1 MEASURING THE UNIVERSE

PRIOR KNOWLEDGE

You will have carried out experiments and made measurements in your previous studies of science, so you will know something about scientific method.

LEARNING OBJECTIVES

In this chapter you will find out how to get a rough idea of atomic size by a simple experiment. You will learn about physics experiments and measurements in general: what units to use and how they are defined; how errors can occur; and how to estimate the uncertainty in your experimental results.

(Specification 3.1.1, 3.1.2, 3.1.3, 3.2.1.1 part)

One of the big questions in physics is: "What is the Universe made of?" Until 1998, most physicists would have said "matter and energy" and been reasonably confident what that meant. "How much matter and energy?" seemed the more pertinent question (Figure 1). Albert Einstein had shown that mass and energy are interchangeable. Their combined amount determines the 'energy density' of our Universe, a quantity that will decide its ultimate fate.

In 1929 Edwin Hubble published measurements that showed that the Universe was expanding. Physicists knew that gravity would act to slow the rate of expansion. If the energy density was low, then the Universe would keep expanding, but at a slower and slower rate. A high value of energy density would eventually stop the expansion, and the Universe would begin to contract, eventually ending in a 'Big Crunch'.

In 1998 observations of distant supernovae showed that the expansion was not slowing at all, but speeding up. The measurements were reproduced by independent research teams, some using different methods. These results suggested that something unknown must be pushing the Universe apart. This is now called 'dark energy' and it seems to make up almost 70% of the Universe. Much of the remaining 30% is also mysterious. Work by Vera Rubin in the 1970s on the rotation of galaxies had shown that there must be a significant amount of mass in the Universe that we cannot observe – now known as 'dark matter'. Current thinking is that the Universe contains a mere 4.9% 'ordinary' matter and energy, and researchers are aiming to discover what the mysterious 'dark' quantities might be.

Physicists are often labelled either theoretical or practical. Einstein was firmly in the theoretical camp. Saul Perlmutter shared the 2011 Nobel Prize for practical measurements of the expansion rate of the Universe. Both aspects of physics are equally important. As Robert Millikan (Nobel Prize winner in 1923 for his work on the elementary charge) put it:

"Physics walks forward on two feet, namely theory and experiment. … Sometimes it is one foot first; sometimes the other, but continuous progress is only made by the use of both."

Figure 1 (background) How much matter and energy is there in the Universe? This Hubble Ultra Deep Field view taken by the Hubble Space Telescope shows a vast number of distant galaxies.

1.1 MEASUREMENT IN PHYSICS

Towards the end of the 20th century, just before the discoveries of dark matter and dark energy, it was suggested that the 'big questions' in physics had been answered. In a remarkably similar way 100 years earlier, some eminent physicists felt that physics was almost complete. Newton's laws described forces and motion, Faraday had linked electricity and magnetism, and Maxwell's equations described electromagnetic waves. Michelson, famous for measurements of the speed of light, went as far as to say:

"The more important fundamental laws and facts of physical science have all been discovered, the possibility of their ever being supplanted (by) new discoveries is exceedingly remote."

But then, as now, physics was turned upside down by experimental discoveries. Radioactive decay, for example, proved hard to explain for 19th century scientists, who were still arguing about whether atoms really existed. Observations, measurements and the analysis of recorded data provide the basis for discoveries and advancement in physics.

1.2 THE SCALE OF THINGS

Scientific notation

Physicists investigate matter and energy in the Universe on every scale, from infinitesimally small measurements of subatomic particles to unimaginably large ones, like galaxies. These measurements generate very large and very small numbers. We need a concise way of writing these numbers, to avoid strings of zeros across the page. Large numbers are written as a number between 1 and 10, multiplied by a power of 10. For example, the speed of light, $c = 300\,000\,000\,\mathrm{m\,s^{-1}}$, can be written as $3.0 \times 10^8\,\mathrm{m\,s^{-1}}$. In a similar way, small numbers are written as a number between 1 and 10, multiplied by a negative power of 10. In this way the wavelength of red light, $\lambda = 0.000\,000\,650\,\mathrm{m}$, would be written as $\lambda = 6.50 \times 10^{-7}\,\mathrm{m}$. This method of writing large or small numbers is known as **scientific notation**, often referred to as **standard form** in the UK.

It is usual to use powers of 10 that go up in steps of 1000, or 10^3, so the wavelength of the red light would probably be written as 650×10^{-9} m. When using SI units (Système International d'Unités) (see the next subsection), the powers of 10^3, 10^6, 10^9 and so on are given names, such as kilo or mega. These have abbreviations used as prefixes, so a distance of 1000 m (10^3 m) is known as a kilometre and is written 1 km. The names and prefixes that you may come across at AS and A-level are shown in Table 1.

QUESTIONS

1. Satellite TV signals are transmitted on a frequency of 27 000 000 Hz. Rewrite this number using scientific notation.
2. The mean distance from the Earth to the Sun is about 149 600 000 km. Rewrite this in scientific notation. (*Careful!* The distance is given in km in the question.)
3. How long does it take light to travel across the room you are in? (Distance = speed × time, speed of light = $3.0 \times 10^8\,\mathrm{m\,s^{-1}}$.)

Multiplication factor		Prefix	Symbol	Example length
1000 000 000 000	10^{12}	tera	T	Radius of Pluto's orbit (5.9 Tm)
1000 000 000	10^{9}	giga	G	Mean Earth–Moon distance (0.4 Gm)
1000 000	10^{6}	mega	M	Mean radius of Earth (6.37 Mm)
1000	10^{3}	kilo	k	Distance from Manchester to London (320 km)
0.001	10^{-3}	milli	m	Microwave wavelength (~mm)
0.000 001	10^{-6}	micro	μ	Wavelength of visible light (~μm)
0.000 000 001	10^{-9}	nano	n	Approximate atomic diameter (~nm)
0.000 000 000 001	10^{-12}	pico	p	Wavelength of a gamma ray (~pm)
0.000 000 000 000 001	10^{-15}	femto	f	Approximate diameter of an atomic nucleus (~fm)
0.000 000 000 000 000 001	10^{-18}	atto	a	Range of weak nuclear force (~am)

Table 1 *SI prefixes and symbols*

Choosing the units

Physics describes the world in terms of the values of physical quantities. A physical quantity is something that can be measured, such as speed, energy or mass. Each measurement needs a unit, a standard value that is well defined. Giving your height as '1.65' means nothing, but giving it as 1.65 metres makes it clear. The numerical value of a measurement depends on the unit that is used (Figure 2).

