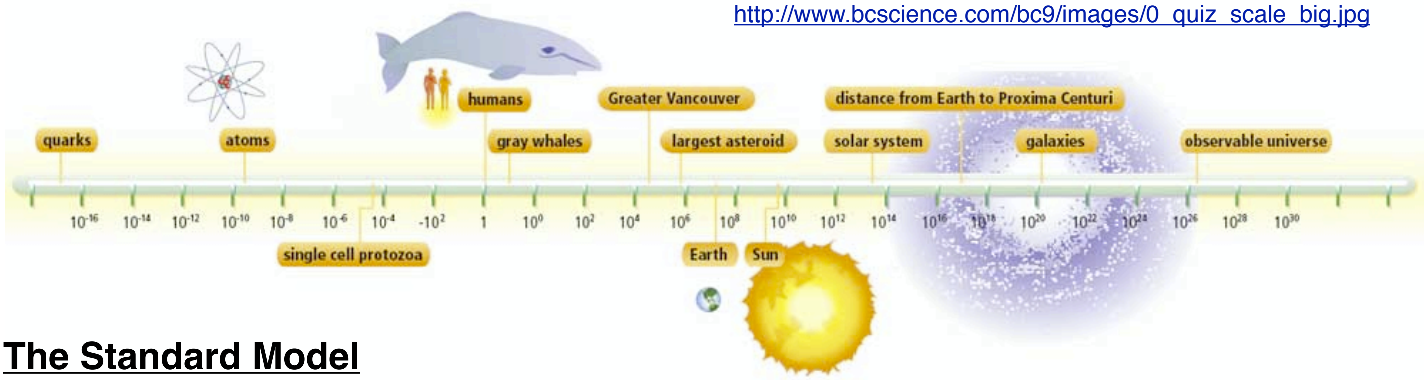
  (**Photons**, **W** and **Z Bosons** and **Gluons**).
- Description of beta decay as the first evidence for the neutrino.

Orders of Magnitude

In Physics it is necessary to measure extremely small and extremely **large** objects, from subatomic **particles** to the size of the **Universe**.

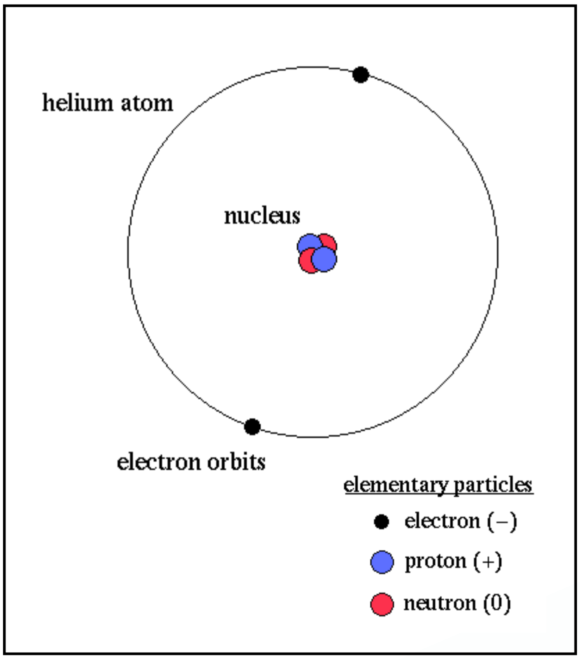
The average distance from the Earth to the Sun is 150 000 000 km. There are two problems with quoting a measurement in this way: the **inconvenience** of writing so many zeros, the **uncertainty** in the value (How many significant figures are important?) These are over come if **scientific notation** is used. 150 000 000 km = 1.5×10^8 km

http://www.bcscience.com/bc9/images/0_quiz_scale_big.jpg



The Standard Model

In a **particle accelerator** a very small particle, eg an electron, can be accelerated by electric and magnetic fields to a **very high speed**. Being very small, speeds near to the speed of light may be achieved. When these particles collide with a stationary target, or other fast-moving particles, a substantial amount of **energy** is **released** in a small space. Some of this energy may be converted into mass ($E = mc^2$), producing showers of **nuclear particles**. By passing these particles through a magnetic field and observing the deflection their **mass** and **charge** can be measured. For example, an electron with low mass will be more easily deflected than its heavier cousin, the muon. A positive particle will be deflected in the opposite direction to a negative particle. Cosmic rays from outer space also contain particles, which can be studied in a similar manner.



Most matter **particles**, such as protons, electrons and neutrons have corresponding **antiparticles**.

These have the same rest mass as the particles but the **opposite charge**. With the exception of the antiparticle of the electron e^-, which is the positron e^+, antiparticles are given the same symbol as the particle but with a bar over the top.

When a particle and its antiparticle meet, in most cases, they will **annihilate** each other and their mass is converted into energy. There are far more particles than antiparticles in the Universe, so annihilation is **extremely rare**.

The Fundamental Particles

Fundamental particles are particles that cannot be divided into smaller particles. In the standard model of particle physics, there are 12 fundamental particles (called Fermions). 6 types of **quarks** and 6 types of **leptons**. These all have corresponding **antiparticles**. There are also 4 **force carriers**.

Leptons have **no size** and in most cases low or no mass. There are **three generations** of leptons, only electrons occur in ordinary mass. Muons occur in the upper atmosphere and the tau has only been seen in laboratory experiments.

Quarks have **fractional charges**. The top quark is the most massive fundamental particle, almost 200 times the mass of a proton. There are also three generations. Individual quarks have never been detected.

	1st	2nd	3rd	Force carriers
Quarks	2.4 MeV/c^2 2/3 u up	1.27 GeV/c^2 2/3 c charm	171.2 GeV/c^2 2/3 t top	0 MeV/c^2 0 γ photon
Quarks	4.8 MeV/c^2 -1/3 d down	108 MeV/c^2 -1/3 s strange	4.2 GeV/c^2 -1/3 b bottom	0 MeV/c^2 g gluon
Leptons	<2.2 eV/c^2 0 ν_e electron neutrino	<0.17 MeV/c^2 0 ν_μ muon neutrino	<15.5 MeV/c^2 0 ν_τ tau neutrino	91.2 GV/c^2 0 Z^0 Z boson
Leptons	0.511 MeV/c^2 -1 e electron	105.7 MeV/c^2 -1 μ muon	1.777 GeV/c^2 -1 τ tau	80.4 GeV/c^2 $W^\pm$ W boson

Hadrons are particles made from quarks that are held together by the strong force, **composite** particles. This force is so strong that quarks have never been found individually. There are two types of hadron:

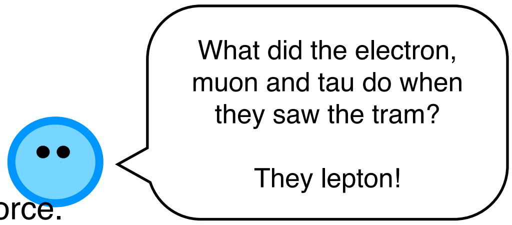
Baryons - made of **three** quarks or **three** antiquarks
Mesons - made of a **quark** and an **antiquark**.

QUARK SONG

The baryons and mesons can only have whole **integer** charges, 2e, e, 0, -e and -2e. There are other rules governing the joining of interactions, strangeness, spin, topness. We will not cover these in this course.

quarks	quark charges	total charge	baryon or meson
uud (proton)	2/3 2/3 -1/3	+1	baryon
$\bar{u}d$ (negative pion)	-2/3 -1/3	-1	meson

Ordinary matter contains only the first generation of quarks.
Very high energies are needed to make hadrons of other quarks.



Particles experience four forces: **strong** (**nuclear**) force, **weak** (**nuclear**) force, **gravitational** force and **electromagnetic** force.

Strong (Nuclear) Force
- Electrostatic theory predicts that the protons in the nucleus should fly apart.
  This does not happen so there must be another force present. This is known as the **strong force** and holds the protons together.
- The strong force acts over a short range and over this short range it is stronger than the electrostatic force.
- Only experienced by quarks.

