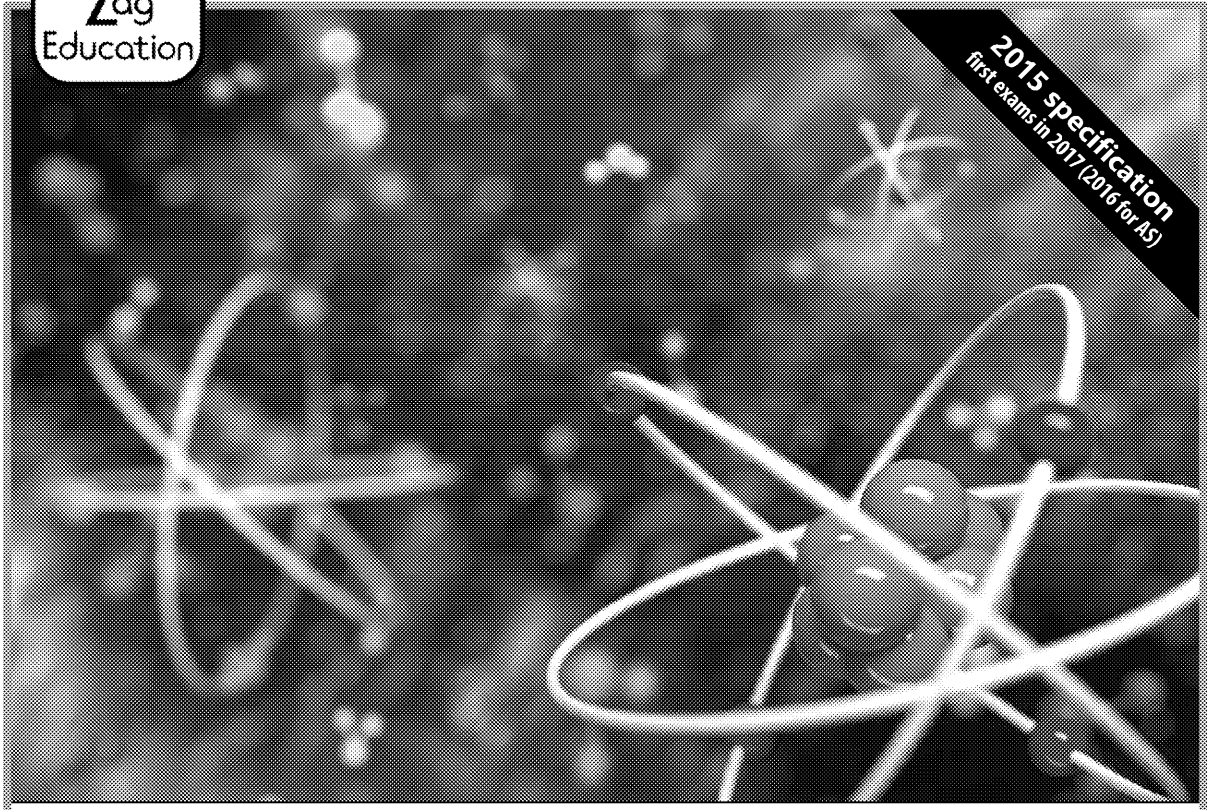
Physics AS / A Level | AQA | 7407/7408



Topic Review

For A Level Year 1 / AS AQA Physics (Sections 1 and 2)

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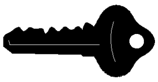
Contents

Teacher's Introduction

This Topic Review covers the first 2 units of AQA Physics A Level and the AQA Physics AS Level. The aim is for this review to go over the topics in the specification in a focused but comprehensive way, allowing students to consolidate their learning and to prepare for their exams. The resource includes questions after each small topic to allow students to test their understanding and ability to apply what they have learnt. Worked answers are included with the questions so students can check their answers and see where they've gone wrong.

Each section of the review starts with a checklist of all the topics in the section, and what students should expect to know about the topic before moving on. This can be used as a self-assessment tool at the start of revision, so students know where to focus their time, or at the end to ensure they have no gaps in their learning.

Worked examples are provided for calculations throughout (including derivations where appropriate), giving students not only knowledge of the appropriate facts and equations, but how they are applied as well.



Key equations and definitions are highlighted with a key symbol.

Equations in the databook are marked with a star so students know what they have to memorise and what they can refer to the data book for in the exam.

Required practicals are covered in the appropriate topic, ensuring students have an understanding of how to perform the practical, and understand the physics behind the practical itself.

Exam tips are included regularly throughout to help students avoid misconceptions and common mistakes and to give students a steer on things they should particularly practise in revision.

Students should be able to work through this review in their own time, after they have completed the topic in lessons, or during revision. It would be a great accompaniment for students as they make their revision notes or an easy reference text as they do practice papers.

I hope that this review will be of real benefit.

May 2017

Chapter 1: Measurements and the

Chapter 1 checklist

By the end of this chapter you should be able to:

1.1
- Understand and use SI units ....
- Attach prefixes to SI units to denote scale ....
- Understand how other units are derived from SI units ....
- Use derived SI units ....
- Understand that equivalent units can have different uses ....
- Use and convert between equivalent units ....

1.2
- Understand the difference between random and systematic errors, how the avoid them ....
- Understand the meanings of:
  - Accuracy ....
  - Precision ....
  - Resolution ....
  - Repeatability ....
  - Reproducibility ....
- Estimate absolute uncertainties in measurements ....
- Convert to fractional and percentage uncertainties ....
- Combine uncertainties to find uncertainties in results ....
- Display uncertainties on graphs using error bars ....
- Find uncertainties on gradients and intercepts from a graph ....
- Identify anomalous results and some ways to get rid of them..

1.3
- Use powers of 10 to discuss orders of magnitude ....
- Estimate orders of magnitude for some physical properties..
- Estimate what order of magnitude a result might be from the values in an eq

1.1 Use of SI units and their prefixes

When giving answers and discussing results, it's important to give the units you'r
answer of 28 could mean seconds, metres, kilograms or anything else to someon

The scientific community uses a standard set of measurements called SI units for
collected in the table below. These are the **base** SI units, meaning that they're in

Measurement	SI unit	
Mass	Kilogram	kg
Length	Metre	m
Time	Second	s
Temperature	Kelvin	K
Electric current	Ampere	A
Amount of substance	Mole	mo

Key term: Kelvin

A temperature increase or decrease of 1 K is the same as a temperature increase or decrease of 1 °C, but the values for kelvin are shifted up by 273, so that 0 K equals -273 °C.

For example,

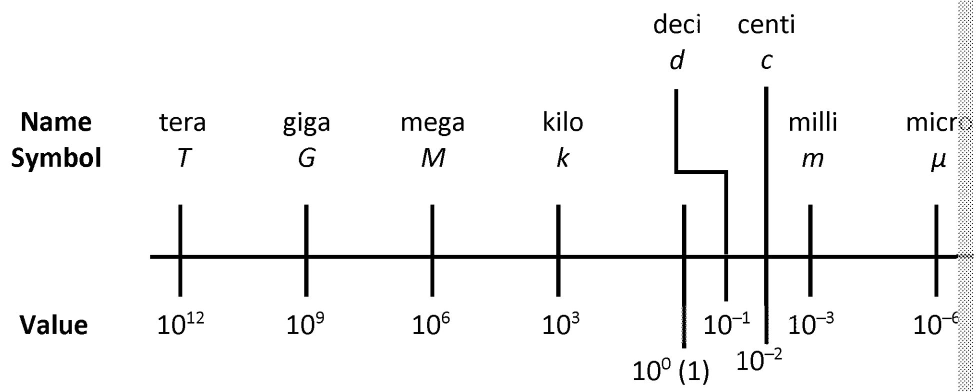
0 °C = 273 K	0 K = -273 °C
50 °C = 323 K	50 K = -223 °C
-50 °C = 223 K	1000 K = 726 °C

Key te

A mole
molecul
6.022

SI prefixes

We often use these units to express incredibly small or large measurements and
alongside **prefixes** which give a multiplication factor describing the scale of the m



Derived SI units

SI units can be used together to express more complicated ideas such as velocity
per second (m s^{-1}), and density, which is measured in kilograms per metre cubed

These are called **derived units** because they are derived from the base SI units.

Some of these combinations of SI units are used commonly enough to have their

Measurement	Name	Symbol
Force	Newton	N
Energy	Joule	J
Power	Watt	W

> **Exam tip**
> Units such as metres per second can be written as m/s or m s^{-1}.
> **m s^{-1}** is the format you'll see it used in exams, and what you should u

Equivalent units
Many SI units will have **equivalent units** for use in particular contexts, for instanc much easier to express energy in electron volts (eV) than in joules because of the Some useful units are collected below.

Name	Symbol	Equivalent uni
Electron volt	eV	1.60×10^{-19} J
Light year	ly	9.46×10^{15} m
Kilowatt-hour	kW h	3.60×10^{6} J

Questions

1. Without looking, write down as many SI units as you can rememb and what they measure.

2. a) Convert the following temperatures to Kelvin:
   (i) 0 °C (ii) 100 °C (iii) 37 °C

   b) Convert the following temperatures to Celsius:
   (i) 150 K (ii) 275 K (iii) 368 K

3. a) Write the following quantities in the base SI units, without pre
   (i) 3.752 Gm (ii) 2.8 ms (iii) 7.34 Mkg

   b) Write the following quantities with appropriate SI prefixes:
   (i) 0.0000087 A (ii) 28,329 mol (iii) 24,892,000 kg

   Remember that although kg has the kilo prefix meaning 10^3, it is

4. a) Convert 13 TeV (the operating power at the Large Hadron C
   b) Convert 0.5 J to eV.

5. A kilowatt-hour is a term used by energy companies to describe 1000 watts over the course of one hour.
   a) Calculate how many joules 5.48 kilowatt-hours represents. 1
   b) A kettle uses 0.0800 kW h boiling water. What is this energy in
   c) If an energy company charges 10p per kilowatt-hour, how m this kettle?

1.2 Limitation of physical measurements

No experiment is perfect and there will always be uncertainties and errors in any
errors aren't mistakes, but just a way of acknowledging the extent of our abilitie
data.

Key terms

Accuracy is how close a measurement it is to the accepted value. If you measure
be 13.4 m s^{-2} and 9.9 m s^{-2}, the second is much more accurate when compared t
9.8 m s^{-2}.

Resolution in measurements is the smallest change in measurement that can be d
smallest division on a scale or the smallest place value digit on a digital meter. A
marked has a resolution of 1 mm.

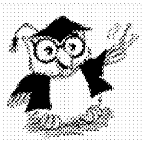
Precision is how spread around the mean value the measurements are. It depen
precise measurement isn't always an accurate measurement.

Repeatability is whether the *original experimenter* can get the same results from
equipment and techniques.

Reproducibility is whether the same results can be found by a *different experime*
equipment and techniques.

Errors are split into two categories: **random** and **systematic**.

	Random errors	S
What are they?	Naturally inconsistent readings	Errors that happ reading
Where can they come from?	Human error Equipment being difficult to read Natural fluctuations in environment – power surges, wind, doors slamming	Equipment calib Ambient conditi
How can we get rid of them?	Repeating the experiment Taking more data	Repeating the ex *equipment or tec* Systematic error look out for stra that should be ze



Exam tip

When making a note of readings and doing calculations, it's important

Use the same number of significant figures as the value with the smalle

This ensures you keep as much information as possible, while not overstating the d

The same is true for doing calculations – use the same number of significant figure
number of significant figures given.

Example

The height of a student is measured several times.
The student's height is measured as 1.645 m, 1.638 m, 1.65 m, 1.6512 m an
Calculate the mean of these measurements.

Mean= $\frac{1.645+1.638+1.65+1.6512+1.642}{5}$ *= 1.64524 m*

This is too many significant figures – the least accurate measurement given is our answer should be to 3 significant figures.

So our mean value for the student's height is ***1.65 m****.*

Uncertainty

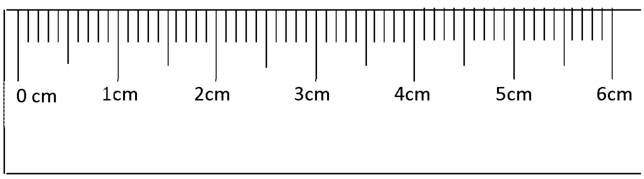
Some pieces of equipment will have their uncertainty written on them, but if not

- For digital readings the uncertainty is no smaller than **half the last digit on t** shows one decimal place the uncertainty is 0.05
- For analogue readings the uncertainty is no smaller than **half the smallest m**

Often when we're measuring, we take two readings. For instance when measurin taking a reading at the 0 cm mark and at the point we're measuring the length at **same as** the last digit displayed or smallest marking.

The uncertainty of a reading is still half the last digit or smallest marking when a refe instance, a thermometer isn't read in reference to the 0 °C mark, but is a single readi

Example



For this ruler the sm the uncertainty is 0.5 1 mm for the total m

If we took a measure write this as ***2.3 cm***

For a range of readings, the uncertainty is given by half the range of the readings

Example

Five readings of a car's speed are taken.
The readings are 11.7 m s^{-1}, 12.2 m s^{-1}, 11.8 m s^{-1}, 11.6 m s^{-1} and 12.0 m s^{-1}
What is the uncertainty of these readings?

The range of the readings is the smallest value taken from the largest value,

So, the uncertainty of the readings is 0.3 m s^{-1}*.*

Exam tip

Uncertainties shouldn't be more detailed than the corresponding mea 0.07882 on a measurement of 2.4 has too many decimal places, inst number of decimal places

Fractional and percentage uncertainties

In the above example 0.1 cm is the **absolute uncertainty** meaning its actual valu
use the uncertainty as a fraction or percentage of the measurement.

The fractional uncertainty is calculated as $\frac{\textbf{absolute uncertainty}}{\textbf{measured value}}$

The percentage unce
absolute unc
measured

Fractional and percentage uncertainties make it a lot easier to compare the accu
and units.

Example

For our measurement of 2.3 cm ± 0.1 cm from above,

Fractional uncertainty $= \frac{0.1\ cm}{2.3\ cm} = 0.043$

Percentage uncertainty $= \frac{0.1\ cm}{2.3\ cm} \times 100 = 4\ \%$

We write this as 2.3 cm (1 ± 0.043) for the fractional uncertainty and 2.3
uncertainty.

Combinations of uncertainties

Often our final results will come from a combination of measurements and so w
uncertainties on the measurements into an uncertainty for the final result.