Figure 2 *Your mass might be 56, 8.8, 123 or 1.1, depending on whether you measured it in kilograms, stones, pounds or hundredweight. British school science lessons have not used imperial units (feet, stones, pounds and so on) since the early 1970s, but most students still give their height in feet and inches.*

Units were often chosen in the past to be a convenient size for the measurement, like the 'grain' (64.8 mg) traditionally used for the mass of medicines and gunpowder, or the carat (200 mg) used for precious stones. But it is awkward to have many different units for each physical quantity. Every unit has to be defined in terms of a standard, so that the entire world can agree on its magnitude. It is not feasible to maintain several standard definitions for each physical quantity like length or mass, and there is the problem of converting between units, which has been known to have disastrous results (Figure 3).

The Système International d'Unités (**SI**) for defining units of measurement was established in 1960 and is now almost universally accepted, by the scientific world at least. SI units are defined in terms of seven **base units**. These are shown in Table 2. All other units, known as **derived units**, can be defined in terms of these base units.

Figure 3 *In 1999, the Mars Climate Orbiter probe was destroyed because one of the control systems used imperial units (feet and inches), but the navigation software used metric (SI) units.*

Base quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 2 *SI base units*

The base units are now almost all defined in terms of physical constants. For example, a length of one metre is defined in terms of the speed of light:

One metre is the length of the path travelled by light in vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second.

This rather arbitrary time is chosen to match the older definition of the metre. This modern definition of length depends on specialised equipment, but in principle every country can have the same standard metre. However, we also need an independent definition of the second.

> One second is the time taken for 9 192 631 770 complete oscillations of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.

The atomic clocks on the satellites that make up the Global Positioning System (GPS, Figure 4) are stable to 1 part in 10^{12}; in other words, they are accurate to within 1 second in 32 000 years.

The only base unit not yet defined in terms of a universal constant is the kilogram. This is still defined as the mass of a particular cylinder of platinum–iridium alloy, the International Prototype Kilogram (IPK), which is kept in a vault in Paris.

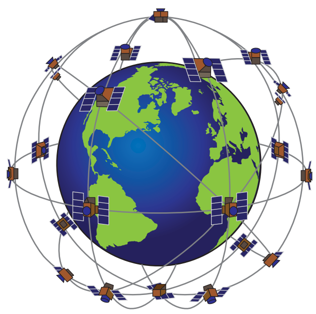


Figure 4 *To use the GPS system, the receiver must be able to see a minimum of four satellites.*

The kilogram is also the only base unit with kilo in its name. Logically, the base unit of mass should be the gram, but a historical quirk meant that the kilogram was chosen. This is important for calculations. If you need to put a value of mass into an equation, you must use kilograms, so a mass of one kilogram = 1 kg, whereas a mass of one gram = 1×10^{-3} kg.

QUESTIONS

4. The IPK is kept in a controlled atmosphere, and is only rarely taken from its vault. Why?

5. The IPK is a right-circular cylinder (height = diameter) of 39.17 mm. Why this shape and why is the choice of metal important?

6. Use the formula density $= \dfrac{\text{mass}}{\text{volume}}$ to find the density of the standard (IPK) kilogram. The SI derived unit for density is kg m^{-3}. Remember that 1 mm = 1×10^{-3} m, so 1 mm^3 = 1×10^{-9} m^3.

7. The earliest units for length were based on the human body, for example the cubit in ancient Egypt was defined as the distance from the tip of the forefinger to the elbow. Give an advantage, and a disadvantage, of this system.

8. The speed of light is now exactly 299 792 458 m s^{-1}. Why 'now' and why 'exactly'?

Units for all the other physical quantities, such as velocity, acceleration, force and energy, are derived from these base units. For example, the unit for velocity is metre per second (m s^{-1}). Derived units are sometimes given names, like newton (N) for force, and joule (J) for energy. As a rule the named unit is written in full with a lower-case initial letter, but the abbreviation begins with an upper-case letter. For example, the SI unit for frequency is the hertz, abbreviated to Hz.

All named derived units can be expressed in terms of the base units. For example, one newton is defined as the force that will accelerate a mass of one kilogram by one metre per second, every second. This definition can be represented by the equation $F = ma$.

As the units have to be the same on both sides of this, or any other, equation (you could not have metres = kilograms, for example), then, in terms of units, $F = ma$ becomes

$$1\,\text{N} = 1\,\text{kg} \times \frac{1\,\text{m}}{(1\,\text{s} \times 1\,\text{s})} = 1\,\text{kg}\,\text{m}\,\text{s}^{-2}$$

QUESTIONS

9. One pascal (1 Pa) is the SI derived unit of pressure. Since pressure $= \dfrac{\text{force}}{\text{area}}$, write 1 Pa in terms of SI base units.

10. Express the joule in terms of base units. *Hint:* What equation links energy or work to other quantities?

Physicists do not always quite stick to the rules for using SI units. Sometimes it is just too clumsy to use the SI base unit. For example, the kilogram is rather large when it comes to the mass of an atom, so the atomic mass unit is used. The metre is too small for interstellar or intergalactic distances, so astronomers use light years or megaparsecs. You might have used kilowatt hours, rather than joules, to measure the electrical energy used in a house. It is of course possible to convert all these to the relevant SI unit.

In the assignment you can find a value for the size of an atom in metres.

ASSIGNMENT 1: FINDING A MAXIMUM SIZE FOR AN ATOM

(MS 0.1, MS 0.2, MS 2.3, MS 4.3, PS 1.1, PS 3.2)

There is a way to find a rough value for the size of an atom using ordinary school laboratory equipment. Olive oil, a very clean tray, a magnifying glass and scale, a ruler and some fine powder, such as lycopodium (this is pollen, a potential allergen) are needed.

The general idea is to let a small drop of olive oil fall onto the surface of some water (Figure A1). The drop will spread out into a very thin film. If the surface of the water is coated with powder first, it will allow the oil film to be seen more clearly.

The volume of the film will be the same as the volume of oil in the drop. In theory the film of oil should be a circle. (In practice it is not!) Imagine the film is roughly cylindrical in shape (a very thin cylinder). Then if the volume and the area of the film are known, its thickness can be calculated. The oil molecules cannot be bigger than this thickness, and an atom must be smaller still, so we can arrive at the maximum size for an atom.

Figure A2 is a scale drawing of typical results. If you are able to do this experiment yourself you can use your own results. Otherwise, use measurements from Figure A2.

A1 Find the volume of the drop (volume of sphere $= \frac{4}{3}\pi r^3$).

A2 Find the area of the film (area of circle $= \pi R^2$).

A3 Find the thickness of the film, h.

A4 An olive oil molecule is 10 atoms long. What is the maximum diameter for an atom in metres?

A5 What have you assumed in this calculation?