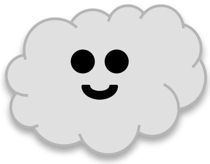
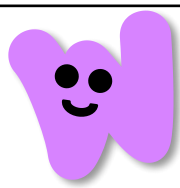
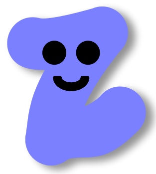
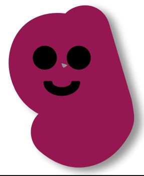
Gravitational Force
- See Unit 1 notes
- Has infinite range
- **Weakest** of all the fundamental forces

Weak (Nuclear) Force
- Involved in radioactive beta decay.
- Acts over a **short range**
- Is **weaker** than the strong nuclear force (hence its name)
- Experienced in quark and lepton interactions

Electromagnetic Force
- Combination of the **electrostatic** and **magnetic** forces
- Has infinite range

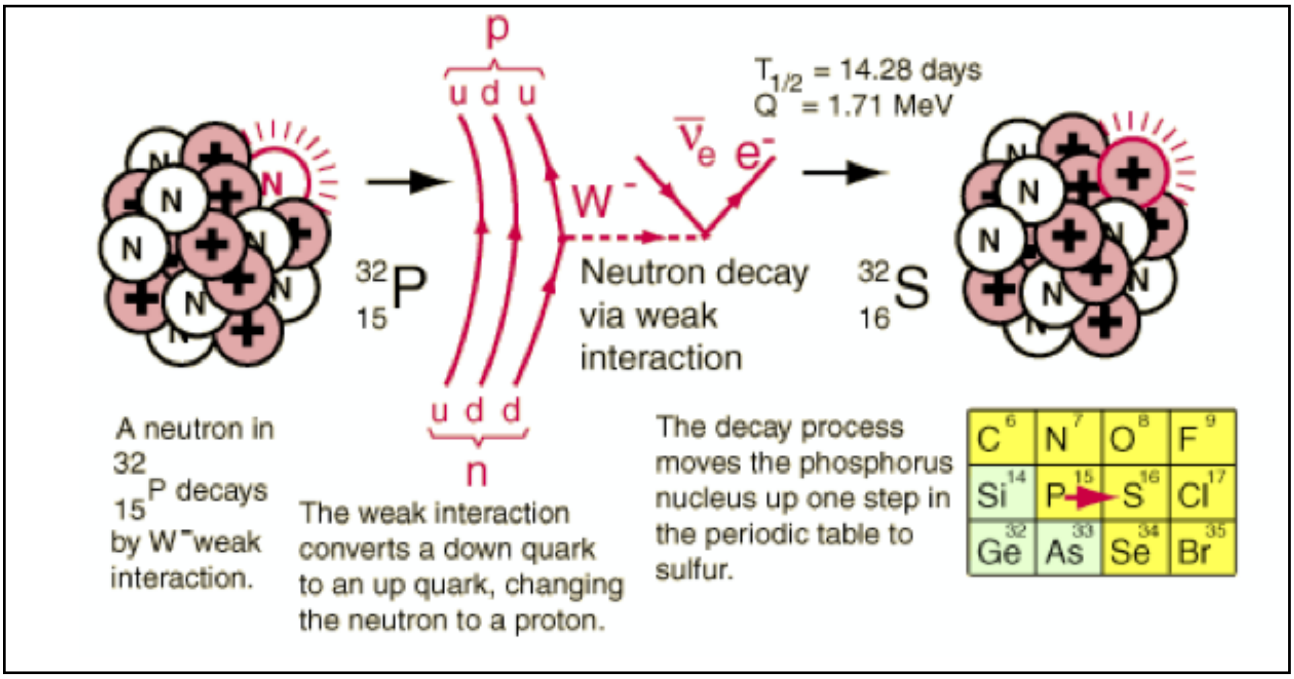
Grand Unification Theory
Scientists are working towards a **Grand Unification Theory** which will link all the forces into one theory. Gravitational Force is proving more difficult to link to the other forces. For this reason the gravitational force is not included in the Standard Model. The gravitational force is relatively **very** weak and therefore can be ignored in terms of subatomic particles.

The sub-atomic non contact forces are explained using **force carriers**. The force carriers are:

				
Photon	Gluon	W boson	Z boson	Graviton*
Electromagnetic	Strong nuclear	Weak nuclear	Weak nuclear	Gravitational

* Gravitons are purely theoretical and have not been discovered.

Beta decay



http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/betaw.gif

When there is beta decay a neutron decays into a proton. (a down quark decays into an up quark). This happens through the emission of a W^- (weak force interaction) and an electron is forced out at high speeds. The emitted electron has less energy than theory predicts. Hence a another particle has to be emitted, due to the conservation of momentum. This particle had to be neutral and penetrating as it did not interact with detectors. This particle was calculated to be an anti-electron neutrino.
There is also another type of beta decay, known as beta +. In this process a proton decays into a neutron. A positron and neutrino are emitted.

HIGHER PHYSICS

2) FORCES ON CHARGED PARTICLES

Can you talk about:

a) Electric fields around charged particles and between parallel plates

- Examples of **electric field patterns** including **single point** charges, systems of **two point** charges and the field between **parallel plates**.

b) Movement of charge in an electric field, p.d. and work, electrical energy

- The relationship between **potential difference**, **work** and **charge** gives the definition of the **volt**.
- Calculating the **speed** of a **charged particle** which has been accelerated in an electric field.

c) Charged particles in a magnetic field

- A **moving charge** produces a **magnetic field**.
- The **direction** of the **force** on a charged particle moving in a magnetic field should be described for **negative** and **positive** charges.

d) Particle accelerators

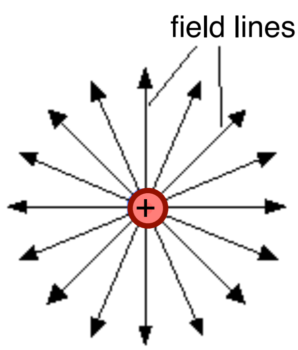
- Basic operations of particle **accelerators** in terms of **acceleration**, **deflection** and **collision** of charged particles.

Electric Fields

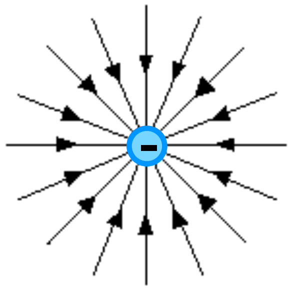
FIELD LINES VIDEO

An **electric field** is a region where a **charged particle** (such as an **electron** or **proton**) experiences a **force** (an **electrical force**) without being touched.

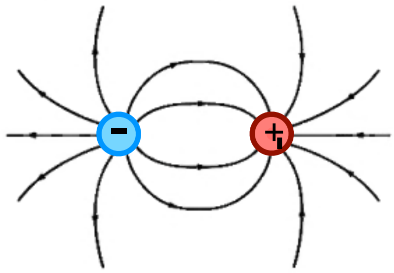
If the charged particle is free to move, it will accelerate in the direction of the unbalanced force.
To represent an **electric field**, we draw **electric field lines**. The **field line** represents the motion of a **test positive charge**.

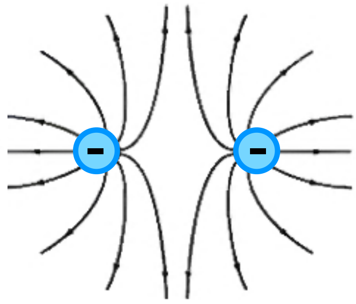


The electric field from an isolated positive charge



The electric field from an isolated negative charge



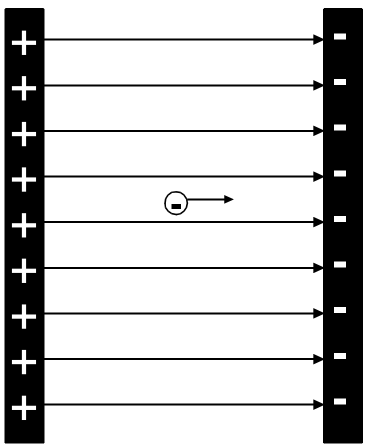


A proton (positive charge will accelerate towards the negative
An electron (negative charge) would accelerate towards the positive.

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

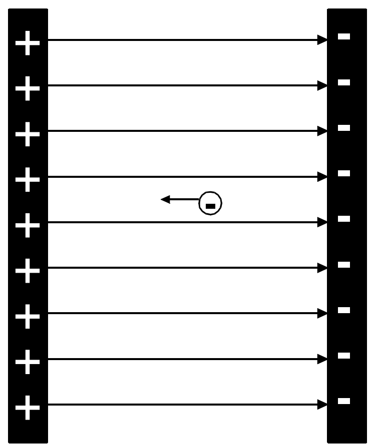
To move an **electron** (negative charge) towards the negatively charged plate, **energy** must be needed in order to overcome the repulsion force between the electron and the negatively charged plate.

The **work done** is gained by the electron as **electrical potential energy**.



If the **electron** is free to move back towards the positively charged plate, the **electric field** does **work on** the electron.

The electron's **electrical potential energy** is changed to **kinetic energy** as the **electric field** moves the electron towards the positively charged plate.



Work Done Moving a Charge and Potential Difference

The **potential difference** (**V**) between 2 points in an electric field is a measure of the **work done** (**W**) in moving **1 coulomb of charge** between the 2 points.

$$E = QV$$

- E: work done in moving quantity of charge between 2 points in an electric field/ joules (J)
- Q: quantity of charge/ coulombs (C)
- V: potential difference between 2 points in an electric field/ joules per coulomb (JC^{-1}) OR volts (V)

This formula defines the **volt**.