- If the result is found by **adding or subtracting** the measurements to or from
up the *absolute uncertainty* to find the uncertainty on the result.
- If the result is found by **multiplying or dividing** the measurements together,
uncertainties to find the uncertainty on the result.
- In the case of **powers**, we multiply the *percentage uncertainty* by the power

You don't have to worry about uncertainties on more complicated logarithmic o

Example

Phil the Snail is on our ruler at the 6.8 cm mark. He is timed using a stop
reach the 9.4 cm mark on the ruler. The precision of the ruler is 0.1 cm a
stopwatch is 1 s.

a) How far does Phil travel? What is the absolute uncertainty?
b) At what speed does Phil make his journey? What is the absolute un

a) *To find out how far Phil travelled we simply do*

$$9.4\ cm - 6.8\ cm = 2.6\ cm$$

To find the uncertainty on this we add the absolute uncertainties for b
measurements are taken with the ruler, these uncertainties are both 0

$$0.1\ cm + 0.1\ cm = 0.2\ cm$$

So our full answer is ***2.6 cm ± 0.2 cm.***

b) *To find the speed we divide the distance by the time taken.*

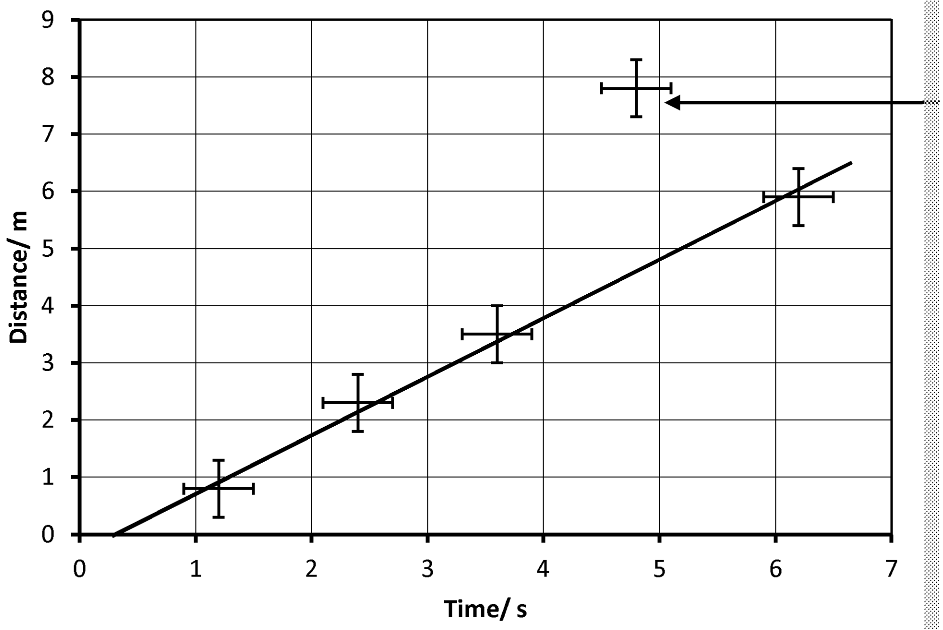
$$2.6\ cm / 34\ s = 0.076\ cm\ s^{-1}$$

For the uncertainty, we add the percentage uncertainties

$$\left(\frac{0.2\ cm}{2.6\ cm} + \frac{1\ s}{34\ s}\right) \times 100\ \% = 11\ \%$$

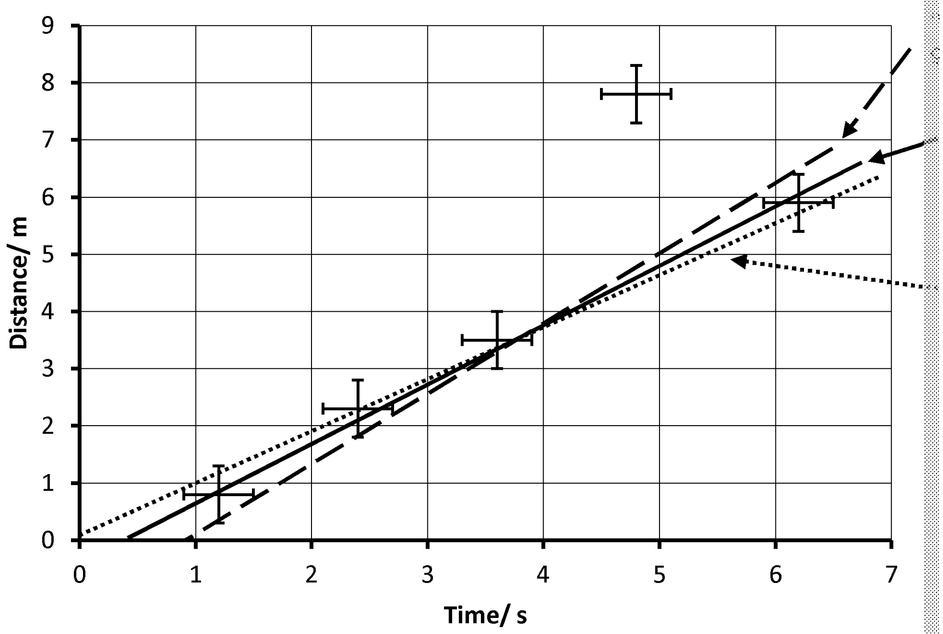
Uncertainties on graphs

When we plot out data we can show the uncertainty on our data points using **err** length of the error bar on each side of the data point is the size of the uncertainty



A good line of best fit will fit through all the error bars. The line of best fit we cho **best line of best fit** which gives us our best gradient and best y-intercept.

To find the uncertainty on the gradient, we draw extra lines of best fit through th bars as seen here. These are our **worst lines of best fit**.



The dashed line has the **greatest possible gradient** we can draw through the poi **smallest possible gradient**. We can work with either of these gradients in our ca

The percentage uncertainty in the gradient is

$$\frac{|\text{best gradient} - \text{worst gradient}|}{\text{best gradient}} \times 100\ \%$$

Similarly, to find the uncertainty on the y-intercept we *continue the same lines t*
for the y-intercept.

The percentage uncertainty in the y-intercept is

$$\frac{|\text{best intercept} - \text{worst intercept}|}{\text{best intercept}} \times 100\,\%$$

Discussing our results

After we have our results with uncertainties, we need to write a discussion of t

This should include

- a **conclusion** of any relationship you found
- how **accurate** and **precise** your results were
- whether your results would be **repeatable** and **reproducible**
- any **improvements** you could make to reduce error
- **further experiments** you could do to find out more about your conclusion

Questions

1. A high-precision digital weighing scale can give a precision of 0. uncertainty on a measurement from this scale?

2. A measurement of 17.53 g is made on the same scale as questi percentage uncertainty on this measurement.

3. An experiment is carried out where a ball is dropped between t takes to pass through both is timed and the speed calculated. L sources of random and systematic errors.

4. A rectangular field is measured to have sides of length 15.07 m What is the field's area, including percentage uncertainty?

5. Plants are measured and temperatures taken at the location of follows:

Plant height (m)	Temperature (K)
0.95	276
1.25	284
1.45	290
1.60	295
1.85	301

The uncertainty in plant height is 0.05 m and the uncertainty in t

Draw a graph of these results, including error bars, and determi uncertainty.

1.3 Estimation of physical quantities

When discussing numbers and trying to find an estimate for an expected result, u
helpful. These provide a way of stating a general size of numbers when the actua

Orders of magnitude come in handy when estimating physical quantities. You might not be able to tell the speed a car is travelling at just by looking, but we can confidently say it'll have a speed of order of magnitude of 10 m s^{-1} while an airplane is more likely to travel at an order of magnitude of 10^2 m s^{-1}.

> **Key term: Order**
> We use powers of 1
> magnitude, so
> 10^2 is 100, 10^3 is 1
> And
> 10^{-1} is 0.1, 10^{-2} is 0
>
> Orders of magnitud
> 2500 has an order c
> it's larger than 100
> the thousands.

Estimating results

When multiplying or dividing numbers, orders of magnitude are especially helpful for estimating what scale our result will be on. We can just add the powers on the 10s together for multiplying and subtract them for dividing.

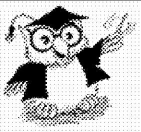
Example

$$\frac{276\,065 \times 7024 \times 0.0024}{2334 \times 0.48}$$

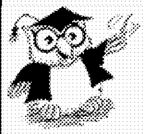
is a complicated equation that would be easy to get wrong, but if we use th
number we have

$$\frac{10^5 \times 10^4 \times 10^{-3}}{10^3 \times 10^{-1}} = \mathbf{10^4}$$

This isn't our final answer, but it gives us useful information, and we can se
the tens of thousands.

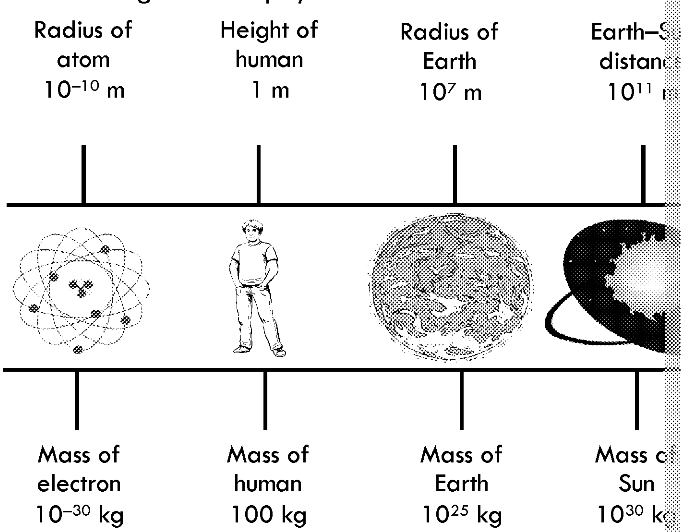


Exam tip
If an order of magnitude has a power applied to it, such as $(10^4)^2$, then we can simply multiply together the two powers to get 10^8.



Exam tip
If a number would b
is ≥ 5), the **rounde**
In the example, 70
10^4 instead of 10^3.

Below are some useful orders of magnitude in physics.



Questions

1. What order of magnitude are:
   a) 4329?
   b) 0.0087?
   c) 60,038?

2. Find the order of magnitude of the answer to

$$\frac{28 \times 0.3 \times 784 \times 0.009}{45 \times 8300}$$

   Compare this to the actual value.

3. The gravitational force between the Earth and the Sun is given b

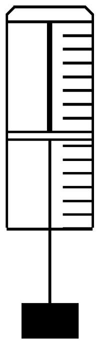
$$\text{Force} = \frac{G \times \text{mass of Earth} \times \text{mass of S}}{(\text{distance from Earth to Sun}}$$

   where G is 6.674×10^{-11} N m^2 kg^{-2}.
   Determine the order of magnitude of this force.

INSPECTION COPY

Exam style questions: Measurements and their errors

1. A wire is held between two bars. The upper bar is fixed while the low
Masses are hung from the lower bar, exerting a force on the wire and
The set-up of the experiment is shown below.



The stiffness of the wire, k, is calculated from the force exerted on the
the wire, x, by using the equation

$$k = \frac{F}{x}$$

The results of the experiment are shown below.

Force, F/ N	Extension, x/ mm
1.00	0.60
2.00	1.10
3.00	1.90
4.00	2.40
5.00	2.90
6.00	3.60

The uncertainty on measured values for the force is $\pm$ 0.2 N.
The uncertainty on measured values for extension is $\pm$ 0.1 mm.

a) State a suitable unit for the stiffness of the wire, k.

....

b) Draw a graph showing the results of the experiment with error b

c) From your graph, calculate a value for the stiffness of the wire, k, i uncertainty.

....

....

....

....

....

....

d) State how the uncertainty in the value of the stiffness could be de

....

....

2. An experiment is performed to determine the acceleration due to gravi
A piece of paper is balled up and dropped through two light gates, wh
the paper ball.
The acceleration of the paper ball can be found via

$$g = \frac{v_2 - v_1}{t}$$

v_1 is the speed of the paper ball as it passes the first light gate, v_2 is the passes the second light gate, t is the time taken for the paper ball to pa gates.

The results of the experiment are listed below.

$$v_1 = 1.87 \pm 0.01 \text{ m s}^{-1}$$
$$v_2 = 8.46 \pm 0.01 \text{ m s}^{-1}$$
$$t = 1.03 \pm 0.05 \text{ s}$$

a) Calculate a value for g from the results obtained from the experim error.

....

....

....

....

....

....

....

b) The value for g found from the results of the experiment is lower t scientific community. Repeated measurements do not decrease th State what type of error this is and how it could be removed.

....

....

....

....

c) State the meaning of the term 'anomalous result'.

....

....

d) The experiment is repeated with a different set-up to try and obta accepted value for g.

The results of this experiment are shown below.

Measurement	Acceleration due to gravity, g/ m
1	9.43
2	10.02
3	13.71
4	9.55

Calculate the mean of these measurements, after disregarding the

....

....

....

....

e) The percentage uncertainty on the mean of the results is 3 %. Discuss the accuracy and precision of the second experiment in co experiment.

....

....

....

....

Chapter 2: Particles and Radia

2.1 Particles

Chapter 2.1 checklist

By the end of this chapter you should be able to:

2.1.1

- Explain a simple atomic model..........
- Give charges and masses for protons, neutrons and electrons..........
- Understand and explain what an isotope is..........
- Understand and use nuclide notation..........
- Determine the specific charge of different particles..........

2.1.2

- Understand how the strong force holds the nucleus together..........
- Explain alpha, beta and gamma decay including equations..........
- Understand how the neutrino conserves energy in beta decay..........

2.1.3

- Understand what a photon is..........
- Calculate the energy, frequency and wavelength of a photon..........
- Understand antiparticles and how their properties relate to normal matter...
- Understand annihilation and calculate the energies involved..........
- Understand pair production and calculate the energies involved..........
- Understand how a PET scanner uses annihilation to create a map of bodily fu

2.1.4

- Understand exchange particles roles in particle interactions..........
- Explain the electromagnetic force in terms of virtual photons..........
- Explain beta-decay and electron capture in terms of the weak nuclear force..
- Use Feynman diagrams to explain particle interactions..........
- Understand the four fundamental forces and what role they play in particle p

2.1.5

- Understand that cosmic rays produce high energy particles and how these pa
- Know basic details about muons, kaons and pions..........
- Understand how particle colliders are used to detect particles..........
- Classify particles as hadrons and leptons..........
- Classify hadrons as baryons and mesons..........
- Understand baryon and lepton numbers and strangeness..........
- Understand how neutrinos relate to electrons and muons..........