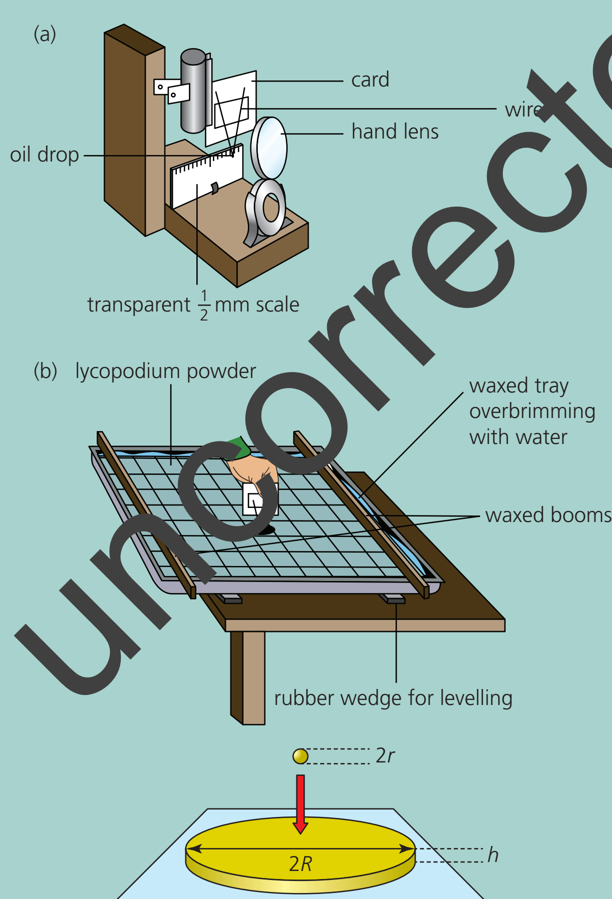


Figure A1 *The oil drop experiment*

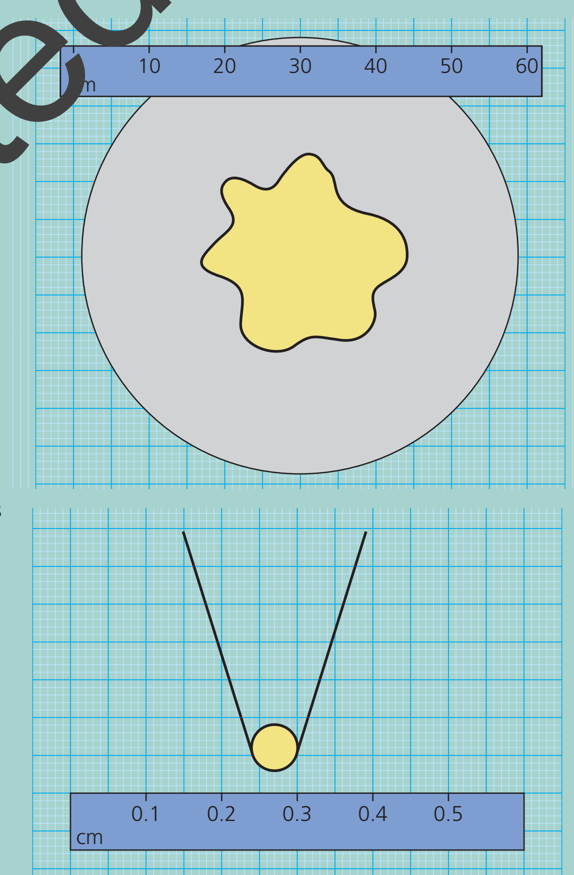


Figure A2 *Volume of the drop = volume of the oil film = area of the oil film × thickness of the film*

KEY IDEAS

- We use SI units. There are seven base units. All other units are derived from these.
- Large and small numbers are expressed in standard form, for example 3.0×10^8.
- Multiples of units in powers of 10 increasing in threes, e.g 10^3, 10^6, and so on, are given standard prefixes, for example, kilo (k), mega (M).

1.3 EXPERIMENTS IN PHYSICS

Experimental error

It is surprising that we can get an estimate for the size of an atom using such simple apparatus as that used in Assignment 1. After all, we have managed to measure something that is far too small to see. How do we know that our answer is right? What errors might we have made? Can we correct them, reduce them or at least account for them?

The term ‘experimental errors’ does not generally refer to the sort of blunders we all make from time to time, such as forgetting to connect the battery, misreading a scale or failing to take a reading at the right time. These are annoying, but repeating the experiment with more care usually solves the problem. Experimental errors fall into two types, random errors and systematic errors.

Random errors can cause readings to be too high or too low. Just as the name suggests, the readings fluctuate about the mean. Random errors may arise due to a number of different causes.

- Observation or reading errors: perhaps when timing the oscillations of a pendulum, or when trying to read the flickering needle on the dial an analogue meter.
- Environmental: perhaps the temperature of the room is fluctuating, or the supply voltage keeps changing.

The crucial thing about a random error is that it is equally likely to give you a result that is too high as one that is too low. Repeating the readings and calculating a mean value is useful because the more readings you have, the more the random fluctuations will be averaged out.

Systematic errors on the other hand lead to results that are consistently wrong. Repeating these readings is pointless, since the error occurs in the same way each time. Systematic errors may also occur due to a number of reasons.

- Instrument error: a poorly calibrated thermometer, for example, or a top-pan balance that has not been zeroed correctly.
- Reading error: perhaps due to parallax error (Figure 5) when reading the scale.
- Poor experimental design: for example, ignoring the effect of an external factor like magnetic field, temperature or pressure.

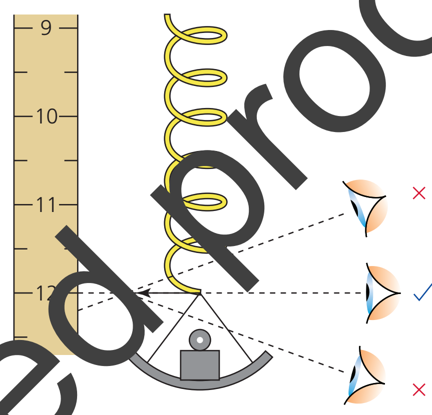


Figure 5 *Try to position your eye close to the scale and look in the correct direction to avoid parallax errors.*

Ernest Rutherford (Figure 6), who discovered the atomic nucleus, believed that experiments should have a clear outcome:

“If your experiment needs statistics, you ought to have done a better experiment.”

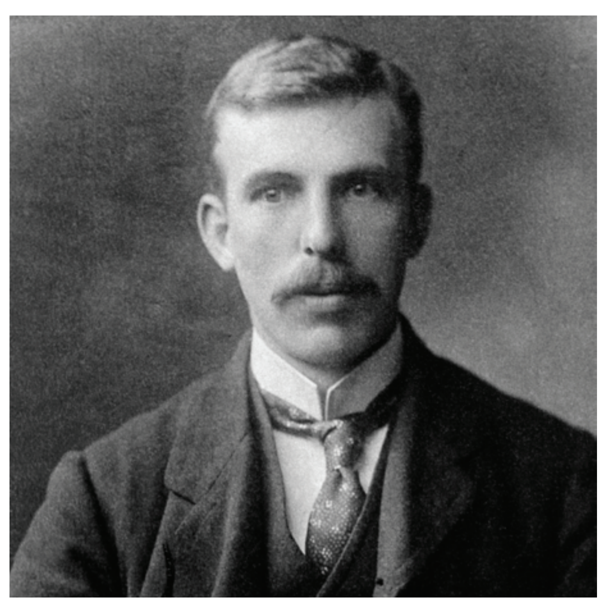


Figure 6 *Ernest Rutherford*

QUESTIONS

11. a. You intend to use a top-pan balance to find the mass of a particular ball bearing. Is it worth repeating the measurement several times and taking an average?

    b. Suppose you need to find the mass of a typical ball bearing. How would you make your result as accurate as possible?