Calculate the potential difference between 2 points in an electric field, if the field does:

25 J of work moving 5 C of charge between the 2 points.	100 J of work moving 2.5 C of charge between the 2 points.
E = 25 J Q = 5 C E = QV 25 = 5 x V V = 5 V	E = 100 J Q = 2.5 C E = QV 100 = 2.5 x V V = 40 V

Electrical Potential Energy to Kinetic Energy

When an **electron** is free to move in the **electric field** between two oppositely charged metal plates, the **work done** by the **electric field** on the **electron** is converted to **kinetic energy** of the **electron**.

work done on electron by electric field = gain in kinetic energy of electron

$$QV = \frac{1}{2}mv^2$$

- Q: magnitude of charge on electron (1.60×10^{-19} C)
- V: potential difference through which electron is moved V
- m: mass of electron (9.11×10^{-31} kg)
- v: speed of electron ms^{-1}

[This equation also applies to any other charged particle in an electric field].

Example

An electron is free to move in an electric field. The electron is accelerated by the field from rest through a potential difference of 500 V. Calculate the **speed** of the the electron at the end of the acceleration.

work done on electron by electric field = gain in kinetic energy of electron

$\therefore$ $QV = 1/2\, m v^2$

$(1.60 \times 10^{-19}) \times 500 = 1/2 \times (9.11 \times 10^{-31}) \times v^2$

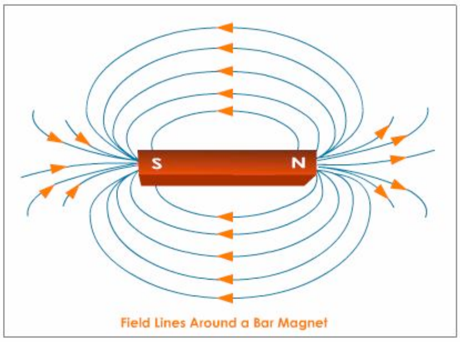
$$\therefore \quad v^2 = \frac{(1.60 \times 10^{-19}) \times 500}{1/2 \times (9.11 \times 10^{-31})}$$

$$\therefore \quad v = \sqrt{\frac{(1.60 \times 10^{-19}) \times 500}{1/2 \times (9.11 \times 10^{-31})}}$$

$\therefore$ $v = 1.33 \times 10^{7}\ m\,s^{-1}$

Charged particles in a magnetic field

Magnetic fields are produced by **moving charges** or currents in wires. In a simple bar magnet there do not appear to be any currents but the magnetic field is generated by **electrons** orbiting atoms that make up the structure of the magnet.



WARNING

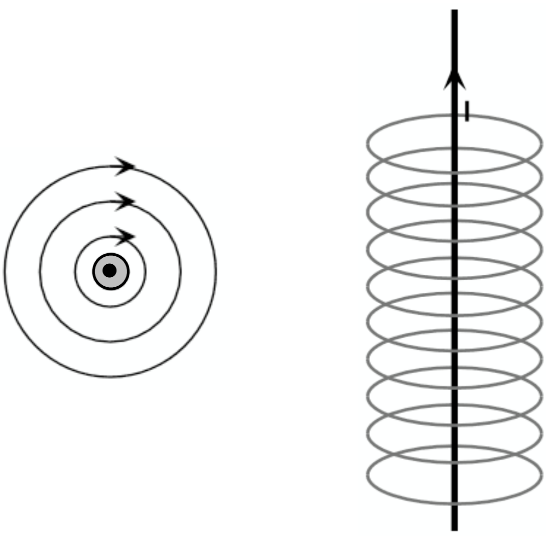
Current can be considered as the flow of electrons or as conventional current (the flow of positive charges). For Higher Physics you need to know how to interpret the effects of BOTH on a current carrying wire.

If a **current** flows through a piece of **wire** then a **magnetic field** will be produced around the wire.

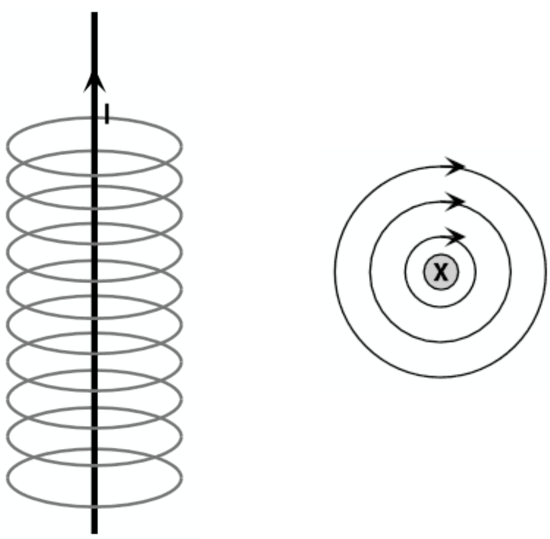
The direction of the magnetic field depends on the **direction** of current flow.

The direction can be determined using the **screw rule**.

Electron Current



Conventional Current

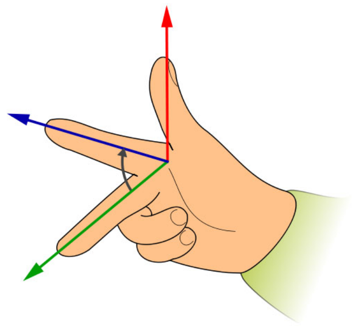


⦿ dots represent current coming out of the page

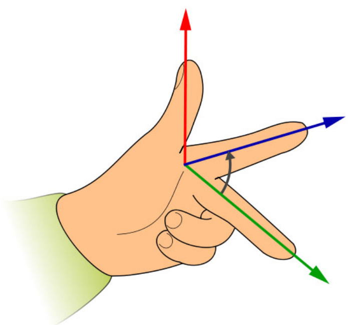
ⓧ crosses represent current going into the page

Forces on a current carrying wire

Electron Current



Conventional Current



A wire carrying an **electric current** will experience a mechanical **force** when placed in a magnetic field. When this happens, the magnetic field pushes on the wire. The force of this "push" relates directly to the **intensity of the current**, the **strength of the magnetic field** and the **length of the wire**.

You can visualize this relationship by using the “**right hand rule**” (electron current) or "**left hand rule**" (conventional current). If the first finger points in the direction of the magnetic field, the second finger in the direction of the current, then the thumb represents the direction of the force thrust (or motion).

Conversely if we have a **magnetic field** acting on a **moving charge** it will experience a **force**. However, if the charge travels **parallel** to the magnetic field, it will not experience an additional force.

The direction of the force is determined using the same “hand rule’s”.

The **speed** of the charge will **not change**, only the direction of motion changes.

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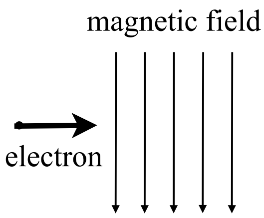
<td>
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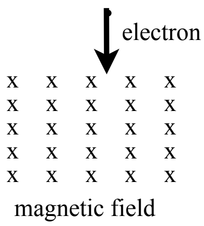
<td>
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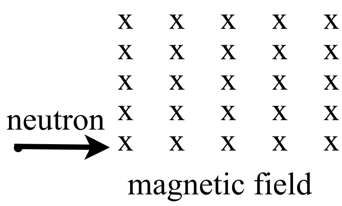
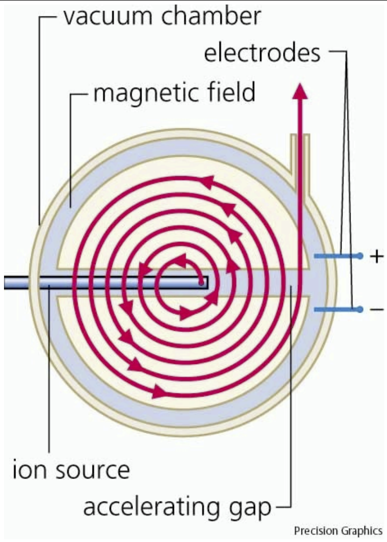
<td>
</td>
</tr>
<tr>
<td>The electron will curve out of the page.</td>
<td>The electron will curve to the right</td>
<td>No change in direction as a neutral particle.</td>
</tr>
</table>

ACCELERATORS

Beams of charged particles experience a deflection by both **electric** and **magnetic** fields. This can be used to **accelerate** particles, cause **collisions** and investigate the particles and energies produced.

Cyclotron

In a **cyclotron,** ions are injected at a point near the **centre**. A **potential difference** between the 'dee' shaped electrodes **accelerates** the particles. A **magnetic field** causes the particles to move in a **circular** path. When the particle crosses from one dee to another it accelerates. After each acceleration the particle moves to a slightly larger orbit. When it reaches the outer edge of the cyclotron the particle beam is extracted and used in other experiments.