2.1.6

- Understand that hadrons are made up of quarks..........
- Describe properties of the up, down and strange quarks..........
- Give the quark make up of the proton, neutron, antiproton, antineutron, pio

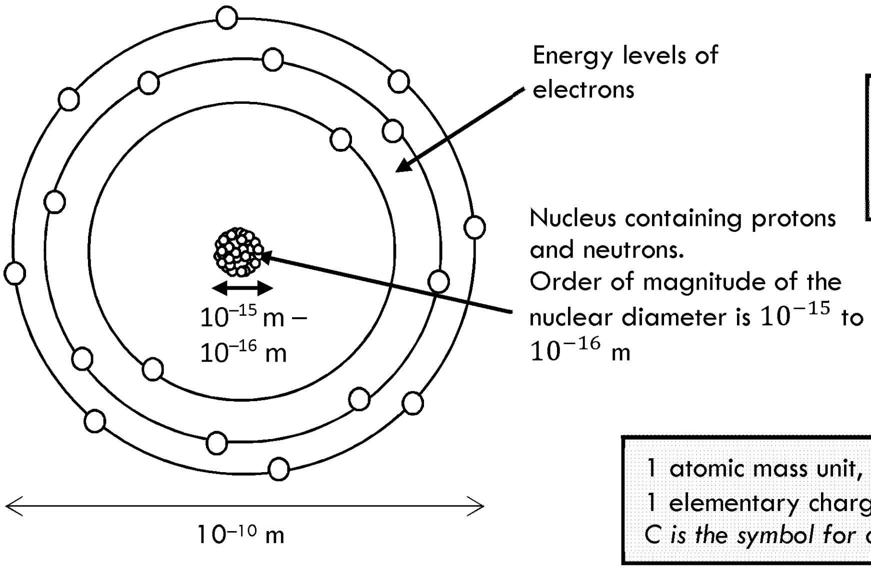
2.1.7

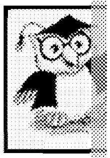
- Use conservation laws to predict which interactions take place..........
- Understand that energy and momentum are conserved throughout physics...
- Understand that charge and baryon and lepton numbers are conserved in al
- State when strangess is conserved and when it might not be..........

2.1.1 Constituents of the atom

All of the matter around you – your chair, your desk, even you – is made up of **at**
blocks of the world around us.

Inside the atom
However, atoms aren't the end of the story. Each atom is made up of various **sub**
Here is a simple model of an atom with its different subatomic particles.



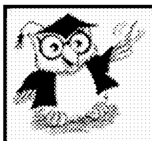


1 atomic mass unit, u = 1.6
1 elementary charge, e =
C *is the symbol for coulomb*

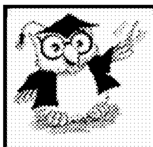
Each atom consists of a positively charged **nucleus** at the centre and negatively c
this nucleus.

The nucleus is made up of **protons** and **neutrons**, which we call **nucleons**.
The electrons are held in very specific **orbits** or **shells** around the nucleus.

	Symbol	Mass (*atomic mass units,* u)
Proton	p	1
Neutron	n	1
Electron	e^-	1/2000



Exam tip
You'll sometimes see charge written as Q in particle physics



Exam tip
When talking about
from the units. So we
of +1 and electrons

Electrons have much less mass than either protons or neutrons, which have roug

Despite making up most of the mass, the nucleus takes up very little space in the
is between 10^5 and 10^6 times smaller than the atomic radius. Most of the atom is

Isotopes

All atoms of the same element contain the same number of protons, which we c
example, every atom of oxygen has 8 protons in its nucleus so it has an atomic n

The total number of nucleons in a nucleus (protons and neutrons) gives us the **nu**
call this the **mass number** because it roughly gives us the weight of the nucleus i

We can use the following representation, known as **nuclide notation**, to give all t

Nucleon number $\longrightarrow$ $^{A}_{Z}X$ $\longleftarrow$ Element s
Atomic number $\longrightarrow$

> **Key terms**
> **Atomic number:** number of protons in a nucleus
> **Nucleon number:** number of nucleons (protons and neutrons) in a nu

Not all atoms of the same element have the same number of neutrons. This mea
the same charge (number of protons), but different masses. We say that atoms w
neutrons are **isotopes**.

For instance, there are three stable isotopes of oxygen, ^{16}O, ^{17}O and ^{18}O. They all
and 10 neutrons respectively.

We can find the number of neutrons, N, by subtracting the atomic number from t

$$N = A - Z$$

We call nuclei of different isotopes of the same element **nuclides**.

Specific charge

All charged particles have a **specific charge**. This is the ratio of the charge of the p

$$\text{Specific charge} = \frac{\text{Charge}}{\text{Mass}}$$

Because electrons have so little mass, they have the largest specific charge of all p

When we talk about specific charges of different isotopes we tend to ignore the n
their charge. This is because their mass is so low.

Example

A $^{23}Na^{+}$ ion with a charge of +1 (i.e. one missing electron) has a specific char

$$\frac{1e}{23u} = \frac{1.60 \times 10^{-19}\ C}{23 \times 1.661 \times 10^{-27}\ kg} = 4.19 \times 10^{6}\ C\ kg$$

Questions

1. Write down how many protons, neutrons and electrons there ar
   a) $^{197}_{79}Au$ b) $^{127}_{53}I$ c) $^{40}_{18}Ar$ d)
2. Would you remove an electron, proton or neutron from an aton
   a) create a different element?
   b) create an ion of the same element?
   c) create a different isotope of the same element?
3. a) Give the specific charge of a nucleus of $^{16}_{8}O$
   b) Give the specific charge of an ion of $^{40}_{20}Ca^{2+}$

2.1.2 Stable and unstable nuclei

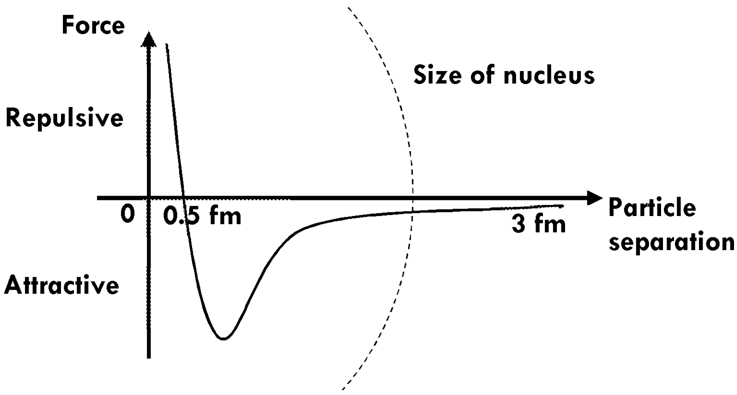
The strong nuclear force

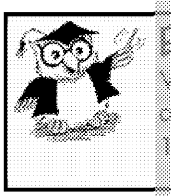
Because protons are all positively charged and neutrons have no charge, there m
protons repelling each other and sending the nucleus of every atom flying apart.

We call this force the **strong nuclear force** or **strong interaction**. The strong nucl
such as neutrons and protons, and affects them exactly the same way, regardless

This strong force has a very limited range – it only affects particles over around 3
nucleus. In comparison, the electromagnetic force has infinite range, although it
away you get.

Below you can see how the strong nuclear force acts over the size of a nucleus.





As you can see, the strong force acts very strangely – from **3 fm down to 0.5 fm**
and neutrons held together tightly. But **below 0.5 fm** it is **repulsive**, keeping pro

Nuclear decay

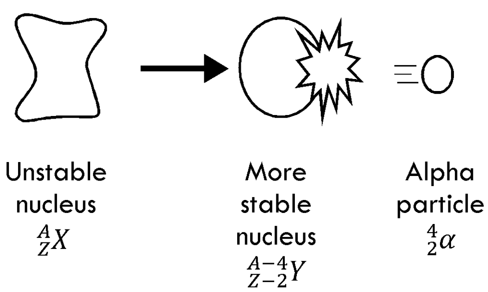
When you put multiple nucleons repelling and attracting each other into a nucle
becoming unstable. The nucleus can eject particles or energy in an attempt to be

There are three main ways this can happen: alpha, beta and gamma decay.

Alpha (α) decay

An unstable nucleus fires off an **alpha particle** (symbol: ${}^{4}_{2}\alpha$).

This leaves an alpha particle made of **2 protons and 2 neutrons**, and a new elem
fewer neutrons than before.



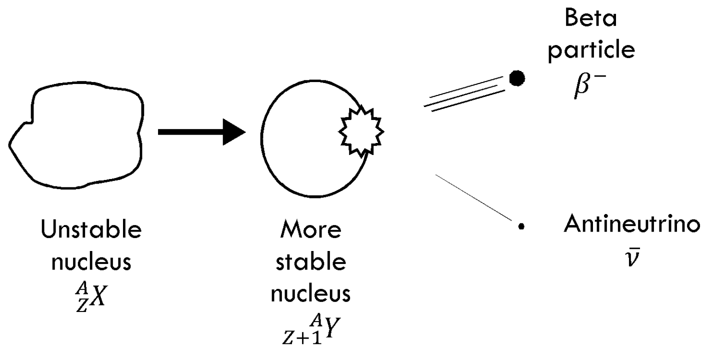
α decay

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

Beta (β^-) decay

A neutron in the nucleus turns into a proton, giving off a **beta particle** (symbol: β
(symbol: $\bar{\nu}$).

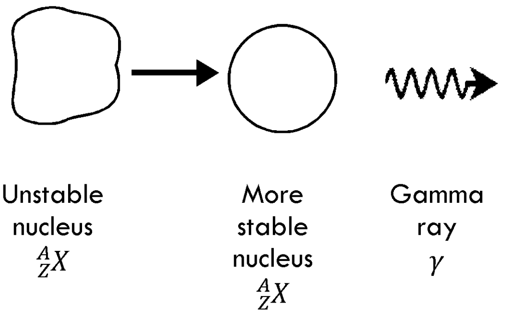
This leaves a beta particle (which is an electron), an antineutrino and a new elem
more proton than before.



β^- d

Gamma (γ) decay

An unstable nucleus gives off a burst of high-energy light called a **gamma ray** (sy
This leaves a gamma ray and the **same nucleus** as before, but with **less energy**.



γ decay

${}^{A}_{Z}X$

Practical skills

Cloud chambers

- A cloud chamber is **a sealed container filled with vapour** – as charged particles pass through, they **ionise the vapour** by pulling electrons off t molecules in the vapour. This ionisation creates droplets of condensed va which we can see.
- Alpha particles are much heavier than beta particles so they ionise the v more easily.
- The strong, straight paths of multiple alpha particles can be seen to the

Geiger counters

- A Geiger counter is used to detect radiation.
- When an α, β or γ particle hits the detector in a Geiger counter, it ionis and causes a surge in current.
- Geiger counters can only give information on how many α, β or γ partic differentiate between types of radiation or give any information on the

The history of the neutrino

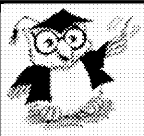
Neutrinos and **antineutrinos** are tiny, non-charged particles that interact very ra

There are billions of neutrinos produced by the sun passing through your body e
detect them because they interact so rarely.

When β^- decay was first discovered, it was found that the momentum of the nev
cancel out – a third particle had to be carrying the extra momentum away.

This third particle didn't show up in cloud chambers so it couldn't be charged, an
decay was accounted for by the new nucleus and beta particle so it had to be ver

This tiny, uncharged particle was called the neutrino.



Exam tip

The neutrino was hypothesised to account for missing momentum in β^-
The missing momentum could only be explained by a third tiny uncha

Questions

1. State whether the following statements are true or false:
   a) The strong force is limited to around 3 fm.
   b) The strong force affects all charged particles.
   c) The strong force affects protons and neutrons equally.
   d) The strong force is responsible for keeping the whole atom t

2. Which type (or types) of nuclear decay:
   a) Does not change the atomic number of the atom?
   b) Significantly changes the mass of the atom?
   c) Increases the atomic number of an atom by one?
   d) Produces a charged particle?

3. $^{215}_{84}Po$ can decay via both beta and alpha decay. Write down a
   type of decay.
   You will find elements along with their atomic and nucleon num

4. Calculate the specific charge of an alpha particle.

5. An atom of $^{235}_{92}U$ decays in a chain, first by alpha decay, then by
   further 2 alpha decays and a beta decay. What element is the

2.1.3 Particles, antiparticles and photons

Light as a wave

Light is composed of electromagnetic waves – an electric wave and a magnetic w

Different wavelengths of light give different colours, with red light having a longe

Photons: Light as a particle

When light hits a metal surface, electrons can be given off. These electrons have a specific energy depending on what wavelength of light hits the metal, implying that the light is carrying a specific energy. This couldn't happen with waves – waves carry a continuum of energy, so an electron could just absorb more energy by absorbing more of the wave.

Key term: Ph
A photon is a si
thought of as a

We represent p

Einstein realised that if we model light as a burst of energy in a wave packet called a **photon**, this problem is solved.

The energy, E, of a photon is given by

$$E = hf = \frac{hc}{\lambda}$$

Example

What is the energy for a photon of

a) Red light (f = 400 THz)?
b) Blue light (λ = 450 nm)?
c) How does the energy of a photon relate to its wavelength and freq

a) $\mathrm{E} = hf = 6.63 \times 10^{-34} \times 400 \times 10^{12} = 2.65 \times 10^{-19}\ \mathrm{J}$

b) $\mathrm{E} = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{450 \times 10^{-9}} = 4.42 \times 10^{-19}\ \mathrm{J}$

c) *A higher energy photon will have a shorter wavelength and higher fre*

Matter and antimatter

Enrico Fermi, an Italian physicist, discovered that for every particle there is an **an**

The antiparticle for the proton is the antiproton, for the neutron it's the antineu counterparts to common particles are listed below.

	Symbol	Mass/ u	C
Antiproton	$\bar{p}$	1	
Antineutron	$\bar{n}$	1	
Anti-electron (positron)	e^+	1/2000	
Antineutrino	$\bar{\nu}$	Almost zero	

You'll notice that antiparticles have the **same mass** as their normal matter count

The symbol for an antiparticle is the symbol for the normal matter particle with a electron, the positron, which is e^+, and the anti-muon, μ^+).

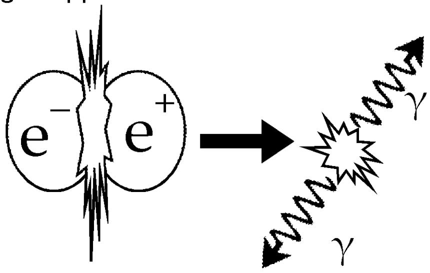
Annihilation

For an electron and positron annihilation, the following process occurs:

$e^- + e^+ \rightarrow 2\gamma$

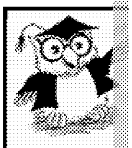
> **Key term: Annihilation**
> When a particle meets its antipartic
> each other. This means that they are
> with only 2 photons left behind.

Two photons are produced travelling in opposite directions to each other with ex
The creation of two photons travelling in opposite directions conserve momentu



The minimum energy for each photon is E_0, the **rest energy** of the electron. If the
formed the photons had kinetic energy, the photons will share this additional en

> **Key term: Rest Energy**
> A particle's rest energy is the energy it has purely from its mass, discounting other forms of energy like kinetic or potential energy.
>
> We often refer to particles' masses in eV. This is their rest energy, which is related to their masses via $E = mc^2$
>
> Particle's total energy = rest energy + kinetic energy



booklet

Any othe
you nee

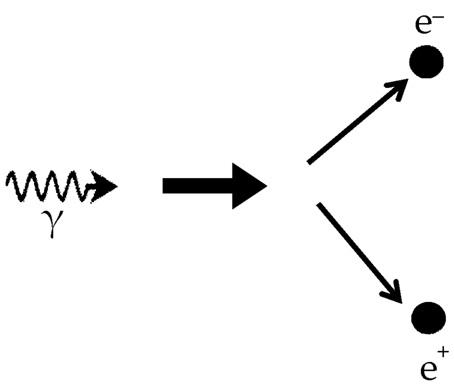
The gamma photons produced by annihilation can be detected because of their a
detector.