12. When you are measuring the diameter of a wire, it is good practice to take readings at several points along the length of the wire. The readings should also be taken in different orientations. Explain why.

Accuracy, precision and uncertainty

How sure of our measurements can we be? This can be a difficult question to answer, especially if you happen to be one of the first to make the measurement. In practice, the experiment is repeated by the experimenter to check that it gives consistent results. If so, then the measurement is said to be **repeatable**. If other experimenters get similar results, preferably in different laboratories using different techniques, then the measurement is said to be **reproducible**.

A result is said to be **accurate** if it is close to the true value, that is the standard or accepted value. In exceptional cases, of course, the new measurement may not agree with the accepted value, because the accepted value is wrong. However, you need to be very sure before making a claim like that. The standard 'textbook' answer will have been repeated many times, probably in different laboratories and using different methods. If the new results prove to be repeatable and reproducible, it may mean that an established theory could be wrong (Figure 7).

'Precision' does not mean that the measurements are right, it merely tells you whether the results are numerically close together. For example, suppose that a measurement was made five times and the results were 3.223, 3.222, 3.223, 3.221 and 3.223. These results vary through a range of 0.002, from the lowest to the highest value recorded. The mean of the five readings is 3.222 (correct to four significant figures), so we can say that the **uncertainty** in this mean value due to the scatter of results is ±0.001. This seems a small uncertainty but it depends on the size of the measurement. We need to compare this uncertainty in the readings with the overall result by expressing it as a percentage. The percentage uncertainty is (0.001/3.222) × 100% = 0.031%. This is a very small percentage uncertainty, so the results could be said to be very precise. That does not mean that the results are correct or even accurate. They could all be wrong in the same way. Figure 8 gives a visual summary of the meanings of precision and accuracy.

Figure 7 *In 2011 physicists at the Gran Sasso laboratory in Italy measured the speed of neutrinos emitted by the accelerator at CERN and found they were travelling faster than the speed of light. Special relativity says it is impossible for a particle to reach the speed of light, as this would give it an infinite mass. Faster-than-light travel also raises the possibility of time travel. Physics professor Jim Al-Khalili promised to eat his boxer shorts on live TV if the measurements were shown to be right. In fact, the measurements were wrong … they were caused by a loose fibre optic cable!*

When recording your results, you should be careful not to overstate the precision by writing an excessive number of digits in your answer. Suppose three teachers have timed the school 100 m sprint race and have recorded times of 12.3, 12.5 and 12.6 s for the winner. The average time was 12.466 66 s. But each teacher's reading had an uncertainty of 0.1 s at least, and the range of their readings was 0.3 s, or ±0.15 s, so the result should be quoted to a similar level of precision: (12.5 ± 0.15) s is more reasonable but, since we usually err on the side of caution, (12.5 ± 0.2) s is probably appropriate.

On a similar theme, it would be a mistake to record this set of readings, all taken with the same equipment:

Time	*T* / s	1.214 1.20 0.800 0.5

If the readings are all made with the same precision, they should all be quoted to the same number of **significant figures**. The trailing zeros are important!

QUESTIONS

13. a. Describe a real situation where measurements could be precise, but not accurate.

b. Describe a real situation where measurements could be accurate, but not precise.

Some readings do not vary widely but are still not precise, simply because they are measured with a device with low **resolution**. The resolution of a measuring device is the smallest increment in the measured quantity that can be shown on the device. For example, you could find the mass of an object using a digital balance with a resolution of (that is, gives readings in) grams, tenths of grams, or hundredths of grams. Suppose you were using the balance that measured to the nearest gram to find the mass of a mango; your readings could be out by 0.5 g. In fact, it is worse than that because when you zeroed the balance, it could also have been out by 0.5 g. So your reading is said to have an uncertainty of ±1 g. As a rule of thumb you can estimate the uncertainty associated with taking a reading to be ± the smallest scale division.

Measurements should always be written with a value, the associated uncertainty and an appropriate unit, for example, mass of a mango = (142.3 ± 0.1) g. This is not too much of a problem, less than 0.1% uncertainty. But if you were finding the mass of a blackcurrant, you would probably want a balance with a higher resolution.

You can improve the precision of measurement of repeatable events, by just doing a lot of them. Galileo is said to have timed the oscillations of a pendulum (candelabras hung from the ceiling of a church) using his pulse as a time keeper. This is not a very high-resolution instrument. But by timing 10 oscillations he could share the uncertainty among all 10 oscillations, and arrive at a more precise answer.

Whether you are measuring the speed of neutrinos, or the area of an oil film, it is important to know how precise your result is. Every experimental result should be accompanied by an estimate of its uncertainty. For example, the currently accepted value for the mass of an alpha particle is given as

$$(6.644\,656\,75 \pm 0.000\,000\,29) \times 10^{-27}\ \text{kg}$$

sometimes written as

$$6.644\,656\,75(29) \times 10^{-27}\ \text{kg}$$

The numbers in brackets indicate the uncertainty in the last two digits. That is a high-precision measurement, an uncertainty of 29/664 465 675, or less than 5×10^{-6}%. That is equivalent to knowing the distance from London to New York to within 25 cm.

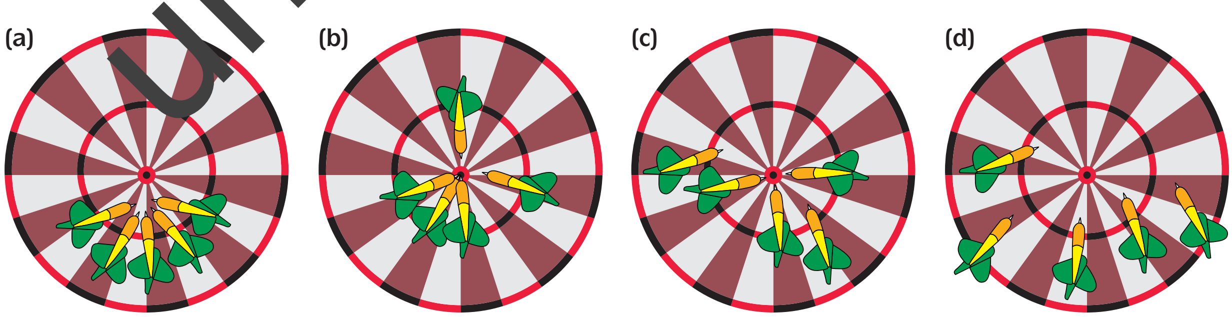


Figure 8 *Precision and accuracy: (a) precise but not accurate; (b) precise and accurate; (c) accurate but not precise; (d) neither accurate nor precise.*

QUESTIONS

14. Estimate the resolution of Galileo's time keeper. Suppose the candelabra took 2 s to complete one oscillation. What would Galileo's result be if he timed one oscillation? What would the uncertainty be? What would the percentage uncertainty be? How would these answers be changed if he now timed 10 oscillations and used that to calculate the time for one oscillation?