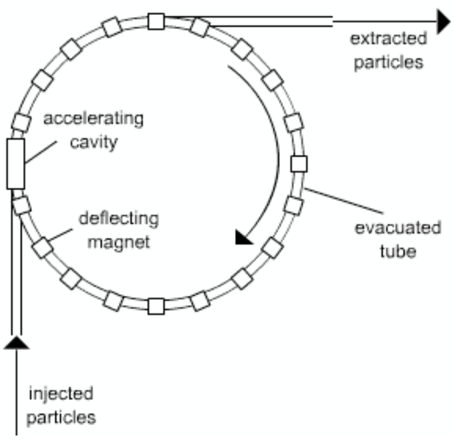


Linear accelerator (LINAC)

Charged particles are accelerated in a vacuum pipe through a **series of electrodes** by an **alternating voltage**. The beam of particles is then directed at a target or into a synchrotron.

Synchrotron

This is similar to a linear accelerator, bent into a ring so the charged particles can be given more energy each time they go round. **Electromagnets** keep the particles in a curved path. **As the speed increases, the magnetic field strength is increased.** As the speed increases and relativistic effect cause the mass of the particles to increase, a larger force is needed to accelerate them and keep them in a circular path.



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

CERN

CERN is the European particle physics laboratory, it is near Geneva in Switzerland and was established in 1954. 20 European countries collaborated in funding and running CERN. About 3000 people work there, with are many visiting scientists that represent over 80 nations. They have a number of accelerators and a number of detectors. LHC, ATLAS, ALICE, CMS and TOTEM.

Scientists working at CERN have a large amount of information to send to each other. In 1989 Tim Berners Lee wrote a proposal for an information system, and by the end of 1990 the World-Wide Web was up and running.

CERN

HIGHER PHYSICS

3 NUCLEAR REACTIONS

Can you talk about:

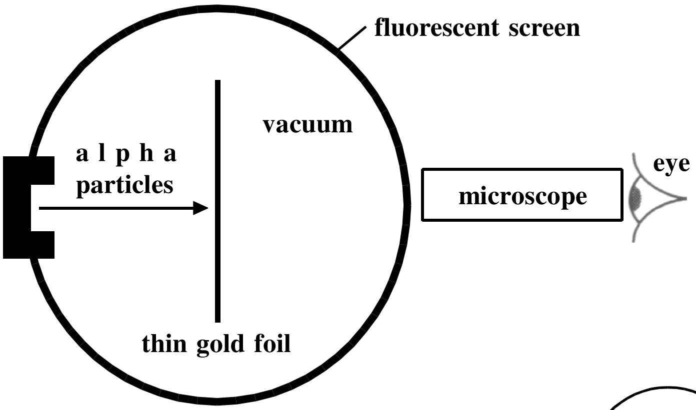
Fission and fusion

- **Nuclear equations** to describe **radioactive decay** and **fission** and **fusion** reactions.
- **Mass** and **energy** equivalence, including calculations.
- **Coolant** and **containment** issues in nuclear fission **reactors**.

RUTHERFORD'S SCATTERING EXPERIMENT

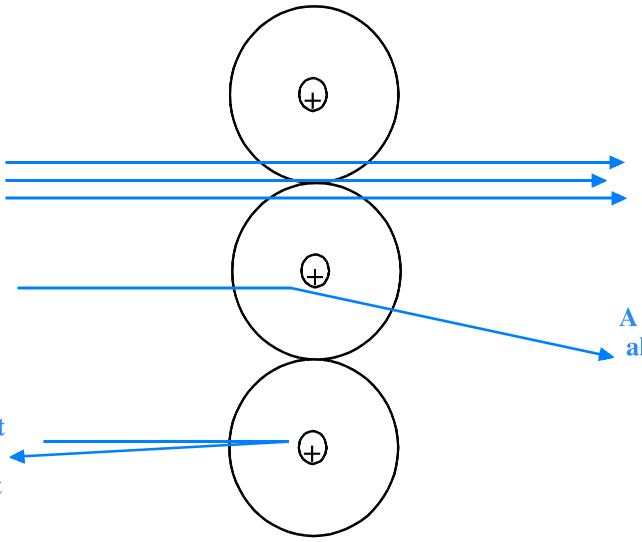
At the start of the 20th century, Ernest Rutherford devised an experiment to investigate the structure of atoms.

Positively-charged alpha particles were fired at a very thin piece of gold foil in the apparatus shown below. Because of the vacuum, the alpha particles were able to travel freely.



Every time an alpha particle hit the fluorescent screen, the screen glowed for a short time.

The microscope was moved all around the outside of the circular fluorescent screen, so that the number of alpha particles hitting the screen at every position could be observed.



Most of the positively-charged alpha particles (99%) passed straight through the gold foil.

A few of the positively-charged alpha particles were deflected slightly.

Very, very few positively-charged alpha particles (about 1 in every 8 000) were deflected backwards in almost the direction they had come from.

gold atoms in thin gold foil

RUTHERFORD EXPERIMENT

Ernest Rutherford

FROM THE RESULTS OF THIS EXPERIMENT, RUTHERFORD MADE THESE DEDUCTIONS ABOUT THE STRUCTURE OF ATOMS:

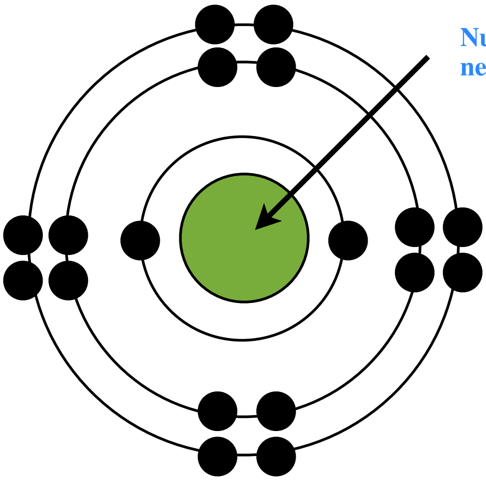
1) Because most of the positively-charged alpha particles passed straight through the gold atoms in the foil, **most of the atom must be empty space**.

2) Because only very, very few positively-charged alpha particles were deflected backwards in almost the direction they had come from, **most of the mass of the atom must be concentrated in a very small central area** (**which we call the nucleus**).

3) Because some of the positively-charged alpha particles were deflected backwards by the **nucleus**, the **nucleus** must be **positively-charged**. (Like charges repel).

MODEL OF THE ATOM

BUILD AN ATOM



Nucleus. Contains protons (+ charge) and neutrons (0 charge), so has overall + charge.

electrons (- charge) circle around nucleus

The symbol for an atom is often written in this form:

$$^{235}_{92}\mathrm{U}$$

mass number (represents the total number of protons plus neutrons in the nucleus) → 235

chemical symbol → U

atomic number (represents the number of protons in the nucleus) → 92

To find the number of **neutrons** in an atom, we subtract the **atomic number** from the **mass number**, e.g., for the atom above: **Number of neutrons = mass number - atomic number = 235 - 92 = 143.**

Atoms which have **the same atomic number** but **different mass numbers** are known as **isotopes**, **e.g., uranium has isotopes:**

$$^{235}_{92}\mathrm{U} \quad \text{and} \quad ^{238}_{92}\mathrm{U}$$

NUCLEAR DECAY

From Intermediate 2 Physics, you know that three types of radioactivity may be emitted from atomic nuclei during radioactive decay - **alpha particles**, **beta particles** and **gamma rays**.

alpha decay

Alpha decay takes place when an **alpha** particle (consisting of **2 protons plus 2 neutrons**) is ejected from an atom's nucleus. An alpha particle is represented by the symbol:

$$^{4}_{2}\mathrm{He}$$

A different atom is created as a result:

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

original (parent) atom — new (daughter) atom — emitted alpha particle

The mass number of the new (daughter) atom is four less than the original (parent). The atomic number is two less than the original.

beta decay

Beta decay takes place when a **neutron** in the **nucleus** splits up into a **proton** and an **electron**. The **proton** stays in the **nucleus** (so the atomic number increases by 1) while the **electron** is ejected from the atom's **nucleus** as a **beta particle**.
A beta particle is represented by the symbol:

$$^{0}_{-1}\mathrm{e}$$

A different atom is created as a result:

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

original (parent) atom — new (daughter) atom — emitted beta particle

The mass number of the new (daughter) atom is the same as the original (parent) atom and the atomic number is one bigger.

gamma decay

Gamma rays are photons of **electromagnetic energy** - They are not **particles**.
When **gamma rays** are ejected from an atom's nucleus, this does not change the mass number or atomic number of the atom. It does however change the energy state of the nucleus.