Pair production

If a photon has enough energy it can sometimes perform the opposite of annihila
where one photon becomes a particle and its antiparticle.

The pair production of an electron-positron is shown by

$$\gamma \rightarrow e^- + e^+$$



For pair production to happen, the photon must have an energy of at least $2E_0$, w
both the particle and antiparticle. Any additional energy the photon has is given t
kinetic energy.

Example

A photon of frequency 3.80×10^{20} Hz creates an electron-positron pair vi
The rest energy of an electron is 0.51 MeV.

a) How much energy does the photon have?

b) If the energy is split equally, how much kinetic energy do the electr

a) $E = hf$, so $E = 6.63 \times 10^{-34} \times 3.80 \times 10^{20} = \mathbf{2.52 \times 10^{-13}}$ **J**

In eV, $\frac{2.52 \times 10^{-13}}{1.6 \times 10^{-19}}$ = **1.57 MeV**

b) One half of the total energy =0.79 MeV

Kinetic energy = total energy – rest energy = **0.28 MeV**

PET scanner

Hospitals regularly make use of annihilation in PET (Positron Emission Tomograph

PET scans allow us to see inside a patient's body. You can see a PET scan of a bra

A nuclide which emits positrons is injected into the body and allowed to circulate. emits positrons which quickly meet with electrons in the patient's body and anni

This produces 2 photons at 180° from each other, which are detected. After many detected photons are used to map out a 3D picture of a patient's internal functio

Questions

1. a) A photon has wavelength 730 nm. Calculate its frequency.
   b) A photon has frequency 5.00 THz. Calculate its wavelength.

2. Calculate the energies of both of the photons in question 1.

3. a) A proton has a rest energy of 1.50×10^{-10} J. Convert this to e
   b) A photon has energy 103 eV. Convert this to joules.

4. An electron and a positron with only their rest energy annihilate photons are produced.
   a) What is the energy of each photon in joules?
   b) What is the frequency of each photon?

5. A photon of wavelength 7.55×10^{26} Hz creates a proton-antipro
   a) How much energy does the photon have in electron volts?
   b) If the energy is split equally then how much kinetic energy d antiproton each have?

2.1.4 Particle interactions

There are four **fundamental forces** affecting particle interactions:

- the electromagnetic force
- the weak nuclear force
- the strong nuclear force
- gravity

These forces are carried by **exchange particles** specific to the force. Some forces

> **Key term: Exchange particles**
> When fundamental particles interact with each other, they do this through excha
> particles transfer forces and quantities such as charge from one particle to anoth
>
> Each of the fundamental forces has a different exchange particle, which is cover

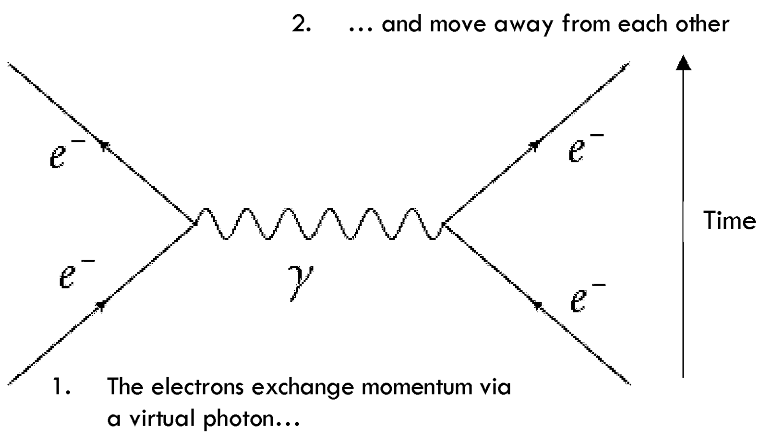
The electromagnetic force

The electromagnetic force affects charged particles and is responsible for pheno
magnetism. The exchange particles for the electromagnetic force are **virtual pho**

Virtual photons differ from other photons in that they can't be detected – if we i
they wouldn't be able to complete any interaction between charged particles.

When two charged particles come close to each other they exchange a virtual ph
the two particles to repel or attract one another.

Imagine two electrons approaching each other. As they came closer they would e
would cause them to move apart.



The
par
whic
out

Similarly, two differently charged particles such as a proton and an electron appr
exchange a virtual photon, pulling the proton and electron together.

The weak nuclear force

In beta-decay a neutron turns into a proton by giving off an electron and an antin

Beta-decay can't be caused by the electromagnetic force because it involves neu electromagnetic force only affects charged particles!

It can't be caused by the strong force either because it involves electrons and ne doesn't affect.

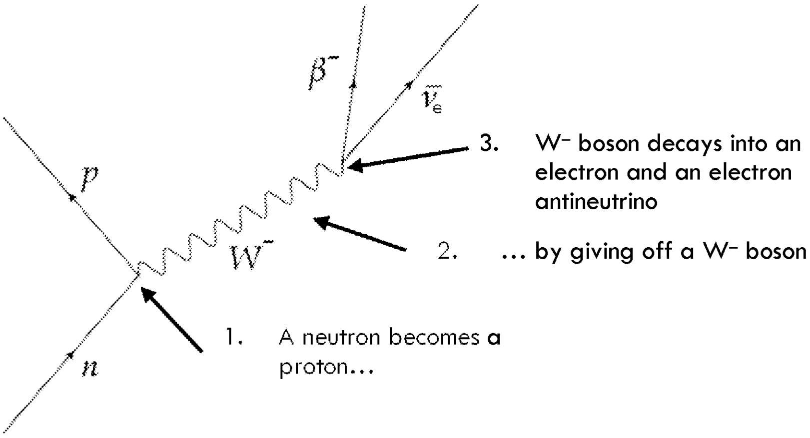
We need a third force – the **weak nuclear force**, sometimes just called the weak f

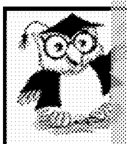
The exchange particle for the weak force is the W boson.

	W^- boson	W^+ boson	Ph
Mass/GeV	80	80	
Range/fm	0.001	0.001	Inf
Charge/*e*	-1	+1	

This weak force affects processes in the nucleus like beta-minus decay. This can b

β^- decay





Similarl
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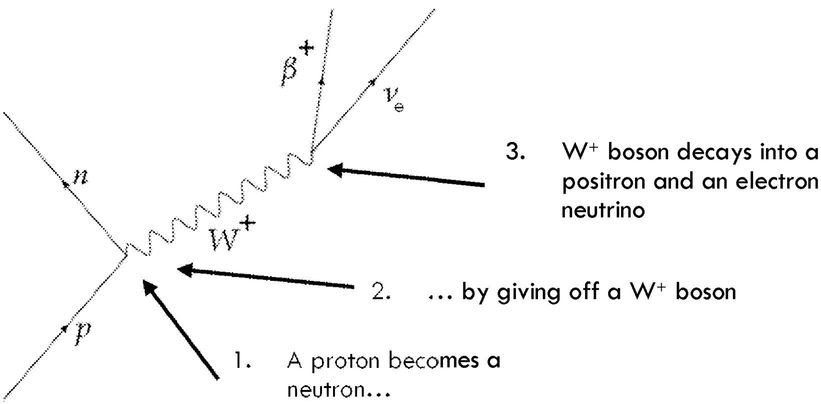
the posi

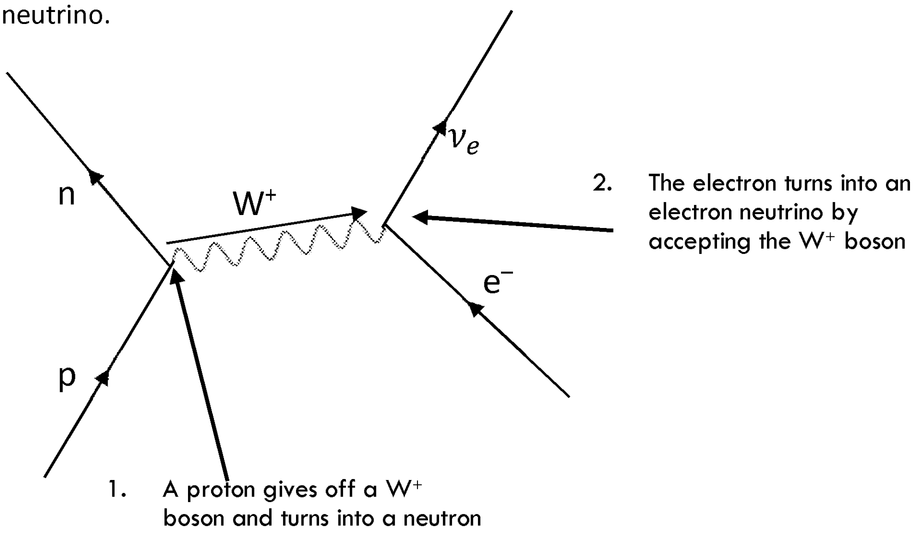
There is also beta-plus, or β^+, decay. In β^+ decay a proton in a nucleus turns into a boson, which then decays into a positron and a neutrino.

β^+ decay



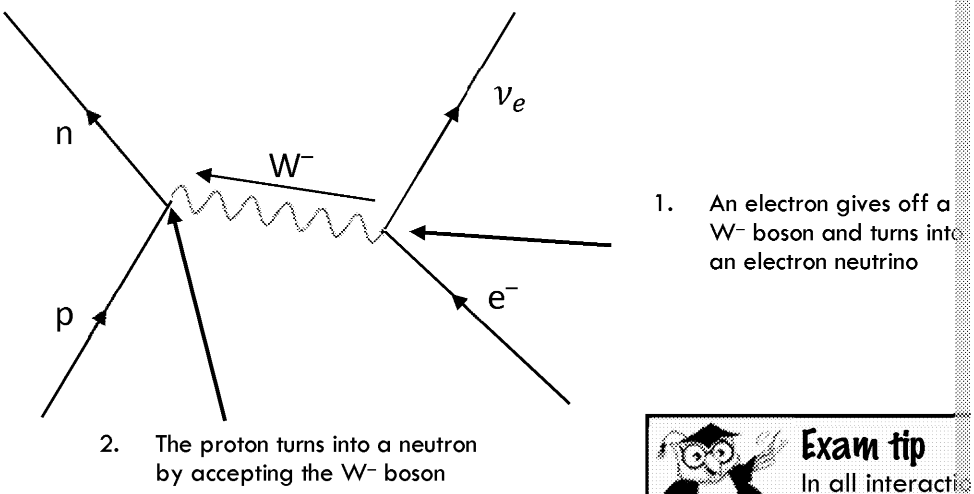
Electron capture

A proton can also turn into a neutron via a process called **electron capture**. This i turns into a neutron by giving off a W⁺ boson, which turns one of the electrons ir neutrino.



Electron proton collisions

Electron proton collisions look similar to electron capture with one crucial differe The electron emits a W⁻ boson, which turns a proton in the nucleus into a neutro



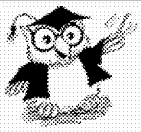
Exam tip
In all interacti particles befo particles afte **charge is con**

The strong force and gravity

The strong force is what holds the nucleus together. Nucleons exchange pions, w
attract each other. However, below 0.5 fm, the strong force is repulsive, keeping

Gravity is the fundamental force you'll be most familiar with, as it's the force tha
Earth. While scientists understand the effects of gravity very well, they don't und
involved.

The graviton has never been observed – we assume it must exist because all the other forces have exchange particles. The graviton is one of the particles that particle accelerators such as the Large Hadron Collider are looking for.



Exam tip
You don't need t
processes for gr
scientists don't kn

Four fundamental forces

Force	Exchange particles	Exchange particle symbol	What particles d affect?
Electromagnetic	Virtual photon	γ	Charged particles
Weak	W bosons	W^+, W^-	Electrons, neutrin protons, neutron
Strong	Pions	π^+, π^-, π^0	Nucleons (proton neutrons)
Gravity	Graviton	G	All particles

Questions

1. Why can't the electromagnetic or strong forces be responsible f
2. As an electron and proton approach each other they exchang attract each other. Draw a Feynman diagram showing this elec
3. A proton turns into a neutron by giving off a W^+ boson. The W^+ b with an electron antineutron, turning it into a positron. Draw a Fe this process.
4. Write down whether each of the following statements applies to
   a) Have a charge of +1 or –1.
   b) Have infinite range.
   c) Have no mass.
5. For each of the statements below, write down which fundamen apply to.
   a) Affects electrons.
   b) Affects neutrons.
   c) Is responsible for a type of radioactive decay.
   d) Has multiple exchange particles.

2.1.5 Classification of particles

Discovering particles

When different types of particles were first being discovered in cloud chambers, stray tracks in the cloud chambers. These tracks weren't connected to the other from outside the chamber.

The tracks were made by high energy particles originating in the upper atmosphe high energy particle interactions. Common particles produced by cosmic rays inc

Key terms:
Muons are similar to electrons but much heavier. Muons decay into electrons.
Symbol: μ^-
Charge: -1

The antiparticle of a muon is the **antimuon**
Symbol: μ^+
Charge: +1

Key term: Pion
Pions are mesons that c strong force between n
Symbol: π^+, π^-, or π^0
Charge: +1, -1 or 0

Key term: Kaon
Kaons are particles tha property called strang Kaons decay into pion
Symbol: K^+, K^-, or K^0
Charge: +1, -1 or 0

Particles created by cosmic rays can also be detected using two Geiger counters particle, the path of a stream of particles must pass both detectors. This helped s particles were in fact coming from high up in our atmosphere.

Scientists are still discovering new particles even today.

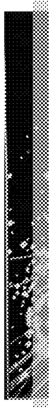
Scientists create new particles by slamming particles together at extremely high e as the Large Hadron Collider at CERN. When particles collide at these high energi in an instant and hundreds of new particles are created in showers.

It can be incredibly difficult to keep track of all of these interactions and particle of scientists to collect and analyse such large amounts of data and even more sci colliders and keep them running.

Practical point

While experiments play the biggest part of verifying a discovery, scientists have to know what they're looking for first.

Computer models are used to model particle collisions that take place in an experiment, to direct scientists where to look and to help make sense of the huge amount of data collected.



Hadrons

Protons, neutrons, pions and kaons are all known as **hadrons**.

Hadrons are **affected by the strong force**. The strong force doesn't interact with any particles that aren't hadrons.

> **Exam tip**
> Remember, ho
> weak force a
> electromagne

Hadrons fall into one of two categories – **baryons** or **mesons**.

- Protons and neutrons are **baryons** and antiprotons and antineutrons are **antibaryons**.
- Pions and kaons are **mesons**.