15. If you did not have a high-resolution balance, how could you find the mass of a blackcurrant more precisely? (Assume that you have a large number of blackcurrants to hand!)

16. Suppose you took three oranges and found their mean mass, using a balance with a resolution of 0.1 g. Why would it be wrong (and certainly misleading) to write your answer as 121.333 333 g ? How would you write it?

17. a. What is the uncertainty associated with measuring the width of this book? (Suppose that you used a 30 cm ruler with mm divisions.) Write your answer as result ± uncertainty, followed by the correct unit.

b. Why is the uncertainty more of a problem if I asked you to use the same ruler to measure the thickness of the book?

c. How would you find the thickness of one page of this book? How precise do you think you could be?

KEY IDEAS

- Experimental errors can be systematic. These tend to affect all readings in the same way. Repeating the readings does not help. Try to improve the method.
- Experimental errors can be random. These fluctuate above and below the mean value. Repeated readings will improve the precision of these readings.
- No measurement of a physical quantity is ever exact. There is always an uncertainty associated with it.
- An accurate measurement is one that is close to the accepted value.
- A precise set of measurements are closely grouped together, with little spread or uncertainty.

1.4 COMBINING UNCERTAINTIES

The final result of an experiment is often a combination of several measurements. That means that the overall uncertainty will depend on a combination of the precision of each measurement.

What if you are *adding* or *subtracting* two quantities? The general rule is:

If you are adding or subtracting quantities, you need to add their absolute uncertainties.

An absolute uncertainty is the actual possible deviation from the mean value, in the unit of measurement. Finding the difference of two measurements can lead to large *percentage* uncertainties.

Worked Example 1

In a situation like that in Figure 9, we might have these readings:

Reading A : Mass of bowl $= (200 \pm 1)\,\text{g}$, which is a percentage uncertainty of 0.5%.

Reading B: Mass of bowl *and* flour $= (220 \pm 1)\,\text{g}$, a percentage uncertainty of $\approx 0.5\%$.

$$\begin{aligned}\text{Mass of flour} &= \text{reading B} - \text{reading A}\\ &= (20 \pm 2)\,\text{g}\end{aligned}$$

The uncertainty in this difference between two measured values is 2 g since reading B might be higher by 1 g and reading A might be lower by 1 g, and vice versa. The percentage uncertainty is now 10% (compared with 0.5% in the measured values).

Figure 9 *Finding a difference in two quantities, for example finding the mass of sugar in a bowl, can lead to large percentage uncertainties.*

What if you are *dividing or multiplying* two quantities? Suppose you have been given a small metal cube, which you suspect is made of lead. You might decide to measure the density of the cube to see if it could indeed be lead. The density of a material is defined as the mass of a given volume. In SI units this should be measured in kilograms per cubic metre, but grams per cubic centimetre is also commonly used. Lead has a density of $11.34\,\mathrm{g\,cm^{-3}}$.

As density equals mass divided by volume, $\dfrac{\text{mass}}{\text{volume}}$ you might begin by using a top-pan balance to measure the mass, and a ruler marked in millimetres to measure the dimensions of the cube.

Mass of metal cube = (89 ± 1) g

Length of metal cube = (2.1 ± 0.1) cm

Width of metal cube = (1.9 ± 0.1) cm

Depth of metal cube = (2.1 ± 0.1) cm

The volume of the cube = $2.1 \times 1.9 \times 2.1 = 8.379\ \mathrm{cm^3}$. But how precise is this measurement? It is possible that all the dimensions have been underestimated by 0.1 cm, so the volume could be as large as $2.2 \times 2.0 \times 2.2 = 9.68\ \mathrm{cm^3}$. Similarly, the volume could be as small as $2.0 \times 1.8 \times 2.0 = 7.20\ \mathrm{cm^3}$. Possible values for the volume of the cube are from 7.20 to 9.68 $\mathrm{cm^3}$, a range of 2.48 $\mathrm{cm^3}$, so the uncertainty is approximately $\pm 1.24\ \mathrm{cm^3}$. The volume of the cube is therefore $(8.38 \pm 1.24)\ \mathrm{cm^3}$, an uncertainty of almost 5%.

It is possible to find the uncertainties in calculated values by inserting the largest and smallest values of your data into the relevant formulae. But this can be time-consuming and there is a better way. You saw in Worked example 1 that to find the uncertainty in the difference of two masses, you simply add the individual uncertainties together. But if you are *multiplying* or *dividing* two quantities, the general rule is:

If you are multiplying or dividing quantities, then you add the *percentage uncertainties* together.

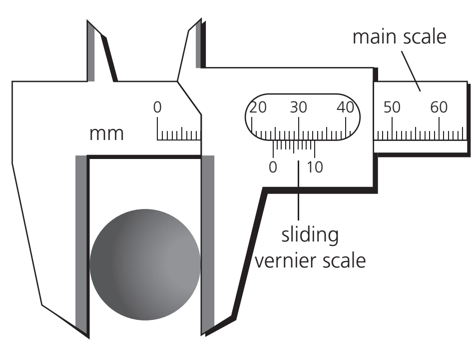
Worked Example 2

Using the data given above for the metal cube, the percentage uncertainties in each measurement of length are 0.1/2.0 = 5%. So the uncertainty in volume = 5 + 5 + 5 = 15%.

To find the density, we need to divide the mass by the volume. The percentage uncertainty in the measurement of mass = 1/89 = 1.1%. The overall uncertainty in the density value is therefore 15 + 1.1 = 16%.

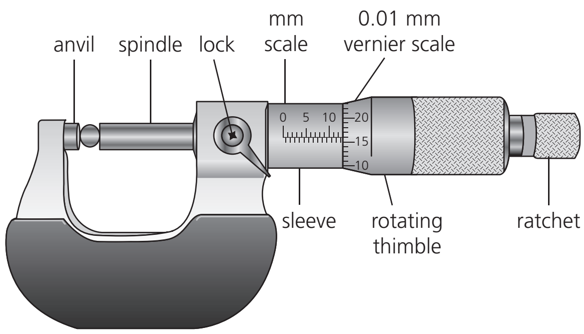
Density of the cube = 89/8.379 = 10.6 ± 16% or $(10.6 \pm 1.7)\ \mathrm{g\,cm^{-3}}$.