NUCLEAR FISSION

In **nuclear fission**, a large **atomic nucleus** splits into **2 smaller nuclei** and sometimes **several neutrons**. The **smaller nuclei** and **neutrons** that are produced gain **large amounts of kinetic energy.**

Fission may be either:

(a) Spontaneous

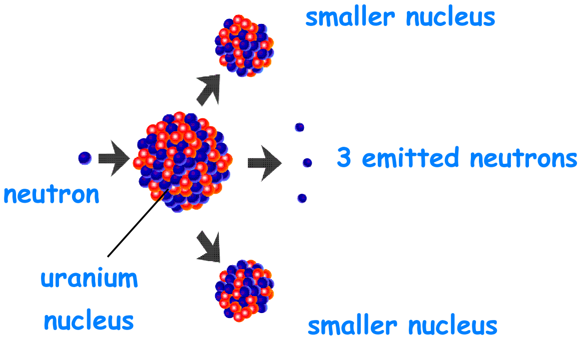
The large **atomic nucleus** splits up by itself at random - There is no **"outside influence"**.

For example:

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

large atomic nucleus — 2 smaller nuclei — 4 neutrons

or (b) Stimulated by Neutron Bombardment



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For example:

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

neutron — uranium nucleus — 2 smaller nuclei — 3 neutrons

A neutron is "fired" at a uranium nucleus, causing the uranium nucleus to split up.

NUCLEAR FUSION

In **nuclear fusion**, **2 small atomic nuclei** combine to form a **larger nucleus**. Other small particles (such as **neutrons**) may also be formed.

For example:

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

2 small atomic nuclei — larger nucleus — neutron

The **larger nucleus** and **other particles** produced gain **large amounts of kinetic energy**.
Nuclear fusion takes place in **stars**, like the **sun**.

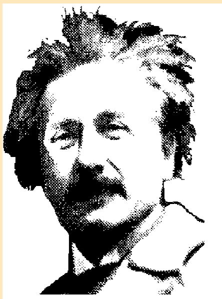
LOST MASS and $E = mc^2$

In both **nuclear fission** and **nuclear fusion** reactions, the **mass** of the **products** formed is **always less than** the **mass** of the **starting species** - **Mass is lost during the reaction.**

The **"lost mass"** is converted into **kinetic energy** of the **products**, in accordance with Albert Einstein's famous equation:

$$E = mc^2$$

- E — kinetic energy of products (J)
- c — speed of light (3×10^8 m s^{-1})
- m — mass lost in reaction (kg)



Albert Einstein

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This is an example of a nuclear fission reaction:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{134}_{52}Te + ^{98}_{40}Zr + 4\,^{1}_{0}n$$

3.901 x 10^{-25} kg | 0.017 x 10^{-25} kg | 2.221 x 10^{-25} kg | 1.626 x 10^{-25} kg | 0.017 x 10^{-25} kg

The mass of each species taking part in the reaction is shown in blue.

(a) Describe what happens in a <u>nuclear fission</u> reaction:

A larger atomic nucleus splints into 2 smaller nuclei, several neutrons and large amounts of energy.

(b) Explain whether the above nuclear fission reaction is "spontaneous" or "induced":

Induced. A neutron is fired at the nucleus to start the process.

c) Calculate the total mass of the species on the left of the arrow (the reactants):

$3.901 \times 10^{-25} + 0.017 \times 10^{-25} = 3.918 \times 10^{-25}$ kg

(d) Calculate the total mass of the species on the right of the arrow (the products):

$2.221 \times 10^{-25} + 1.626 \times 10^{-25} + (4 \times 0.017 \times 10^{-25}) = 3.915 \times 10^{-25}$ kg

(e) Calculate the <u>lost mass</u> when this nuclear fission reaction happens once:

$3.918 \times 10^{-25} - 3.915 \times 10^{-25} = 0.003^{-25}$ kg

(f) Calculate the <u>kinetic energy</u> gained by the products when this nuclear fission reaction happens once:

$E = mc^2$

$E = 0.003 \times 10^{-25} \times (3 \times 10^8)^2$

$E = 2.7 \times 10^{-11}$ J

This is an example of a nuclear fusion reaction:

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

3.342 x 10^{-27} kg | 3.342 x 10^{-27} kg | 5.004 x 10^{-27} kg | 1.674 x 10^{-27} kg

The mass of each species taking part in the reaction is shown in blue.

Calculate the <u>kinetic energy</u> gained by the products when this nuclear fusion reaction happens once.

lost mass = $(3.342 \times 10^{-27} + 3.342 \times 10^{-27}) - (5.004 \times 10^{-27} + 1.674 \times 10^{-27})$

lost mass = 0.006×10^{-27} kg

$E = mc^2$

$E = 0.006 \times 10^{-27} \times (3 \times 10^8)^2$

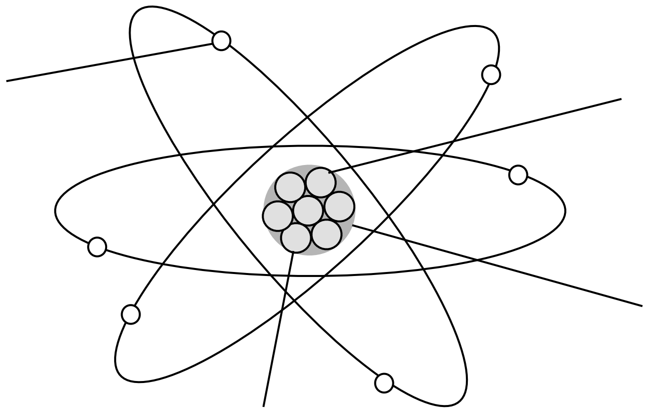
$E = 5.4 \times 10^{-13}$ J

TUTORIAL QUESTIONS

Section 1: The standard model

Orders of magnitude

1. The diagram shows a simple model of the atom.



Match each of the letters A, B, C and D with the correct word from the list below.

electron neutron nucleus proton

2. In the following table the numbers or words represented by the letters A, B, C, D, E, F and G are missing.

Order of magnitude/m	Object
10^{-15}	A
10^{-14}	B
10^{-10}	Diameter of hydrogen atom
10^{-4}	C
10^{0}	D
10^{3}	E
10^{7}	Diameter of Earth
10^{9}	F
10^{13}	Diameter of solar system
10^{21}	G

Match each letter with the correct words from the list below.

diameter of nucleus diameter of proton diameter of Sun
distance to nearest galaxy height of Ben Nevis
size of dust particle your height

The standard model of fundamental particles and interactions

1. Name the particles represented by the following symbols.

   (a) p (b) $\overline{p}$ (c) e (d) $\overline{e}$

   (e) n (f) $\overline{n}$ (g) v (h) $\overline{v}$

2. A particle can be represented by a symbol $^{M}_{A}\mathrm{X}$ where M represents the mass number, A the atomic number and X identifies the type of particle, for example a proton can be represented by $^{1}_{1}\mathrm{p}$. Give the symbols, in this form, for the following particles.

   (a) $\bar{p}$ (b) e (c) $\bar{e}$ (d) n (e) $\bar{n}$

3. Copy and complete the table by placing the fermions in the list below in the correct column of the table.

   bottom charm down electron electron neutrino
   muon muon neutrino strange tau
   tau neutrino top up

Quarks	*Leptons*

4. (a) State the difference between a hadron and a lepton in terms of the type of force experienced by each particle.
   (b) Give one example of a hadron and one example of a lepton.

5. Information on the sign and charge relative to proton charge of six types of quarks (and their corresponding antiquarks) is shown in the table.

Quark name	Charge relative to size of proton charge	Antiquark name	Charge relative to size of proton charge
up	+2/3	antiup	–2/3
charm	+2/3	anticharm	–2/3
top	+2/3	antitop	–2/3
down	–1/3	antidown	+1/3
strange	–1/3	antistrange	+1/3
bottom	–1/3	antibottom	+1/3

Calculate the charge of the following combinations of quarks:

(a) two up quarks and one down quark
(b) one up quark and two down quarks
(c) two antiup quarks and one antidown quark
(d) one antiup quark and two antidown quarks.

6. Neutrons and protons are considered to be composed of quarks.

(a) How many quarks are in each neutron and in each proton?
(b) Comment briefly on the different composition of the neutron and proton.

7. (a) Briefly state any differences between the 'strong' and 'weak' nuclear forces.
(b) Give an example of a particle decay associated with the weak nuclear force.
(c) Which of the two forces, strong and weak, acts over the greater distance?