> **Key term: Baryon numb**
> Baryon number, *B*, is a q
> is conserved in particle i
> - Baryons have a ba
> - Antibaryons have a
> - Everything else has

Protons are the **only stable baryon**. All other baryons will decay to protons given

> **Exam tip**
> The only strange particles you'll have to worry about are kaons.

Strangeness

Some hadrons have a property know
particles are produced in strong inte
interactions.

Strangeness, *S*, is conserved in strong interactions but not in weak interactions. I
can change by +1, -1 or 0.

Leptons

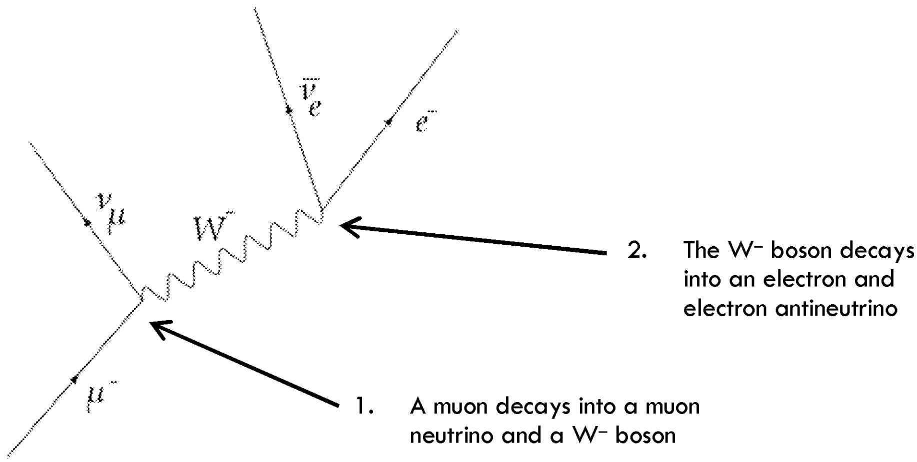
Electrons, muons and neutrinos (which can be electron neutrinos, ν_e, or muon n
leptons. Leptons interact through the weak interaction, gravity and the electrom
charged.

Leptons are **fundamental**. This means that they can't be broken down any more i

> **Key term: Lepton number**
> Lepton number, *L*, is a quantum number that is conserved in particle interactions.
>
> Electrons and electron neutrinos have electron-lepton numbers of 1.
> Positrons and electron antineutrinos have electron-lepton numbers of -1.
> Everything else has an electron-lepton number of 0.
>
> Muons and muon neutrinos have muon-lepton numbers of 1.
> Antimuons and muon antineutrinos have muon-lepton numbers of -1.
> Everything else has a muon-lepton number of 0.
>
> Lepton numbers are often stated without reference to which type of lepton numbe

Muon decay

Below you can see the Feynman diagram of a muon decaying into an electron, an
muon neutrino.



Questions

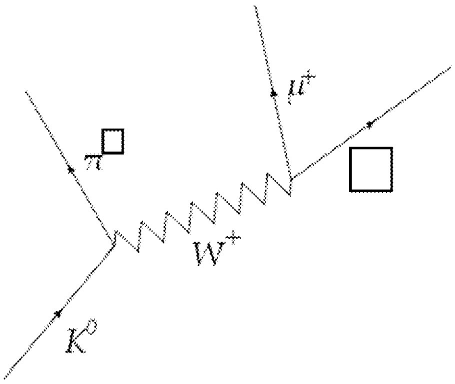
1. Fill in the table below

	Charge	Lepton number	Baryon number	
K^+	+1	0	0	
ν_e				
p				
$\bar{n}$				
e^-				
π^0				
μ^+				

2. Write whether each of the following statements are true or false
   statements are wrong.
   a) A lepton is always charged.
   b) All baryons and antibaryons have a baryon number of 1.
   c) A particle cannot have a baryon number of 1 and a lepton
   d) All mesons are hadrons.
   e) All hadrons are mesons.

3. A π^- meson decays into a μ^- and a $\bar{\nu}_\mu$ via a W⁻ boson. Draw a Feyn

4. Complete the Feynman diagram for kaon decay below.



5. Draw a Feynman diagram for antimuon decay.

2.1.6 Quarks

All hadrons are made of fundamental particles called **quarks** and **antiquarks**. There are **up**, **down**, and **strange** quarks and antiquarks. This is called the quark's

	Quarks			
	Up u	**Down** d	**Strange** s	**Up** $\bar{u}$
Charge	+2/3	-1/3	-1/3	-2/3
Baryon number	1/3	1/3	1/3	-1/3
Strangeness	0	0	-1	0

Exam tip

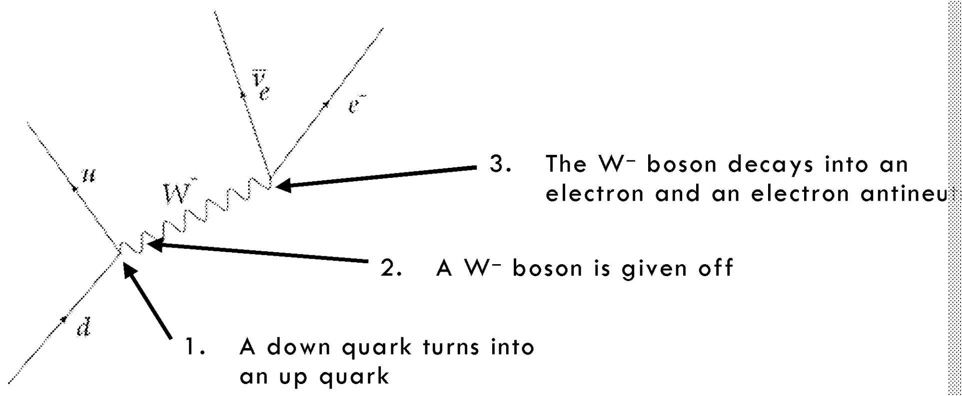
These properties are given in the exam data booklet for up, down

Baryons each contain 3 quarks (and antibaryons contain 3 antiquarks) while mesons are

Baryons	Quark make-up
p	uud
$\bar{p}$	$\bar{u}\bar{u}\bar{d}$
n	udd
$\bar{n}$	$\bar{u}\bar{d}\bar{d}$

Mesons
π^+
π^-
π^0
K^+
K^-
K^0

We can now have another look at β^- decay. A neutron turning into a proton repr uud; two of the quarks stay the same and one down quark turns into an up quark.



Questions

1. Write down the baryon numbers, strangeness and charge for each
   a) p (uud) b) $K^+(u\bar{s})$ c) $\bar{\Sigma}$ ($\bar{d}\bar{d}\bar{s}$)
2. A Xi particle, Ξ^0, has a strangeness of -2, a baryon number of 1 a quark composition does the Xi particle have?
3. A K^+ can decay via

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

For each of these particles, state their quark content.
If a strange antiquark can turn into a down antiquark, then track to its placement in the products. Where could any additional q

2.1.7 Conservation laws

Particle interactions follow **conservation laws** – the total properties of the partic
after an interaction.

This doesn't mean that each individual particle's properties don't change, but tha
properties for all the particles doesn't change.

Some conservation laws always apply and some only apply in certain cases.

Energy and momentum

Energy can't be created or destroyed, only changed into a new form. In all interac
energy before a process is the same as the energy after a process. This takes into
interaction – kinetic energy and the rest energies that make up the particles' mas

The same applies for momentum; if before an interaction none of the particles ha
products of the interaction do, the momentums of the products will add up to ze

Example

An electron travelling at 32 m s^{-1} interacts with an electron at rest. After t
electron travels at 16 m s^{-1} in its original direction.

a) What is the initial momentum of both electrons?
b) What velocity does the second electron have after the interaction?

a) $p = mv$ so $p_{1(before)} = m_e \times v_{1(before)} = 9.1 \times 10^{-31}$ kg $\times$ 32 m s^{-1} = **2.9 × 1**

P_2 (before) = $m_e \times v_2$ (before) = $m_e \times 0$ = **0 kg m s^{-1}**

p_{total} = **2.9 × 10^{-29} kg m s^{-1}**

b) Momentum is conserved.

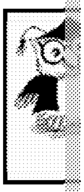
$p_{total(before)} = p_{total(after)}$ so $m_e v_{1(before)} + m_e v_{2(before)} = m_e v_{1(after)} + m_e v_{2(a}$

We can divide everything by m_e to keep everything nice and simple.

$v_{1(before)} + v_{2(before)} = v_{1(after)} + v_{2(after)}$

$v_{2(after)} = v_{1(before)} + v_{2(before)} - v_{1(after)} = 32 + 0 - 16 =$ **16 m s^{-1}**

Particle interactions



There are also conservation laws in particles physics – interactions must follow these laws to be possible – we say that these are **allowed** interactions. Conservation laws allow us to predict whether an interaction is possible.

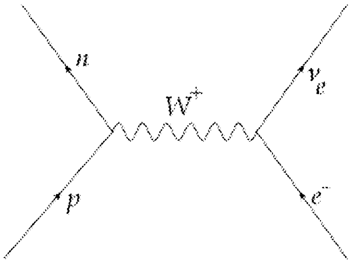
Charge, **baryon number** and **lepton number** are always conserved in all interacti

Strangeness is conserved in strong and electromagnetic interactions, but is **not** a
interactions.

Quark character is conserved in strong and electromagnetic interactions, but is **n**
interactions, as in beta-decay when an up quark changes to a down quark.

Questions

1. For each of the interactions below, track charge, baryon and le strangeness in the initial and final conditions and determine whe are broken and therefore determine whether the interactions ca
   a) $\nu_e + n \rightarrow e^- + e^+$
   b) $p + p \rightarrow p + n + \pi^+$
   c) $\mu^- \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$
   d) $\bar{p} + p \rightarrow p + n + \pi^-$
   e)



2. A proton in a particle accelerator hits into a stationary proton, p interaction

$$p + p \rightarrow p + p + p + \bar{p}$$

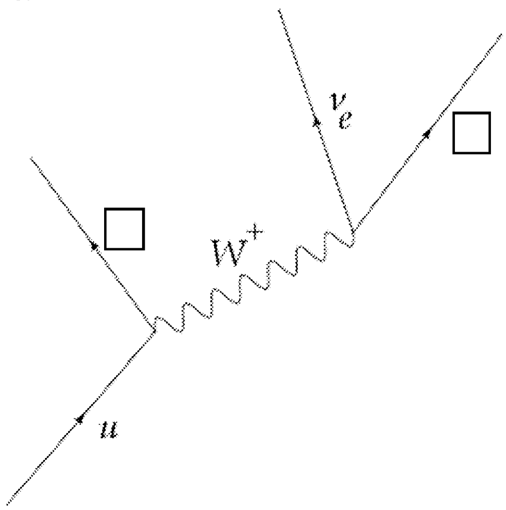
   Determine the minimum kinetic energy the protons must have fo Does this interaction follow other conservation laws?
   A proton's rest mass is 938 MeV.

3. The following interactions involve three imaginary particles, X, Y a

$$p + \pi^0 \rightarrow X + \bar{n} + p$$
$$\pi^+ + \pi^- \rightarrow p + Y$$
$$Z \rightarrow \mu^+ + \nu_\mu$$

   Determine the charge and baryon and lepton numbers of X, Y a

4. In β⁺ decay a proton turns into a neutron. Complete the Feynma process in terms of quarks.



Exam style questions: Particles, antiparticles and photons

1. $^{245}_{98}\mathrm{Cf}$ is an artificial element, created by bombarding Curium with α p

a) How many protons and neutrons are in a nucleus of $^{245}_{98}\mathrm{Cf}$?

....

....

b) Calculate the specific charge of a nucleus of $^{245}_{98}\mathrm{Cf}$.

....

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c) $^{245}_{98}\mathrm{Cf}$ is produced in the interaction shown by the equation below

$$^{X}_{Y}\mathrm{Cm} + \alpha \rightarrow {}^{245}_{98}\mathrm{Cf} + \mathrm{n}$$

Determine the values of X and Y, showing your working.

....

....

d) $^{245}_{96}\mathrm{Cf}$ decays via β^- in the decay process shown in the equation b

$$^{245}_{96}\mathrm{Cf} \rightarrow {}^{245}_{97}\mathrm{Bk} + \beta^- + \bar{\nu}_e$$

Why was the antineutrino shown in this process hypothesised?

....

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e) Which fundamental force is responsible for the β^- decay of $^{245}_{96}\mathrm{Cf}$
Give reasons for your answer.

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f) $^{245}_{96}Cf$ and $^{245}_{97}Bk$ are part of a decay chain.

$^{245}_{97}Bk$ decays to $^{225}_{89}Ac$ by 5 α decays and a number of β^- decays.

How many β^- decays does $^{245}_{97}Bk$ undergo in the decay chain to ^{2}

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2. The K^- particle is a meson with a quark composition of $\bar{u}s$.

a) Explain what is meant by the term meson.

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b) Determine, explaining your answer, the charge, baryon number, l strangeness of the K^- particle.

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c) The decay of the K^- particle is shown below.

$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Energy and momentum are conserved in this decay.

State **two** other quantities that are **conserved** and **one** quantity th decay.

....

....

....

d) State which fundamental force is responsible for the decay of the

....

e) The μ^- particle produced in the decay of the K^- particle can furth

$$\mu^- \rightarrow e^- + \nu_\mu + \text{X}$$

Identify X by ticking **one** box from the following list.

Electron, e^-	☐
Positron, e^+	☐
Electron neutrino, ν_e	☐
Electron antineutrino, $\overline{V}e$	☐
Muon, μ^-	☐
Antimuon, μ^+	☐
Muon neutrino, ν_μ	☐
Muon antineutrino, $\overline{V}\mu$	☐
Neutral pion, π^0	☐

2.2 Radiation

Section 2.2 checklist

By the end of this section you should be able to:

2.2.1

- Explain the photoelectric effect in terms of photons.......................................
- Understand how the wave model of light doesn't explain the photoelectric e
- Calculate work functions, electron kinetic energy and photon energy.............
- Understand stopping potential ....

2.2.2

- Explain ionisation and excitation ....
- Understand where the electronvolt comes from..

2.2.3

- Understand discrete energy levels in an atom ....
- Explain how electrons move between energy levels using photons of specific
- Calculate the energy of a photon required for an electron to move energy le
- Understand how absorption and emission spectra are produced and what th

2.2.3

- Understand how light and matter can act as both particles and waves ....
- Calculate a de Broglie wavelength for a particle ....
- Understand electron diffraction and why it suggests that electrons are waves
- Appreciate how our understanding of physics can change over time..............

2.2.1 The photoelectric effect

When light above a certain frequency is shone onto a metal surface, electrons ar
photoelectric effect.

Particles or waves?

- Electrons will only be given off from the surface of a metal if the frequency o **threshold frequency**, f_0.
- Shining more light onto the metal surface will increase the **number** of electr **kinetic energy** and no matter how intense the light is, if the frequency is bel electrons will be released.
- This effect happens **straight away** – as soon as light is shone onto the metal,

> **Key term: Threshold frequency**
> The threshold frequency is the minimum frequency a photon can have to cause a
> metal surface.
> Below this frequency, no electrons are given off.
> Different metals have different threshold frequencies.