Since the accepted value for the density of lead, $11.34\ \mathrm{g\,cm^{-3}}$, falls within the range of uncertainty, the metal could be lead. The measured value for density is not precise enough, however, to rule out other metals. We could improve the precision by using instruments with better resolution to measure length and mass. Two instruments commonly used in the laboratory to measure length precisely are shown in Figures 10 and 11. They both use a vernier scale – a movable scale that allows a fractional part on the main scale to be determined.



The reading in mm is taken from the position of the zero on the sliding scale. Here this is between 24 and 25. The next significant figure (to 0.1 mm) is found by judging which scale mark on the sliding scale is perfectly aligned with a mark on the main scale. Here this is 5.
The reading is 24 + 0.5 = 24.5 mm.

Figure 10 *Vernier callipers can measure length to one-tenth of a millimetre.*



Turning the ratchet moves the spindle until it just touches the object. The ratchet then slips to avoid deforming the object.

The reading to the nearest 0.5 mm is taken where the thimble meets the sleeve. Here this is 12.5 mm. The final significant figures are given by judging which mark on the rotating scale coincides with the horizontal line on the sleeve. Here this is 16.

The reading is 12.5 + 0.16 = 12.66 mm.

Figure 11 *A micrometer can measure length to one-hundredth of a millimetre.*

QUESTIONS

18. Suppose you could improve the precision of either the measurement of length or the measurement of mass, for the small metal cube considered in the text. Which would most improve your final answer?

19. The cube may not be perfect, so that the dimensions may differ at different points. How would you allow for this?

20. You have been asked to find the density of a liquid, which you suspect is ethanol, which has a density of around 80% that of water. Suppose that you measure the volume using a measuring cylinder and its mass on a top-pan balance. By estimating the values of the mass and volume of ethanol you would use, and the resolution of the measuring instrument, calculate an approximate value for the uncertainty in your answer.

KEY IDEAS

- If two physical quantities are to be added or subtracted, then their uncertainties must be added.
- If two physical quantities are to be multiplied or divided, then their percentage uncertainties must be added.

ASSIGNMENT 2: FINDING THE UNCERTAINTY IN THE ATOMIC DIAMETER MEASUREMENT

(MS 0.4, MS 1.1, MS 1.5, PS 1.1, PS 2.1, PS 2.3, PS 3.2, PS 3.3)

It would be useful to estimate the uncertainty in our measurement of atomic size in Assignment 1.

- First you need to estimate the uncertainty in all your measurements.
- Then calculate the percentage uncertainty for your readings.
- Estimating the uncertainty in the area of the oil film is difficult. One way would be to estimate the largest and smallest area that the film could be. This will give you a spread of results. Halve this to find the uncertainty.
- Combine the uncertainties.

For example, the uncertainty in the diameter of the oil drop could be ± 0.1 mm. This is a significant uncertainty, since the drop only has a diameter of 0.5 mm, so that is a $\pm 20\%$. uncertainty. The radius $= (0.25 \pm 0.05)$ mm since we divide the uncertainty by 2 as well. But the uncertainty in the volume will be larger than that because volume depends on the radius cubed, $V \propto r^3$, so that is three times the percentage uncertainty. In this case volume has a percentage uncertainty of 60%.

A1 What is the final uncertainty in your value for atomic diameter?

A2 How would you improve the experimental method to try to reduce the uncertainty in this answer?

1.5 USING GRAPHS

A common way of reducing the uncertainty in a measured quantity is to repeat the reading, using a set of different values of the independent variable, and then plot a graph. Suppose you were asked to find the mass of a raindrop. You have an electronic top-pan balance with resolution of 0.01 g. Assume that you can count the raindrops! You could use any one of the following methods:

A Catch one raindrop and find its mass.

B Repeat the above method lots of times and find the mean mass.

C Collect 100 drops, find the mass and divide by 100.

D Collect 100 drops, recording the mass after every 10 drops. Then plot a graph of your answers.

Which method will give the most precise, and the most useful, results?

Method A will give a very large percentage uncertainty. The average mass of a raindrop depends on the type of rain (it varies from mist to downpour!) but is unlikely to be much more than 100 mg. The reading would have a percentage uncertainty of

$$\left(\frac{0.01}{0.1}\right) \times 100 = 10\%$$

Method B is better, but tedious! Theoretically the precision is equivalent to that of method C, which would give a percentage uncertainty of

$$\left(\frac{0.01}{10}\right) \times 100 = 0.1\%$$

In practice, drying the container between each drop be ridiculous. Method D gives the same uncertainty as method C, but allows you to spot any results that do not fit the pattern and ignore them if they are genuinely anomalous results. The results of such an experiment are shown in Table 3 and the graph obtained is shown in Figure 12.

Number of raindrops	Accumulated mass / g
10	3.60
20	3.70
30	3.80
40	3.90
50	4.01
60	4.11
70	4.20
80	4.30
90	4.40
100	4.49

Table 3 *Mass of every 10 raindrops*

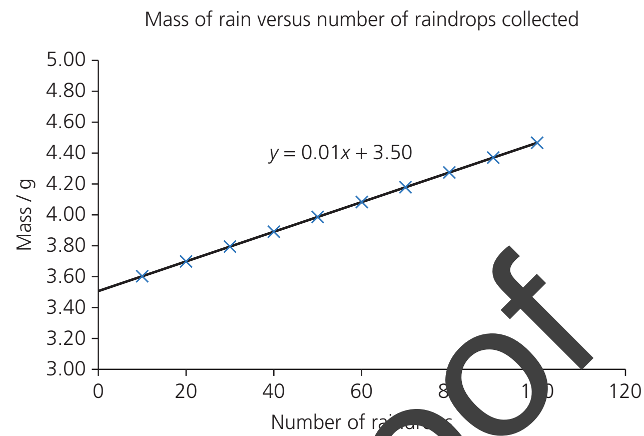


Figure 12 *The equation of a straight line is always of the form $y = mx + c$, where y is the variable plotted vertically, x is the variable plotted horizontally, m is the gradient and c is the intercept on the y-axis. If the equation is to be a straight line, m must be a constant (fixed number). In this case the equation says mass collected (y) = average mass of a raindrop (m) × number of raindrops (x) + any other mass (perhaps the container or a zero error on the balance).*

The gradient of the line is found by calculating $\frac{\text{difference in } y}{\text{difference in } x}$, which in this case is

$$\frac{\text{mass}}{\text{number of drops}} = \text{mass of one raindrop.}$$

The intercept of the line on the y-axis gives a mass reading before any raindrops are collected. This value, 3.50 g in this case, is a zero error, which might not be noticed without the graph.

QUESTIONS

21. Look at the graph in Figure 13. It shows another set of results from the raindrop experiment. What do you think happened? Could you still use the results?