Section 2: Forces on charged particles

Electric fields

1. Draw the electric field pattern for the following point charges and pair of charges:

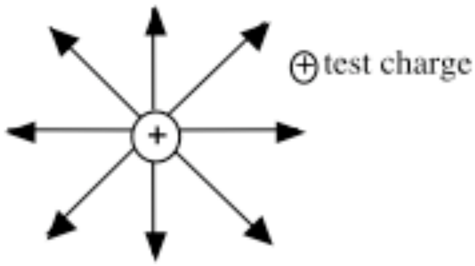
(a) 

(b) 

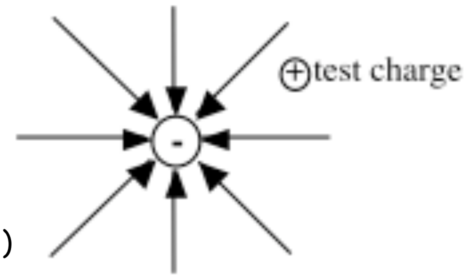
(c) 

2. Describe the motion of the small positive test charges in each of the following fields.

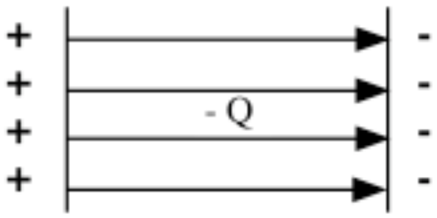
(a)



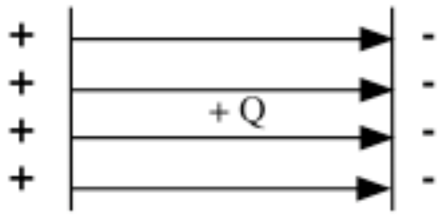
(b)



(c)



(d)



3. An 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 1 V (the size of the charge on an electron is
$1{\cdot}6 \times 10^{-19}$ C).
What is the equivalent energy of 1 eV in joules?

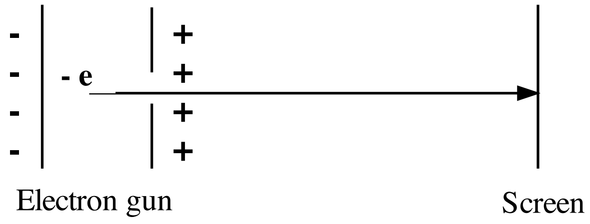
4. An electron has energy of 5 MeV. Calculate its energy in joules.

5. The diagram shows an electron accelerates between two parallel conducting plates A and B.

The p.d. between the plates is 500 V.
(mass of electron = $9{\cdot}1 \times 10^{-31}$ kg
charge on electron = $1{\cdot}6 \times 10^{-19}$ C)

(a) Calculate the electrical work done in moving the electron from plate A to plate B.
(b) How much kinetic energy has the electron gained in moving from A to B?
(c) What is the speed of the electron just before it reaches plate B?

6. Electrons are 'fired' from an electron gun at a screen.



The p.d. across the electron gun is 2000 V.
The electron gun and screen are in a vacuum.
After leaving the positive plate the electrons travel at a constant speed to the screen.
Calculate the speed of the electrons just before they hit the screen.

7. A proton is accelerated from rest across a p.d. of 400 V.
Calculate the increase in speed of the proton.

8. In an X-ray tube electrons forming a beam are accelerated from rest and strike a metal target.
The metal then emits X-rays.
The electrons are accelerated across a p.d. of 25 kV. The beam of electrons forms a current of 3·0 mA.

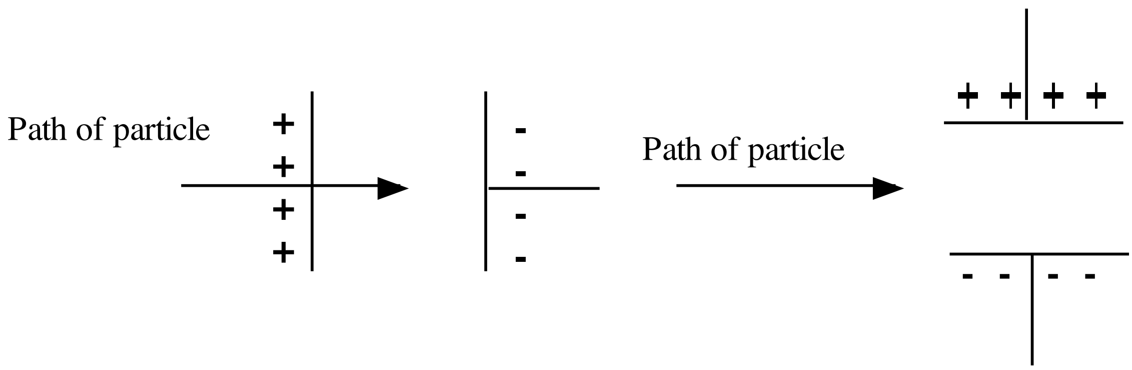
(a) (i) Calculate the kinetic energy of each electron just before it hits the target.
(ii) Calculate the speed of an electron just before it hits the target.
(iii) Find the number of electrons hitting the target each second.
(mass of electron = $9{\cdot}1 \times 10^{-31}$ kg
charge on electron = $1{\cdot}6 \times 10^{-19}$ C)

(b) What happens to the kinetic energy of the electrons?

9. Sketch the paths which

(a) an alpha-particle
(b) a beta-particle
(c) a neutron

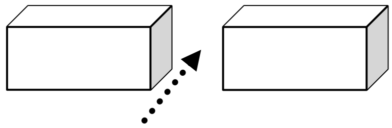
would follow if each particle, with the same velocity, enters the electric fields shown in the diagrams.



Charged particles in a magnetic field

1. An electron travelling with a constant velocity enters a region where there is a uniform magnetic field. There is no change in the velocity of the electron. What information does this give about the magnetic field?

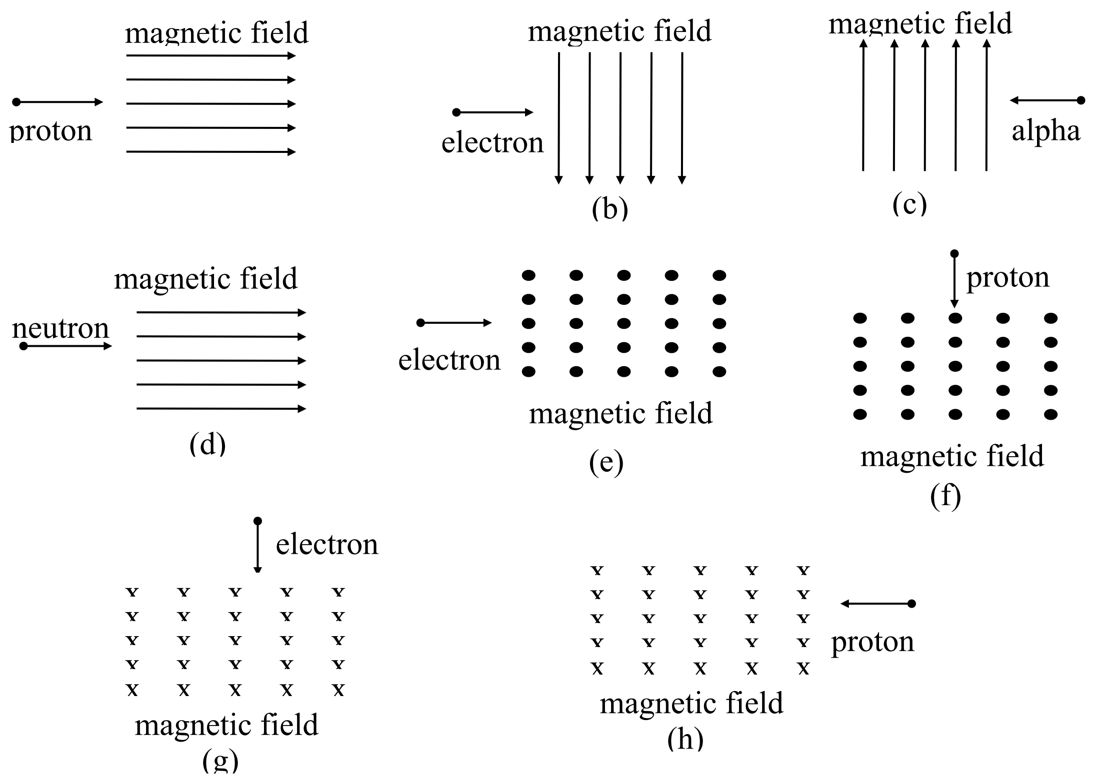
2. The diagram shows a beam of electrons as it enters the magnetic field between two magnets. The electrons will:



A be deflected to the left (towards the N pole)
B be deflected to the right (towards the S pole)
C be deflected upwards
D be deflected downwards
E have their speed increased without any change in direction.

3. The diagrams show particles entering a region where there is a uniform magnetic field. (X denotes magnetic field into page and • denotes magnetic field out of page.)