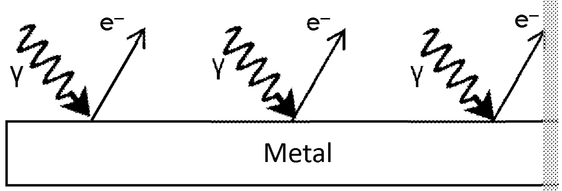
These properties can't be explained by a wave model of light, but Albert Einstein
explained by a particle model of light.

He called these particles of light **photons**.

	Can the wave model of light explain it?	Can the
Electrons are given off instantly	**No** – it would take time to absorb energy from a wave.	**Yes** – A absorb
Electrons only given off above threshold frequency	**No** – any wavelength of light could be absorbed; you'd just have to wait until enough energy was absorbed from the wave.	**Yes** – A the pho energy
Number but not energy of electrons given off increases in more intense light	**No** – more light would mean more energy could be absorbed by each electron, giving it higher energy. Electrons across the surface would all absorb light so the number wouldn't change.	**Yes** – M more p have th could b energy.

Photons hit the surface of the metal…

… and ele



The energy of a photon is given by

$$E = hf$$

or

$$E = \frac{hc}{\lambda}$$

> E = energy of
> f = frequency
> λ = wavelengt
> h = Planck cons
> c = speed of li

Work function

Key term: Work function

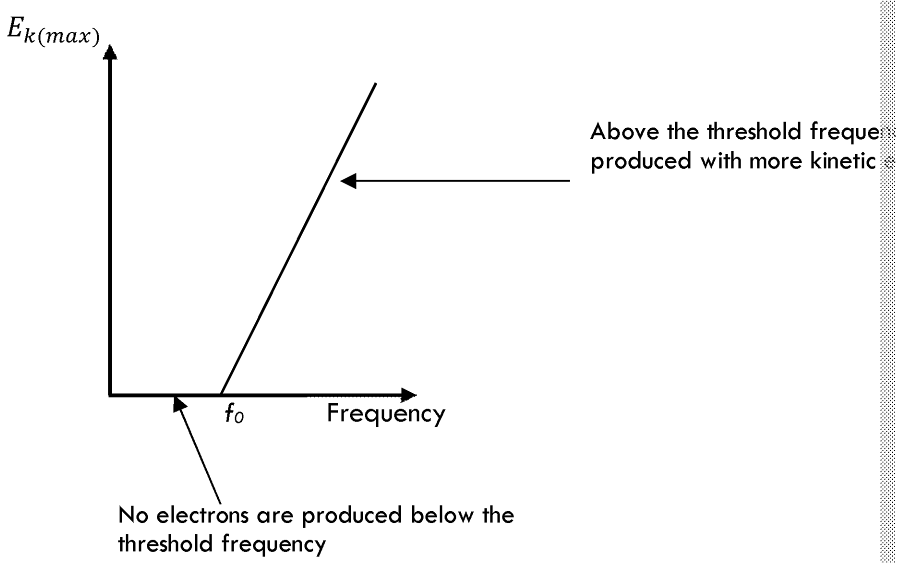
The work function, Φ, of a metal is the minimum energy a photon needs to reach t
cause a metal to release electrons. Any additional energy is given to the electro

$$E = \Phi + E_{k(\max)}$$

$$\Phi = hf_0$$

$E_{k(\max)}$ = maximu
available to the elec

The graph below shows the maximum kinetic energy of a released electron agai



Example

A light of frequency 1.55 × 10[15] Hz is shone onto a beryllium surface. D
electrons would be released, and if so, what would their kinetic energy

The work function of beryllium is 4.98 eV

Energy of light $E = hf = 6.626 \times 10^{-34} \times 1.55 \times 10^{15} = 1.03 \times 10^{-18}$ J

in eV $\frac{1.03 \times 10^{-18}}{1.6 \times 10^{-19}}$ = **6.42 eV**

This is above the work function so electrons will be released from the beryll

$E_{k(max)} = E - \Phi = 6.42 - 4.98 =$ **1.44 eV**

Stopping potential

If we apply a potential to the metal we can attract the electrons back to the surfa
If we apply a high enough potential, the electrons won't be able to escape at all –
energy to free the electrons.

The potential at which electrons can no longer be freed is the **stopping potentia**
$E_{k(\max)}$ of an electron is equal to its charge (in coulombs) multiplied by the stopp

$$E_{k(max)} = e \times V_e$$

> **Key term: Stopping potential**
> The stopping potential is the potential required to stop electrons being released f
> photoelectric effect.

Questions

1. A piece of copper foil is connected up to an ammeter. When a
   metal a current is measured, but not when a red light is shone o

   Explain why this is. Would there be any change with a more inte
   be any change with a more intense UV light?

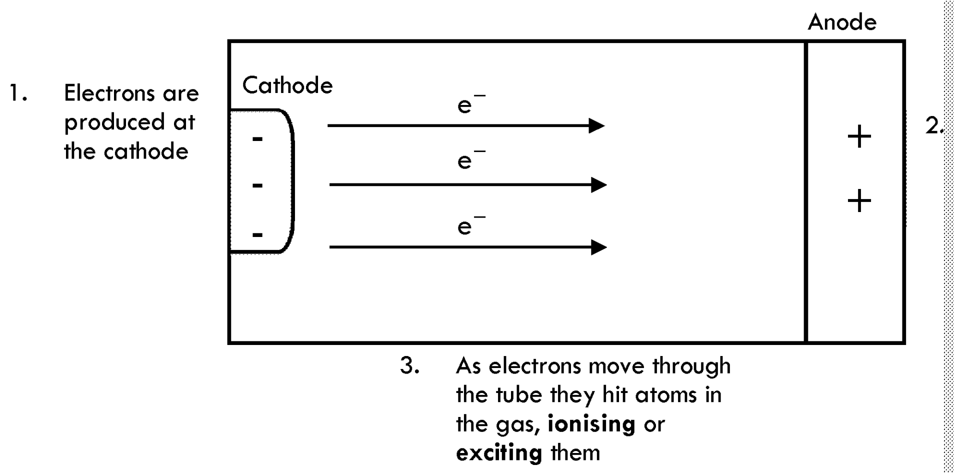
2. a) Calculate the energy of a photon with a wavelength of 480
   b) Calculate the frequency of a photon with an energy of 8.90

3. The threshold frequency for copper is 1120 THz.
   a) Calculate the work function for copper in
      (i) joules (ii) electronvolts
   b) Calculate the maximum kinetic energy of an electron that h
      by a photon with energy 7.28 eV.

4. The work function for nickel is 5.15 eV.
   a) What is this in joules?
   b) What is the threshold frequency for nickel?
   c) A photon with frequency 1810 THz is shone onto nickel. What
      energy of an electron given off?

2.2.2 Collisions of electrons with atoms

A fluorescent tube is a tube filled with low pressure gas that has a potential diffe
charge at the anode and a negative charge at the cathode.



Ionisation

Fast moving particles can ionise atoms by colliding with the atom and knocking off electrons.

> **Key term: Ion**
> A charged atom or molec
> Negative ions have more
> Positive ions have more p

The electrons in a fluorescent tube can only ionise the gas atoms when they have high enough speed – the electrons in the gas atoms are strongly attracted to the nuclei of the gas ator
to overcome that attraction.

The energy required for ionisation differs from atom to atom and depends on ho
attracted to the nucleus.

We can find the ionisation energy by

ionisation energy = eV

> e = charge on an
> V = minimum pote

> **Exam tip**
> We use eV to express the small energies involved in pa
> equations will often use SI units, so we have to convert t
> 1 eV = 1.6 x 10^{-19} J

Example

What potential is needed to ionise an atom with ionisation energy of 3.9

First we have to convert the ionisation energy to joules

$3.9\ eV = 3.9\ eV \times 1.6 \times 10^{-19} = 6.24 \times 10^{-19}$ J

Then we use the formula above

$V = \frac{\text{ionisation energy}}{e} = \frac{6.24 \times 10^{-19} J}{1.6 \times 10^{-19}} = \mathbf{3.9\ eV}$ *The same number!*

This is because an electron volt is defined as the energy needed to move an el difference of 1 V.

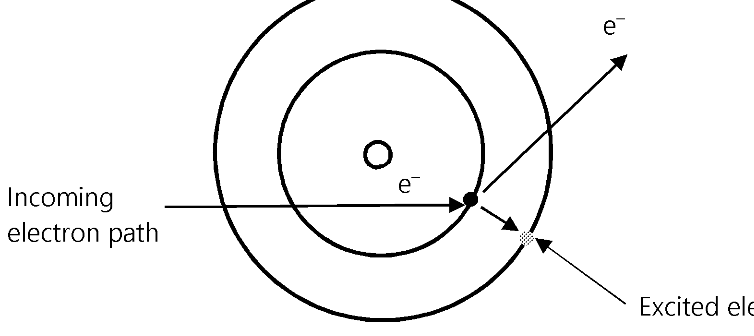
Excitation

An atom can absorb energy without being ionised – we call this **excitation**. When will move to a higher energy level.

An atom can only absorb very specific energies depending on the element.

- An electron *at this specific energy* will lose all kinetic energy, and the atom w of energy.
- If an electron *doesn't have enough* energy to excite the atom, it will be defle
- If an electron has *more than* the specific amount of energy required for excit energy and continue with a lower energy.

Excitation energies are always less than ionisation energies because increasing th much easier than removing the electron completely.



This diagram s electron in an a transferring en

The atomic ele energy level.

Questions

1. Write whether the following statements refer to *excitation*, *ionisa*
   a) An electron collides with an atom, transferring energy.
   b) The atom loses an electron.
   c) The colliding electron must have at least a specific amount o
   d) An electron in the atom moves to a higher energy level.
   e) The required energy is specific to the type of atom.

2. An excitation energy for hydrogen is 2.5 eV. What would happe with a hydrogen atom with:
   a) 1.7 eV b) 3.9 eV c) 2.5 eV

3. Hydrogen has an ionisation energy of 13.6 eV. An electron with hydrogen atom. Describe what happens and how much kinetic after the collision.

2.2.3 Energy levels and photon emission

Photons and energy levels

An electron in an atom can absorb a photon and go up an energy level but only i
equal to the difference in energy levels.

> **Key terms**
> The **ground state** of an electron is its state when it is in the lowest possible energ
> An **excited state** of an electron is its state when it has been excited to a higher e

An excited atom is unstable – excited electrons leave vacancies in lower energy l
excited it will quickly *de-excite* to fill the vacancy.

An electron will de-excite by emitting a photon. The photon will have the exact s
between the energy levels.

The energy of a photon emitted or absorbed by an atom is given by

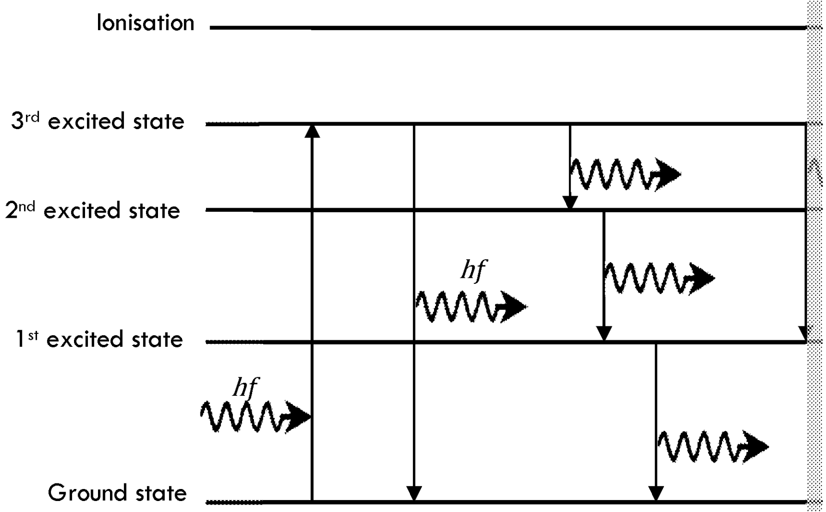
DB

$$hf = E_1 - E_2$$

> E_1 = energy level the
> E_2 = energy level the

Hydrogen energy levels

This diagram shows the energy levels for a hydrogen atom.



Energy levels are quoted in relation to the energy required for ionisation – they a
attractive energies between the electron and the nucleus.

The arrows show an electron being excited to the 3rd excited state and then de-e

An electron can de-excite straight to the ground level or in stages, stopping at lo

Example

What are the energies of photons given off by an electron in the 2nd exci
ground state?

Straight to ground state: $hf = E_1 - E_2 = -1.5 - (-13.6) = \mathbf{12.1\ eV}$

Falls to 1st excited state... : $hf = E_1 - E_2 = -1.5 - (-3.4) = \mathbf{1.9\ eV}$

... and then the ground state: $hf = E_1 - E_2 = -3.4 - (-13.6) = \mathbf{10.2\ eV}$

Atomic Spectra

When a gas is heated, electrons are excited to a higher energy level. These electr
photons of exactly the same energy as the difference in energy levels. This mean
frequencies which give a signature pattern for each gas.

The opposite can also happen; light passing through a substance will be absorbe
to energy levels and so the resultant light will have that frequency missing.

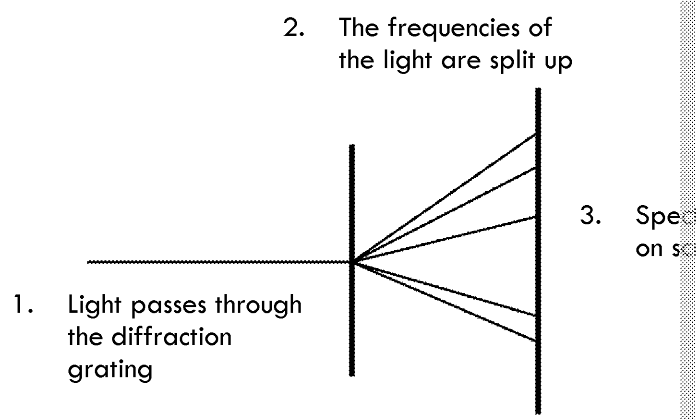
Line spectra can be produced from absorption or emission of photons, and the d
defined orbits of the atom.