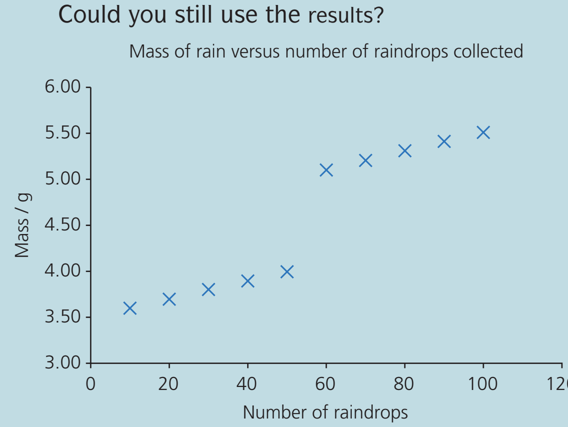


Figure 13 *Plot of another set of results*

Plotting graphs of experimental results

Graph-plotting in physics is not quite the same as in mathematics, where you are often plotting a function with perfectly accurate points that lie on an ideal curve. Physics data is often taken from real-life experiments and has some uncertainty associated with it. The data points will be scattered rather than being a perfect fit to a function. We often do not know whether the results are following a mathematical law or not. Indeed, that is often what we are trying to find out. In practice, it is difficult to draw quantitative conclusions from a curve, so we try to draw straight-line graphs to test relationships between quantities. This may mean that we plot a function of the variables, for example, x^2 or $1/x$, instead of the raw data.

Suppose that you were studying a falling object (Figure 14) and took a series of measurements showing how far the object had fallen after certain periods of time, say after 1, 2, 3, … seconds. You would get a graph like the one shown in Figure 15(a). It may *look* as if distance depends on time squared but we cannot be sure from a curved graph. The distance fallen, *s*, and the time taken, *t*, could be related by a quadratic (squared) equation like $s = At^2 + B$, where A and B are constants (just a fixed number). This needs to be compared with the equation of a straight line, $y = mx + c$:

$$\begin{array}{ccccc} s & = & At^2 & + & B \\ \downarrow & & \downarrow\downarrow & & \downarrow \\ y & = & mx & + & c \end{array}$$

Figure 14 *Time-lapse image of a falling object*

Plotting s on the y-axis and t on the x-axis gives a curve (Figure 15a), but if we plot s on the y-axis and t^2 on the x-axis, we should get a straight line (Figure 15b). If the points are a good fit to the straight line, we can deduce that the experimental data follows the relationship. The gradient will equal the constant A and the y-intercept will equal the constant B.

Table 4 shows a few examples of what to plot in order to confirm a relationship.

Good practice in graph drawing

Accuracy in graph work is important, not least because it often accounts for a significant number of exam marks. So here are a few tips on good practice:

- Choose your scales on each axis so that your data spreads over at least half of the axis. Use a false origin if necessary. You do not need to start the graph at (0, 0) unless you have a measured data point to plot there.
- Use a sharp pencil and a ruler to draw the axes.
- Label each axis with the quantity and unit separated by a solidus (slash) /, for example T^2 / s^2, F / N, λ / m, and so on.
- Plot points (using a sharp pencil) with a small cross.
- Give the graph a meaningful title.

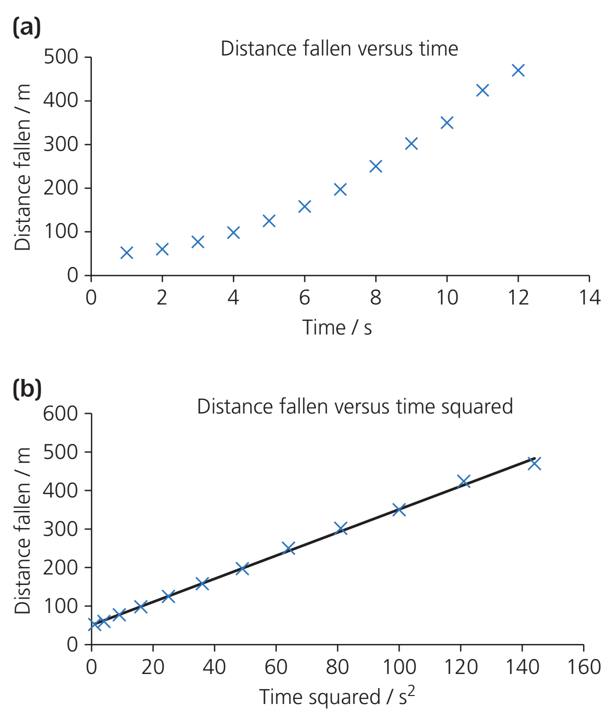


Figure 15 *Finding the relationship between distance fallen and time taken*

Variables	Constant(s)	Possible relationship	Rearrange to	y	x	Gradient (constant for a straight line)	y-intercept
m, T	k	$T = 2\pi\sqrt{\frac{m}{k}}$	$T^2 = 4\pi^2\left(\frac{m}{k}\right)$	T^2	m	$\frac{4\pi^2}{k}$	0
f, λ	c	$c = f\lambda$	$f = \frac{c}{\lambda}$	f	$\frac{1}{\lambda}$	c	0
V, i	E, r	$V = E - ir$	$V = E - ir$	V	i	$-r$	E
F, r	G, M, m	$F = \frac{GMm}{r^2}$	$F = \frac{GMm}{r^2}$	F	$\frac{1}{r^2}$	GMm	0

Table 4 *Examples of what to plot to confirm a relationship*

Drawing a best-fit straight line and calculating the gradient

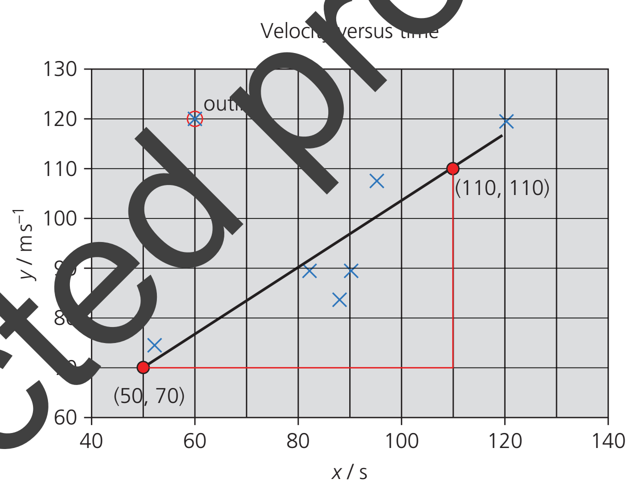
If the points look as if they may fall close to a straight line, you may opt to draw a 'best-fit' straight line. When a computer does this mathematically, it chooses the straight line that minimises the total distance of the points from the line. You should aim to do the same. You have two advantages over the computer:

- You can use your discretion and ignore any **outliers**, especially if you have practical reasons to suspect their accuracy. An outlier may pull a computer's best-fit line way off course. Try to identify these anomalous results, repeat them or at least try to explain why they are going to be ignored.
- You may know that the line must go through a given point, (0, 0) for example, and you can pivot your ruler about that point. (Make sure you have a 30 cm clear plastic ruler so that you can see the points through it.)