Use the terms: up, down, into the paper, out of the paper, left, right, no change in direction to describe the deflection of the particles in the magnetic field.



4. An electron enters a region of space where there is a uniform magnetic field. As it enters the field the velocity of the electron is at right angles to the magnetic field lines. The energy of the electron does not change although it accelerates in the field. Use your knowledge of physics to explain this effect.

Particle accelerators

In the following questions, when required, use the following data:

Charge on electron = $-1{\cdot}60 \times 10^{-19}$ C Mass of electron = $9{\cdot}11 \times 10^{-31}$ kg
Charge on proton = $1{\cdot}60 \times 10^{-19}$ C Mass of proton = $1{\cdot}67 \times 10^{-27}$ kg

1. In an evacuated tube, an electron initially at rest is accelerated through a p.d. of 500 V.

   (a) Calculate, in joules, the amount of work done in accelerating the electron.
   (b) How much kinetic energy has the electron gained?
   (c) Calculate the final speed of the electron.

2. In an electron gun, electrons in an evacuated tube are accelerated from rest through a potential difference of 250 V.

   (a) Calculate the energy gained by an electron.
   (b) Calculate the final speed of the electron.

3. Electrons in an evacuated tube are 'fired' from an electron gun at a screen. The p.d. between the cathode and the anode of the gun is 2000 V. After leaving the anode, the electrons travel at a constant speed to the screen. Calculate the maximum speed at which the electrons will hit the screen.

4. A proton, initially at rest, in an evacuated tube is accelerated between two charged plates A and B. It moves from A, where the potential is 10 kV, to B, where the potential is zero. Calculate the speed of the proton at B.

5. A linear accelerator is used to accelerate a beam of electrons, initially at rest, to high speed in an evacuated container. The high- speed electrons then collide with a stationary target. The accelerator operates at 2·5 kV and the electron beam current is 3 mA.

   (a) Calculate the gain in kinetic energy of each electron.
   (b) Calculate the speed of impact of each electron as it hits the target.
   (c) Calculate the number of electrons arriving at the target each second.
   (d) Give a reason for accelerating particles to high speed and allowing them to collide with a target.

6. The power output of an oscilloscope (cathode-ray tube) is estimated to be 30 W. The potential difference between the cathode and the anode in the evacuated tube is 15 kV.

   (a) Estimate the number of electrons striking the screen per second.
   (b) Calculate the speed of an electron just before it strikes the screen, assuming that it starts from rest and that its mass remains constant.

7. In an oscilloscope electrons are accelerated between a cathode and an anode and then travel at constant speed towards a screen. A p.d. of 1000 V is maintained between the cathode and anode. The distance between the cathode and anode is $5{\cdot}0 \times 10^{-2}$ m. The electrons are at rest at the cathode and attain a speed of $1{\cdot}87 \times 10^{7}$ ms^{-1} on reaching the anode. The tube is evacuated.

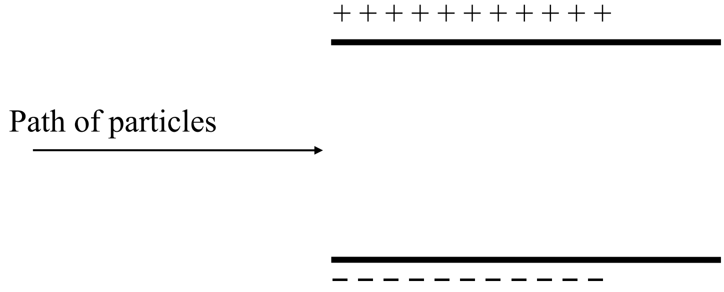
(a) (i) Calculate the work done in accelerating an electron from the cathode to the anode.
(ii) Show that the average force on the electron in the electric field is $3{\cdot}20 \times 10^{-15}$ N.
(iii) Calculate the average acceleration of an electron while travelling from the cathode to the anode.
(iv) Calculate the time taken for an electron to travel from cathode to anode.
(v) Beyond the anode the electric field is zero. The anode to screen distance is 0·12 m. Calculate the time taken for an electron to travel from the anode to the screen.

(b) Another oscilloscope has the same voltage but a greater distance between cathode and anode.
(i) Would the speed of the electrons be higher, lower or remain at $1{\cdot}87 \times 10^{7}$ ms^{-1}? Explain your answer.
(ii) Would the time taken for an electron to travel from cathode to anode be increased, decreased or stay the same as in (a) (iv)? Explain your answer.

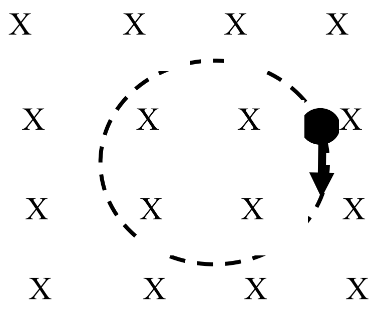
8. In an X-ray tube a beam of electrons, initially at rest, is accelerated through a potential difference of 25 kV. The electron beam then collides with a stationary target. The electron beam current is 5 mA.

(a) Calculate the kinetic energy of each electron as it hits the target.
(b) Calculate the speed of the electrons at the moment of impact with the target assuming that the electron mass remains constant.
(c) Calculate the number of electrons hitting the target each second.
(d) What happens to the kinetic energy of the electrons?

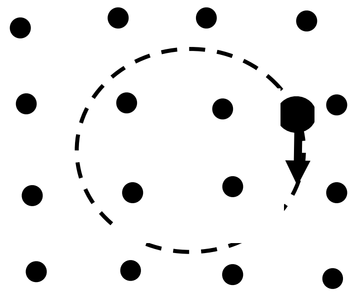
9. On the same diagram shown below sketch the paths that
10. (a) an electron, (b) a proton and (c) a neutron would follow if each particle entered the given electric fields with the same velocity.



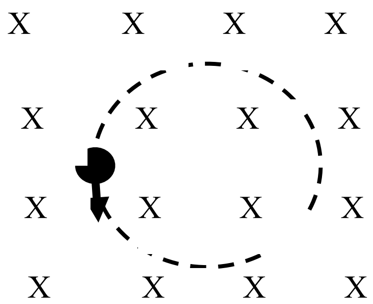
10. In the following examples identify the charge of particle (positive or negative) which is rotating in a uniform magnetic field. (X denotes magnetic field into page and • denotes magnetic field out of page.)



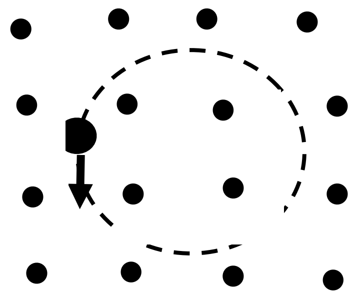
(a)



(b)



(c)



(d)

11. In the following descriptions of particle accelerators, some words and phrases have been replaced by the letters A to R.

In a linear accelerator bunches of charged particles are accelerated by a series of ____A____. The final energy of the particles is limited by the length of the accelerator. This type of accelerator is used in ____B____ experiments.

In a cyclotron the charged particles are accelerated by ____C____. The particles travel in a ____D____ as a result of a ____E____, which is ____F____ to the spiral. The radius of the spiral increases as the energy of the particles ____G____. The diameter of the cyclotron is limited by the ____H____ of the magnet. The resultant energy of the particles is limited by the diameter of the cyclotron and by ____I____.

This type of accelerator is used in ____J____ experiments.

In a synchrotron bunches of charged particles travel in a ____K____ as a result of C shaped magnets whose strength ____L____. The particles are accelerated by ____M____. As the energy of the particles increases the strength of the magnetic field is ____N____ to maintain the radius of the path of the particles. In synchrotron accelerators the particles can have, in theory, an unlimited series of accelerations as the particles can transit indefinitely around the ring. There will be a limit caused by ____O____.

In this type of accelerator particles with ____P____ mass and ____Q____ charge can circulate in opposite directions at the same time before colliding. This increases the energy of impact. This type of accelerator is used in ____R____ experiments.

Letter	List of replacement word or phrase
A, C, E, M	constant magnetic field, alternating magnetic fields, alternating electric fields, constant electric fields
B, J, R	colliding-beam, fixed-target
D, K	spiral of decreasing radius, spiral of increasing radius, circular path of fixed radius
F	perpendicular, parallel
G	decreases, increases
H	physical size, strength
I, O	gravitational effects, relativistic effects
L	can be varied, is constant
N	decreased, increased
P, Q	the same, different

Section 3: Nuclear reactions

Fission and fusion

1. The following is a list of atomic numbers:

   (a) 6
   (b) 25
   (c) 47
   (d) 80
   (e) 86
   (f) 92

   Use a periodic table to identify the elements that have these atomic numbers.