Below is an emission spectrum from hydrogen

The lines are for frequencies of light given off by hydrogen. Each frequency corre
levels – the energies of the photons given off as electrons fall to lower energy lev

Experiment

A **diffraction grating** is a piece of glass with a series of closely etched lines. As
is split up into the different frequencies it contains by diffraction and interferen



If we heated up a gas and passed the light produced through a diffraction gra
frequencies of light emitted as electrons de-excite. This is the emission spectrum

Questions

1. An emission spectrum for oxygen has emission lines at 687 nm an
   a) Calculate the energies of the photons responsible for these e
   b) What do these emission lines tell us about the structure of an
   c) How does an absorption spectrum differ from an emission sp

2. A He^+ ion has a ground state of -54.4 eV, a first excited state of -1
   state of -6.0 eV, a third excited state of -3.4 eV and a fourth exci

   a) Draw a diagram showing these energy levels.

   b) A photon excites an electron to the third excited state.
      (i) Draw this process on your diagram.
      (ii) What is the energy of the photon in eV and J?

   c) A photon excites an electron to the fourth excited state. The
      second excited state, then falls to the first excited state and
      by emitting photons.
      (i) Draw this process on your diagram.
      (ii) Calculate the energies of all of the **emitted** photons in e
      (iii) Calculate the frequencies of all of the **emitted** photons i

2.2.4 Wave–particle duality

Light diffracting, refracting and reflecting shows that light is a wave. But as we sa
act as particles – the photoelectric effect is an example of light acting as particles

A french physicist, Louis de Broglie, thought that this might apply the other way a
traditionally thought of as particles could act as waves.

Experiment: Electron diffraction

It wasn't long before experiments were done to prove de Broglie correct.

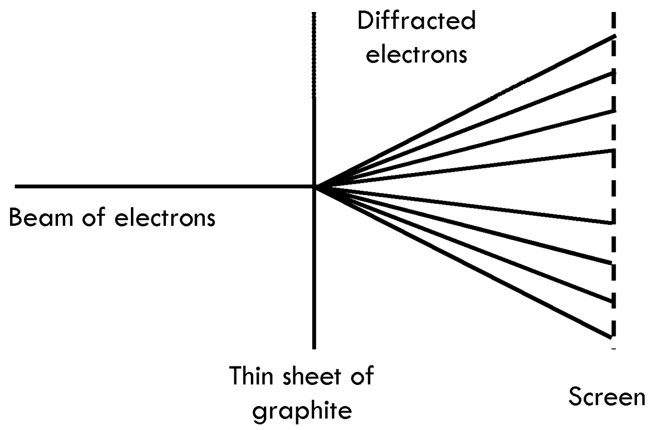
A beam of electrons was passed through the tiny gap between atoms, and was fo
of waves.

This is similar to light diffracting when it gets passed through a thin slit.

This is despite evidence of electrons acting as particles, such as in the photoelectri
electrons bend in magnetic fields.

Below shows the set-up of the experiment, and the pattern seen on the screen.

The multiple rings are caused by different-sized gaps between atoms diffracting
amounts.



The electrons in the beam that have been more diffracted have longer waveleng

de Broglie wavelength

A particle's de Broglie wavelength is related to its particle properties.

DB

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

So a particle with higher momentum, p, will have a shorter wavelength (and will g
diffraction occurs when the size of the gap the particle is diffracting through is si

This applies to all matter – all particles have a de Broglie wavelength and similarl
momentum.

Exam tip
Wavelengths of light are given in nm.
1 nm = 1×10^{-9} m.

Acceptance of wave–particle duality

Electrons had been discovered as particles in the late 19th century and light had b
17th century!

Treating light as particles and electrons as waves went against years of accepted s
even well-established theories are approached critically, with thorough evaluatio
theory.

All new scientific discoveries have to agree with experiments to be accepted by th
and must be peer reviewed before publication.

Scientific ideas such as quantum mechanics wouldn't have been able to progress
being an accepted theory.

Questions

1. a) Give examples of light acting as a particle and as a wave.
   b) Give examples of electrons acting as particles and as a wav

2. A photon has a wavelength of 6.3×10^{-7} m.
   a) What is this in nanometers?
   b) What is the momentum of this photon?

3. Calculate the de Broglie wavelength of an electron moving at 8
   The mass of an electron is 9.1×10^{-31} kg.

4. Calculate the speed of an electron with a de Broglie waveleng

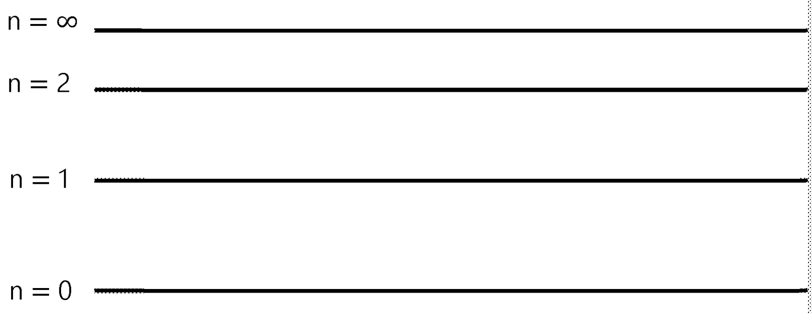
5. An electron and a muon are both travelling at 4.6×10^{7} m s^{-1}.
   The mass of an electron is 9.1×10^{-31} kg.
   The mass of a muon is 1.9×10^{-28} kg.

   a) Calculate the momentum for both.
   b) Calculate the de Broglie wavelength for both.
   c) In a diffraction experiment, which would be diffracted by a g

Exam style questions: Radiation

1. When ultraviolet light interacts with an atom, atomic electrons can be

The energy level diagram of an electron in a sodium atom is shown be



a) Explain why electrons are only given off when light above a speci

b) Calculate the minimum frequency of light required to ionise sodi
from the first excited state.

c) Discuss what would happen to the electrons in an atom if a photo
that required for ionisation were absorbed.

d) An electron in the first excited state of a sodium atom absorbs a p
Calculate the maximum velocity of this electron after the atom ha

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e) Explain how the ionisation of atoms by the absorption of light ca
theory of light and how the particle model of light provides a bet

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2. An electron is created via pair production.
The electron travels at 435 m s^{-1}.

a) State what is meant by the term pair production.

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b) Describe what happens to any other products of pair production
after their creation.

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c) The electron is diffracted through the space between atoms. Calculate the de Broglie wavelength of the electron.

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d) Explain how the diffraction pattern created by a muon travelling a diffracted would be different to that created by the electron.

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e) State how the pair production of a muon would be different to the electron.

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Answers

Chapter 1

1.1 Use of SI units and their prefixes

1. Kilogram, kg, mass.
   Metre, m, length.
   Second, s, time.
   Kelvin, K, temperature.
   Ampere, A, electric current.
   Mole, mol, amount of substance.

2. a) (i) 273 K (ii) 373 K (iii) 310 K
   b) (i) -123 ˚C (ii) 2 ˚C (iii) 95 ˚C

3. a) (i) 3.752 Gm $= 3.752 \times 10^9$m $=$ 3,752,000,000 m (ii) 2.8 ms $= 2.8 \times$
   (iii) 7.34 Mkg $= 7.34 \times 10^6$ kg $=$ 7,340,000 kg
   b) (i) 0.0000087 A $= 8.7 \times 10^{-6}$ A $=$ 87 µ A (ii) 28329 mol 28.329×1
   (iii) 24892000 kg $= 24.892 \times 10^6$ kg $=$ 24.892 Mkg

4. a) 2.083×10^{-6} J
   b) 3.125×10^{18} eV

5. a) $5.48 \times 60 \times 60 \times 1000 = 19.7$ MJ
   b) $3\,600\,000 \times 0.08 = 288\,000$ J
   c) $10 \times 0.0800 = 0.800$ p

1.2 Limitation of physical measurements

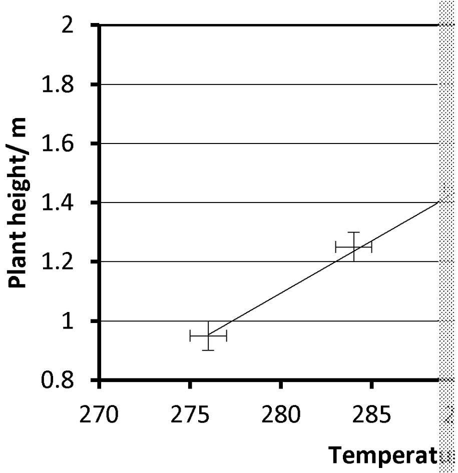
1. 0.005 g

2. $\text{Percentage uncertainty} = \frac{0.005}{17.53} \times 100\ \% = 0.03\ \%$

3. Systematic – markers may be incorrectly placed, timer may be fast/slow
   Random – ball may be dropped at an angle / with spin, delays in pressing timer, inc
   marker, wind, ball dropped from wrong height

4. $\text{Area} = 15.07 \times 14.7 = 221.5$ m²
   $\text{Error} = \frac{0.02}{15.07} \times 100\ \% + \frac{0.1}{14.7} \times 100\ \% = 0.8$ %
   $\text{Area} = 222$ m² $\pm\ 0.81\ \%$

5. gradient $= 0.035$
   max gradient $= 0.040$
   min gradient $= 0.032$
   $\frac{|0.035-0.040|}{0.035} \times 100\ \% = 14\ \%$
   $\text{gradient} = 0.035 \pm 14\ \%$



1.3 Estimation of physical quantities

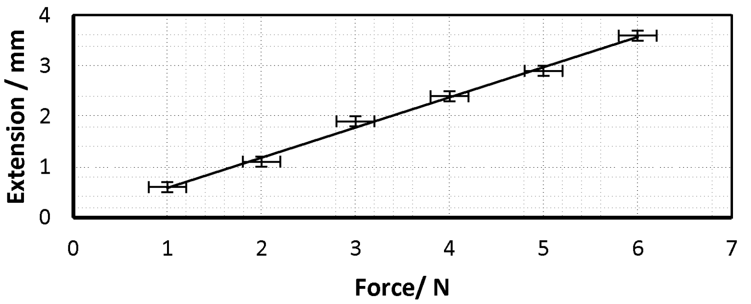
1. a) 10^{3}
   b) 10^{-3}
   c) 10^{4}

2. $\frac{10\times10^{-1}\times10^{3}\times10^{-2}}{10\times10^{4}} \rightarrow 1-1+3-2-(1+4)=-4$

   Order of magnitude $= 10^{-4}$
   Actual value 1.6×10^{-4}
   ∴ Order of magnitude gives close estimate of true value

3. $Force \sim \frac{10^{-10}\times10^{25}\times10^{30}}{(10^{11})^{2}} \rightarrow -10+25+30-(11\times2)=23$
   Force~ 10^{23} N

Exam style questions

1a	N m^{-1} ✓
1b	Axes labelled correctly and units ✓ Points placed correctly ✓ Line of best fit ✓ Error bars drawn correctly ✓ 
1c	Stiffness = gradient ✓ $\text{Gradient} = \frac{\text{Change in y}}{\text{Change in x}} = \frac{3.55-0.60}{6.00-1.00}$ $\text{Gradient} = 0.59$ ✓ Error in gradient = |best fit gradient – worst fit gradient| Error in gradient = |0.59 – 0.64| (from steepest gradient) Error in gradient = $\pm$ 0.05 ✓ ($k = 0.59 \pm 0.05$ N m^{-1})
1d	Repeat experiment ✓ Take more data ✓ Equipment with better resolution ✓
2a	$g = \frac{v_2 - v_1}{t}$ $g = \frac{8.46-1.87}{1.03}$ ✓ $g = 6.40$ m s^{-2} ✓ Uncertainty in $v_2 - v_1 = 0.01 + 0.01 = 0.02$ $v_2 - v_1 = 6.59 \pm 0.02$ m s^{-1} $\text{Uncertainty in } g = \left(\frac{0.02}{6.59}\times 100\ \%\right) + \left(\frac{0.05}{1.03}\times 100\ \%\right)$ ✓ Uncertainty in $g = 5.16\ \%$ ✓
2b	Systematic error ✓ Possible improvements: ✓ • e.g. Replace/recalibrate equipment • e.g. Swap paper ball for one less affected by air resistance
2c	Data which does not fit with the other data from the experiment ✓
2d	Disregard third measurement ✓ $g_{average} = \frac{9.43 + 10.02 + 9.55}{3}$ $g_{average} = 9.67$ m s^{-2} ✓
2e	Second set more accurate (closer to accepted value of 9.81 m s^{-2}) ✓ Second set more precise (lower uncertainty) ✓

Chapter 2

2.1 Particles

2.1.1 Constituents of the atom

1. a) Protons = 79, Neutrons = 118, Electrons = 79
   b) Protons = 53, Neutrons = 74, Electrons = 53
   c) Protons = 18, Neutrons = 22, Electrons = 18
   d) Protons = 29, Neutrons = 34, Electrons = 27

2. a) Proton b) Electron c) Neutron

3. a) $\text{specific charge} = \frac{\text{charge}}{\text{mass}} = \frac{8 \times 1.60 \times 10^{-19}}{16 \times 1.66 \times 10^{-27}} = 4.82 \times 10^{7}\ \text{C kg}^{-1}$
   b) $\text{specific charge} = \frac{\text{charge}}{\text{mass}} = \frac{20 \times 1.60 \times 10^{-19}}{40 \times 1.66 \times 10^{-27}} = 4.82 \times 10^{6}\ \text{C kg}^{-1}$

2.1.2 Stable and unstable nuclei

1. a) True
   b) False: The strong force affects hadrons, which can either be charged (like the p
   neutron). There are also particles that are charged but not hadrons, like electr
   strong force.
   c) True
   d) False: The strong force is responsible for holding the nucleus together, but the
   electrons to the nucleus.

2. a) Gamma b) Alpha c) Beta d)

3. Alpha – $^{215}_{84}\text{Po} \rightarrow \mathbf{^{211}_{82}Pb} + \boldsymbol{\alpha}$ $\mathbf{^{211}_{82}Pb}$
   Beta – $^{215}_{84}\text{Pb} \rightarrow \mathbf{^{215}_{83}Bi} + \boldsymbol{\beta^{-}} + \boldsymbol{\bar{\nu}_e}$

4. $\text{specific charge} = \frac{\text{charge}}{\text{mass}} = \frac{2 \times 1.60 \times 10^{-19}}{4 \times 1.66 \times 10^{-27}} = 4.82 \times 10^{7}\ \text{C kg}^{-1}$

5. $^{235}_{92}\text{U} \rightarrow {}^{231}_{90}\text{Th} \rightarrow {}^{231}_{91}\text{Pa} \rightarrow {}^{227}_{89}\text{Ac} \rightarrow {}^{223}_{87}\text{Fr} \rightarrow \mathbf{^{223}_{88}Ra}$ (Radium)

2.1.3 Particles, antiparticles and photons

1. a) $f = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{730 \times 10^{-9}} = 4.10 \times 10^{14}$ Hz
   b) $\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{5.00 \times 10^{12}} = 60.0\ \mu\text{m}$

2. a) $E = hf = 6.63 \times 10^{-34} \times 4.1 \times 10^{14} = 2.72 \times 10^{-19}$ J
   b) $E = hf = 6.63 \times 10^{-34} \times 5.00 \times 10^{12} = 3.31 \times 10^{-21}$ J

3. a) $E = \frac{1.50 \times 10^{-10}}{1.60 \times 10^{-19}} = 938$ MeV
   b) $E = 103 \times 1.60 \times 10^{-19} = 1.65 \times 10^{-17}$ J

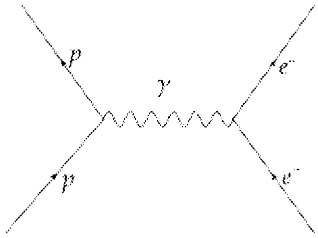
4. a) $E =$ rest energy = 0.51 MeV
   0.51 MeV = 8.17×10^{-14} J
   b) $f = \frac{E}{h} = \frac{8.17 \times 10^{-14}}{6.626 \times 10^{-34}} = 1.23 \times 10^{20}$ Hz

5. a) $E = hf = 500$ nJ = 3.12 GeV
   b) $\frac{3.12\ \text{GeV}}{2}$ = 1.56 GeV
   kinetic energy = total energy − rest energy = $1.56 \times 10^{9} - 938 \times 10^{6}$ = 622 Me

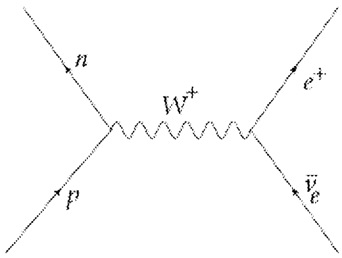
2.1.4 Particle interactions

1. Electromagnetic force only affects charged particles – neutrons and neutrinos are n
   Strong force only affects hadrons – electrons and neutrinos aren't hadrons

2.