2. The list shows the symbols for six different isotopes.

   (i) $^{7}_{3}\text{Li}$ (ii) $^{64}_{30}\text{Zn}$ (iii) $^{109}_{47}\text{Ag}$

   (iv) $^{131}_{54}\text{Xe}$ (v) $^{239}_{94}\text{Pu}$ (vi) $^{257}_{103}\text{Lw}$

   For each of the isotopes state:

   (a) the number of protons
   (b) the number of neutrons.

3. The incomplete statements below illustrate four nuclear reactions.

   $^{228}_{90}\text{Th} \longrightarrow {}^{224}_{88}\text{Ra} + \text{A}$ $^{220}_{86}\text{Rn} \longrightarrow {}^{4}_{2}\text{He} + \text{B}$

   $^{211}_{82}\text{Pb} \longrightarrow {}^{211}_{83}\text{Bi} + \text{C}$ $\text{D} \longrightarrow {}^{219}_{86}\text{Rn} + {}^{4}_{2}\text{He}$

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

4. Part of a radioactive decay series is represented below:

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

   Identify the particle emitted at each stage of the decay.
   Such a series does not always give a complete picture of the radiations emitted by each nucleus. Give an explanation why the picture is incomplete.

5. For a particular radionuclide sample 8×10^7 disintegrations take place in 40 s. Calculate the activity of the source.

6. How much energy is released when the following 'decreases' in mass occur in various fission reactions?

(a) $3{\cdot}25 \times 10^{-28}$ kg
(b) $2{\cdot}01 \times 10^{-28}$ kg
(c) $1{\cdot}62 \times 10^{-28}$ kg
(d) $2{\cdot}85 \times 10^{-28}$ kg

7. The following statement represents a nuclear reaction involving the release of energy.

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

The masses of these particles are given below.

Mass of $^{3}_{1}H$ = $5{\cdot}00890 \times 10^{-27}$ kg

Mass of $^{2}_{1}H$ = $3{\cdot}34441 \times 10^{-27}$ kg

Mass of $^{4}_{2}He$ = $6{\cdot}64632 \times 10^{-27}$ kg

Mass of $^{1}_{0}n$ = $1{\cdot}67490 \times 10^{-27}$ kg

(a) Calculate the decrease in mass that occurs when this reaction takes place.
(b) Calculate the energy released in this reaction.
(c) What is the name given to this type of nuclear reaction?
(d) Calculate the number of reactions required each second to produce a power of 25 MW.

8. Plutonium can undergo the nuclear reaction represented by the statement below:

$$^{239}_{94}Pu + ^{1}_{0}n = Te + ^{100}_{42}Mo + 3\ ^{1}_{0}n$$

The masses of the nuclei and particles involved in the reaction are as follows.

Particle	n	Pu	Te	Mo
Mass/kg	$1{\cdot}675 \times 10^{-27}$	$396{\cdot}741 \times 10^{-27}$	$227{\cdot}420 \times 10^{-27}$	$165{\cdot}809 \times 10^{-27}$

(a) What kind of reaction is represented by the statement?
(b) State the mass number and atomic number of the nuclide Te in the reaction.
(c) Calculate the decrease in mass that occurs in this reaction.
(d) Calculate the energy released in this reaction.

Solutions

Section 1: The standard model

Orders of magnitude

1. A= electron; B = proton; C = nucleus; D = neutron

2. A = diameter of proton; B = diameter of nucleus; C = size of dust particle; D = your height; E = height of Ben Nevis; F = diameter of Sun; G = distance to nearest galaxy

The standard model of fundamental particles and interactions

1. (a) proton (b) antiproton (c) electron (d) positron
   (e) neutron (f) antineutron (g) neutrino (f) antineutrino

2. (a) ${}^{1}_{-1}\overline{p}$ (b) ${}^{0}_{-1}e$ (c) ${}^{0}_{-1}\overline{e}$ (d) ${}^{1}_{0}\text{n}$ (e) ${}^{1}_{0}\overline{n}$

3. Quarks: bottom, charm, down, strange, top, up
   Leptons: electron, electron neutrino, muon, muon neutrino, tau, tau neutrino

4. (a) Leptons are particles that are acted on by the weak nuclear force but not by the strong nuclear force. Hadrons are particles that are acted on by the weak and strong nuclear force.
   (b) Leptons – any one of electron, electron neutrino, muon, muon neutrino, tau and tau neutrino. Hadron – any one of up, down, charm, strange, top and bottom.

5. (a) +e (b) 0 (c) –e (d) 0

6. (a) 3
   (b) For the neutron the three quarks must give a charge of zero. For the proton the three quarks must give a charge of +e.

7. (a) Strong force has a range of less than 10^{-14} m; weak force has a range of less than 10^{-17} m.
   (b) Beta decay
   (c) Strong force.

Section 2: Forces on charged particles

Electric fields

3. $1{\cdot}6 \times 10^{-19}$ J

4. $8{\cdot}0 \times 10^{-13}$ J

5. (a) $8{\cdot}0 \times 10^{-17}$ J (b) $8{\cdot}0 \times 10^{-17}$ J (c) $1{\cdot}3 \times 10^{7}$ ms^{-1} ¶

6. $2{\cdot}65 \times 10^{7}$ ms^{-1}

7. $2{\cdot}76 \times 10^{5}$ ms^{-1}

8. (a) (i) $4{\cdot}0 \times 10^{15}$ J (ii) $9{\cdot}4 \times 10^{7}$ ms^{-1} (iii) $1{\cdot}9 \times 10^{16}$

Charged particles in a magnetic field

1. Magnetic field is in the same plane and in the same or opposite direction to the velocity of the electron.

2. C: be deflected upwards

3. (a) no change in direction (b) out of the paper
   (c) into the paper (d) no change in direction
   (e) up (f) left
   (g) left (h) down

Particle accelerators

1. (a) 8×10^{-17} J (b) 8×10^{-17} J (c) $1·33 \times 10^{7}$ ms^{-1}

2. (a) 4×10^{-17} J (b) $9·37 \times 10^{6}$ ms^{-1}

3. $2·65 \times 10^{7}$ ms^{-1}

4. $1·38 \times 10^{6}$ ms^{-1}

5. (a) 4×10^{-16} J (b) $2·96 \times 10^{7}$ ms^{-1} (c) $1·88 \times 10^{16}$

6. (a) $1·25 \times 10^{16}$ (b) $7·26 \times 10^{7}$ ms^{-1}

7. (a) (i) $1·6 \times 10^{-16}$ J (iii) $3·51 \times 10^{15}$ ms^{-2}
   (iv) $5·34 \times 10^{-9}$ s (v) $6·42 \times 10^{-9}$ s
   (b) (i) Same since Q and V same
   (ii) Longer since acceleration is smaller

8. (a) $4·0 \times 10^{-15}$ J (b) $9·37 \times 10^{7}$ ms^{-1} (c) $3·12 \times 10^{16}$
   (d) Heat and X-rays are produced

9. (a) Electron accelerated towards positive plate
   (b) Proton accelerated towards negative plate but less curved than that of electron
   (c) Neutron straight through.

10. (a) Negative (b) Positive (c) Positive (d) Negative

11. A = alternating electric fields; B = fixed-target; C = alternating electric fields; D = spiral of increasing radius; E = constant magnetic field; F = perpendicular; G = increases; H = physical size; I = relativistic effects; J = fixed-target; K = circular path of fixed radius; L = can be varied; M = alternating magnetic fields; N = increased; O = relativistic effects; P = the same; Q = opposite; R = colliding beam.

Section 3: Nuclear reactions

Fission and fusion

2. (i) (a) 3 (b) 4
   (ii) (a) 30 (b) 34
   (iii) (a) 47 (b) 62
   (iv) (a) 54 (b) 77
   (v) (a) 94 (b) 145
   (vi) (a) 103 (b) 154

3. A is $^{4}_{2}\mathrm{He}$ or α B is $^{216}_{84}\mathrm{Po}$ C is $^{0}_{-1}e$ or β D is $^{223}_{88}\mathrm{Ra}$

4. α then β then α

5. $A = 2 \times 10^{6}$ Bq

6. (a) $2{\cdot}93 \times 10^{-11}$ J (b) $1{\cdot}81 \times 10^{-11}$ J
   (c) $1{\cdot}46 \times 10^{-11}$ J (d) $2{\cdot}57 \times 10^{-11}$ J

7. (a) $3{\cdot}209 \times 10^{-29}$ kg (b) $2{\cdot}89 \times 10^{-12}$ J (d) $8{\cdot}65 \times 10^{18}$

8. (b) mass number 136, atomic number 52
   (c) $1{\cdot}62 \times 10^{-28}$ kg
   (d) $1{\cdot}46 \times 10^{-11}$ J