3.



4. a) W bosons
   b) Photon
   c) Photon

5. a) Electromagnetic, weak, gravity
   b) Strong, weak, gravity
   c) Strong, weak
   d) Weak, strong

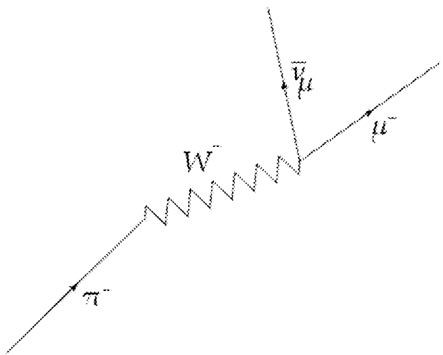
2.1.5 Classification of particles

1.

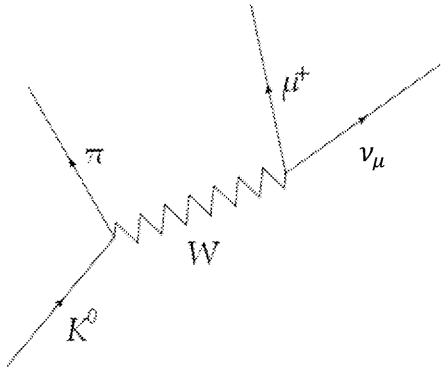
	Charge	Lepton number	Baryon number
K⁺	+1	0	0
ν_e	0	+1	0
p	+1	0	1
n̄	0	0	-1
e⁻	-1	+1	0
π^0	0	0	0
μ^+	+1	-1	0

2. a) False – neutrinos are uncharged leptons
   b) False – antibaryons have baryon number -1
   c) False
   d) True
   e) False – baryons are hadrons but not mesons

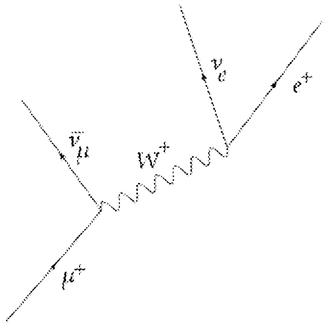
3.



4.



5.

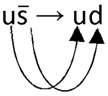


2.1.6 Quarks

1. a) Baryon number = +1, strangeness = 0, charge = +1
   b) Baryon number = 0, strangeness = +1, charge = +1
   c) Baryon number = -1, strangeness = +1, charge = +1

2. uss

3. $u\bar{s} \rightarrow u\bar{d} + u\bar{d} + d\bar{u}$



d/$\bar{d}$ and u/$\bar{u}$ produced as antiparticle pairs

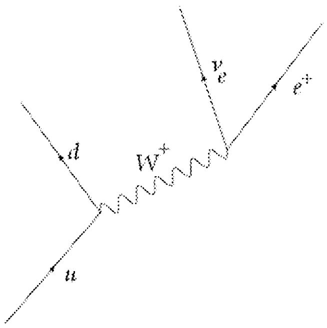
2.1.7 Conservation laws

1.	a)	Before Q=0, B=1, L=1, S=0	After Q=0, B=0, L=0, S=0	Bary cons
	b)	Before Q=2, B=2, L=0, S=0	After Q=2, B=2, L=0, S=0	Allov
	c)	Before Q=-1, B=0, L=1, S=0	After Q=-1, B=0, L=-1, S=0	Lepto allov
	d)	Before Q=0, B=0, L=0, S=0	After Q=0, B=2, L=0, S=0	Bary allov
	e)	Before Q=0, B=1, L=1, S=0	After Q=0, B=1, L=1, S=0	Allov

2. Need to create a proton and an antiproton (extra energy = 1.876 GeV). All kinetic en therefore kinetic energy of this proton = 1.876 GeV. Charge, baryon number, lepton conserved.

3. **X**, Q=0, B=1,L=0 **Y**, Q=-1, B=-1, L=0 **Z**, Q=

4.



Exam style questions

1a	Protons: 98 Neutrons: 147 ✓	1
1b	$\text{specific charge} = \frac{\text{charge}}{\text{mass}}$ $\text{specific charge} = \frac{98 \times 1.6 \times 10^{-19}}{245 \times 1.66 \times 10^{-27}}$ ✓ $\text{specific charge} = 3.86 \times 10^{7}$ C kg^{-1} ✓	
1c	$X + 4 = 245 + 1$ $X = 242$ ✓ $Y + 2 = 98 + 0$ $Y = 96$ ✓	N C
1d	To account for missing momentum (in β decays) ✓	
1e	Weak force ✓ (Can't be strong force) because non-hadrons involved ✓ (Can't be electromagnetic) because uncharged particles involved ✓	
1f	$97 = 89 + 5 \times 2 - X \times 1$ ✓ $X = 2$ ✓	
2a	Hadron ✓ (Containing) a quark and an antiquark ✓	
2b	Charge $= -1$, $Q_{\overline{u}} = -\frac{2}{3}$, $Q_s = -\frac{1}{3}$, $Q_{\overline{u}} + Q_s = -1$ ✓ Baryon number $= 0$, $B_{\overline{u}} = -\frac{1}{3}$, $B_s = \frac{1}{3}$, $B_{\overline{u}} + B_s = 0$ ✓ Lepton number $= 0$, $L_{\overline{u}} = 0$, $L_s = 0$, $L_{\overline{u}} + L_s = 0$ ✓ Strangeness $= -1$, $s_{\overline{u}} = 0$, $s_s = -1$, $s_{\overline{u}} + s_s = -1$ ✓	N
2c	Conserved: baryon number, lepton number, charge ✓✓ Not conserved: strangeness ✓	M
2d	Weak force ✓	
2e	Electron antineutrino, $\overline{\nu}_e$ ✓	

2.2.1 The photoelectric effect

1. UV light has shorter wavelength / higher frequency, therefore more energy – over t
   Red light longer wavlength / shorter frequency, therefore less energy – below thres
   More intense red – no change (i.e. no electrons released).
   More intense UV – higher current – more electrons released.

2. a) $E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{480 \times 10^{-9}} = 4.14 \times 10^{-19}$ J
   b) $f = \frac{E}{h} = \frac{8.90 \times 1.6 \times 10^{-19}}{6.626 \times 10^{-34}} = 2.15 \times 10^{15}$ Hz $= 2150$ THz

3. a) (i) $\Phi = hf = 6.626 \times 10^{-34} \times 1120 \times 10^{12} = 7.42 \times 10^{-19}$ J
   (ii) $\frac{7.42 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.64$ eV
   b) $E_{k(\max)} = \text{E} - \Phi = 7.28 - 4.64 = 2.64$ eV

4. a) 5.15 eV $\times 1.6 \times 10^{-19} = 8.24 \times 10^{-19}$ J
   b) $f_0 = \frac{\Phi}{h} = \frac{8.24 \times 10^{-19}}{6.626 \times 10^{-34}} = 1.24 \times 10^{15}$ Hz $= 1240$ THz
   c) $E = hf = 6.626 \times 10^{-34} \times 1810 \times 10^{12} = 1.20 \times 10^{-18}$ J
   $E_{k(\max)} = E - \Phi = 1.20 \times 10^{-18} - 8.24 \times 10^{-19} = 3.76 \times 10^{-19}$ J$= 2.35$ eV

2.2.2 Collisions of electrons with atoms

1. a) Both b) Ionisation c) Both d) Excitation e) Both

2. a) Electron is deflected
   b) Electron loses 2.5 eV of kinetic energy, continues with 1.4 eV of kinetic energy
   c) Electron loses all its kinetic energy

3. The hydrogen atom loses an electron i.e. it is ionised. Electron loses 13.6 eV and co

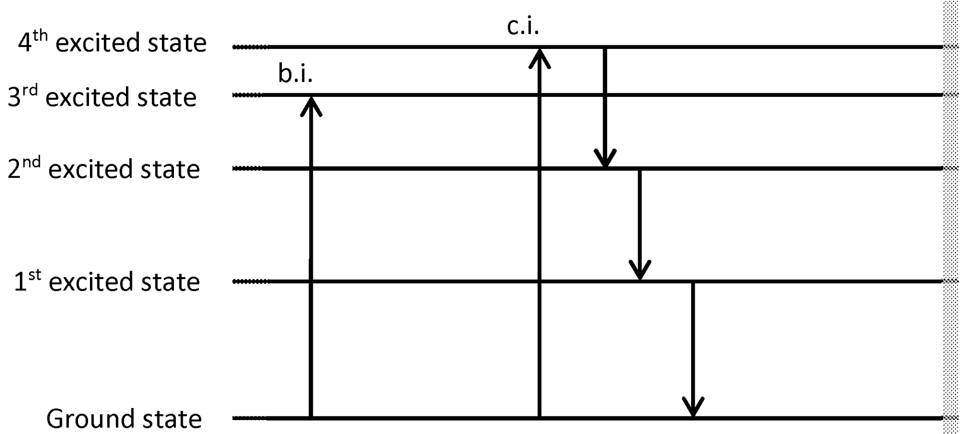
2.2.3 Energy levels and photon emission

1. a) $E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-24} \times 3 \times 10^{8}}{687 \times 10^{-9}} = 2.89 \times 10^{-19}$ J

   $E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-24} \times 3 \times 10^{8}}{780 \times 10^{-9}} = 2.55 \times 10^{-19}$ J

   b) Oxygen has energy levels that are 2.89 x 10^{-19} J and 2.54 x 10^{-19} J apart. This co state, or combinations of 3 or more excited states.
   c) Absorption – all wavelengths of light apart from those relating to energy levels wavelengths relating to energy levels present. Emission – electrons must be fir original excitation.

2. a)



   b) (i) See diagram (ii) $-54.4 - 3.4 = -51.0$ eV $= -8.16 \times 10^{-19}$ J
   Negative sign means photon is absorbed. Energy

   c) (i) See diagram
   (ii) 4th – 2nd state = 3.8 eV $= 6.1 \times 10^{-19}$ J
   2nd – 1st state = 7.6 eV $= 1.2 \times 10^{-19}$ J
   1st – ground = 40.8 eV $= 6.5 \times 10^{-18}$ J
   (iii) 4th – 2nd $= f = \frac{E}{h} = 920$ THz
   2nd – 1st $= f = \frac{E}{h} = 1800$ THz
   1st – ground $= f = \frac{E}{h} = 9900$ THz

2.2.4 Wave–particle duality

1. a) Light as a particle – photoelectric effect
   Light as a wave – refraction, diffraction, reflection
   b) Electron as a particle – photoelectric effect, beams bending in magnetic fields
   Electron as a wave – diffraction

2. a) 6.3×10^{-7} m $= 630 \times 10^{-9}$ m $= 630$ nm
   b) $mv = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{630 \times 10^{-9}} = 1.05 \times 10^{-27}$ m kg s^{-1}

3. $\lambda = \frac{h}{mv} = \frac{6.626 \times 10^{-34}}{9.1 \times 10^{-31} \times 8 \times 10^{6}} = 91$ pm

4. $v = \frac{h}{m\lambda} = \frac{6.626 \times 10^{-34}}{9.1 \times 10^{-31} \times 7.5 \times 10^{-12}} = 9.7 \times 10^{7}\ \mathrm{m\ s^{-1}}$

5. a) Electron, $p = mv = 4.6 \times 10^{7} \times 9.1 \times 10^{-31} = 4.2 \times 10^{-23}\ \mathrm{kg\ m\ s^{-1}}$
   Muon, $p = mv = 4.6 \times 10^{7} \times 1.9 \times 10^{-28} = 8.7 \times 10^{-21}\ \mathrm{kg\ m\ s^{-1}}$
   b) Electron, $\lambda = \frac{h}{p} = \frac{6.626 \times 10^{-34}}{4.2 \times 10^{-23}} = 1.6 \times 10^{-11}$ m
   Muon, $\lambda = \frac{h}{p} = \frac{6.626 \times 10^{-34}}{8.7 \times 10^{-21}} = 7.6 \times 10^{-14}$ m
   c) Electron will be diffracted more – less momentum, longer de Broglie waveleng

Exam-style questions

1a	Photon frequency proportional to energy ✓ (Below minimum frequency) not enough energy to overcome binding energy of electron ✓	
1b	E = hf f = E/h $f = \frac{3.76 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}}$ ✓ $f = 9.07 \times 10^{14}$ Hz ✓	
1c	Electron would move to higher energy level ✓ If the energy exceeded the gap between energy levels ✓	A
1d	$E_e = E_\gamma - E_{n=1}$ $E_e = 3.84$ eV $E_e = 6.14 \times 10^{-19}$ J ✓ $E_e = \frac{1}{2}mv^2$ $v = \sqrt{\frac{2E_e}{m}} = \sqrt{\frac{2 \times 6.14 \times 10^{-19}}{9.11 \times 10^{-31}}}$ ✓ $v = 1.16 \times 10^{6}$ m s^{-1} ✓	
1e	Electrons given off instantaneously ✓ Electrons given off above minimum frequency ✓ Energy of electrons doesn't vary with intensity of light ✓	
2a	A particle-antiparticle pair ✓ Created by a photon ✓	
2b	(Positron) moves off with equal magnitude and opposite direction velocity to electron ✓ (Positron is) annihilated after interacting with another electron ✓	
2c	$\lambda = \frac{h}{mv}$ $\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 435}$ ✓ $\lambda = 1.67 \times 10^{-6}$ m ✓	
2d	Muon has a higher mass, so higher momentum (and smaller de Broglie wavelength) ✓ (Muon diffraction pattern would have) less spacing between fringes ✓	
2e	Photon of higher energy required ✓ Antimuon would be produced (instead of positron) ✓	