The gradient of a graph in physics often represents an important physical quantity. For example, if you plot velocity (y-axis) against time (x-axis), the gradient at a particular point gives the value of the acceleration at that time. You will often need to find the gradient of a best-fit line. Choose a large section of the graph, covering at least two-thirds of each axis (Figure 16). This will reduce the effect of any uncertainties in reading the points. Choose your two points, say (x_1, y_1) and (x_2, y_2); then

$$\text{gradient} = \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

It is useful to include the unit when quoting the value of a gradient. The unit will be that of the quantity on



gradient = $(y_2 - y_1)/(x_2 - x_1)$ = (110 − 70)/(110 − 50) = 40/60 = 0.66 m s^{-2}

Figure 16 *Calculating the gradient of the best-fit line*

the y-axis divided by that of the quantity on the x-axis. So for a velocity against time graph, the gradient will have a unit of (m s^{-1})/s = m s^{-2}.

Uncertainties in graph plotting

Uncertainties on graphs may arise in two ways:

- There may be a large uncertainty in each measurement.
- It might be difficult to choose the best-fit line to find the gradient.

The first problem can be dealt with using 'error bars'. Plot the reading with a small cross as before. Then use bars through the point to show the horizontal and vertical extent of the uncertainty (see Figure 17).

The second problem can be dealt with by drawing a best-fit line and then a 'worst-case' best-fit line (see Figure 17). Find the gradient and intercept of both lines. Your answer can be quoted as best-fit gradient ± (difference between the values).

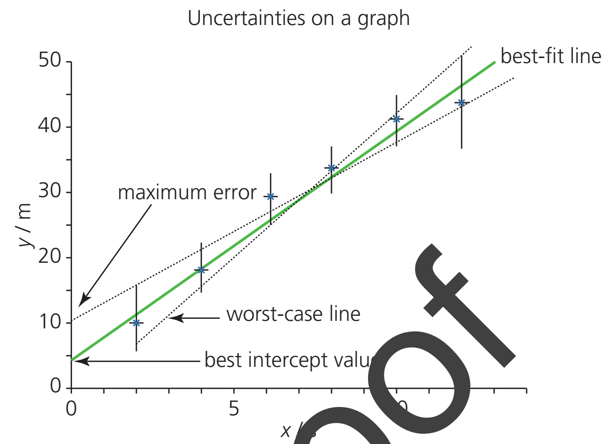


Figure 17 *Best and worst fit through points with error bars*

KEY IDEAS

- The equation of a straight line is of the form $y = mx + c$, where m is the gradient and c is a constant equal to the y-intercept.
- Uncertainty in a data point can be shown on a graph by drawing error bars.
- Best-fit and worst-fit lines can be drawn through the error bars to estimate the uncertainty in the gradient and intercept values.

ASSIGNMENT 3: PLOTTING A GRAPH

(MS 0.1, MS 1.1, MS 1.5, MS 3.1, MS 3.2, MS 3.3, MS 3.4, PS 1.1, PS 2.3, PS 3.1, PS 3.2, PS 3.3)

An experiment has been carried out to measure the time it takes for a pendulum to complete 10 oscillations. Theory suggests that the time for one oscillation, T, depends on the length of the pendulum, l, according to the following equation:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

The results are shown in Table A1.

Time for 10 oscillations / s	Length of pendulum / cm
8.[illegible]	20.0
[illegible].0	30.2
13.[illegible]	40.4
1[illegible].2	49.8
14.3	60.2
16.7	70.0
17.0	80.2
19.2	89.9
19.0	100.2
22.0	110.0
25.0	120.0

Table A1

The uncertainty in the time measurement was estimated to be ±0.1 s. The uncertainty in the length was estimated at ±0.1 cm.

A1 Plot a suitable graph to test the relationship.

A2 Find the gradient of the best and 'worst' case lines.

A3 Find the value of g that this gives you.

A4 Estimate the uncertainty in your answer. Comment on the precision of this result.

A5 The accepted value for g is 9.81 m s^{-2}. Is your result accurate?

1.6 MAKING AN ESTIMATE

Finding a rough value for the diameter of an atom, and the uncertainty in this value, is an example of estimation, helped by a practical measurement or two. Estimation is a very useful skill in physics, and indeed in life!

It is possible to estimate the answers to questions such as: How much water is there in the reservoir? How many people could it supply? How many cars are there on the M25 at a given time? How many wind turbines would be needed to provide all the electricity for a small town? You do not always need an exact answer – sometimes an order of magnitude will do. It is good enough to know whether the answer is tens, hundreds, thousands or millions. An estimate is also useful for checking your answer in an exam question, for example, "could the radius of the Earth really be 6000 m or have I made an error?"

Enrico Fermi, a physicist who built the world's first nuclear reactor in a squash court, used to ask his students questions like these, which could be solved, very approximately, on the back of an envelope.

- How many grains of sand are there on Earth's beaches?
- How many piano tuners are there in Chicago?
- How many atoms are in your body?

(This sort of question has also become popular in some university interviews – popular with the interviewers rather than with candidates!)

If you are faced with one of these, such as "How many cows could you fit in a barn?":

- Do not panic!
- Think of something you know, or can reasonably guess or find out about the situation.
- Break the problem down into smaller, hopefully easier, questions.
- Make simplifying assumptions, for example treat the cow as a cube!

Fermi gave this example. When asked "What is the diameter of the Earth?", he reasoned like this:

1. I pass through three time zones when I fly from New York to Los Angeles.
2. I know that it is about 3000 miles from New York to Los Angeles.
3. That is 1000 miles per time zone, on average.
4. There are 24 hours in a day, so there must be 24 time zones around the world.
5. 24 time zones × 1000 miles per time zone = 24 000 miles.

So that is a circumference of about 24 000 miles. Circumference = $\pi \times$ diameter. Take π as approximately equal to 3, which gives the diameter of the Earth as about 8000 miles. An accurate value is 7926 miles, so 8000 is not a bad estimate!

ASSIGNMENT 4: MAKING AN ESTIMATE

(MS 0.4, MS 1.4)

Here are a few 'Fermi-type' questions for you to try. At this stage the way you approach this is just as important as the result, so record your method as well as your answer. It would be useful to work with a partner, or in a small team, at first so that you can discuss different approaches to the problem. You can look up some of the basic facts if necessary, but try to make as much progress as you can by reasoning from what you know.

A1 How many Jelly Babies could you fit into a supermarket carrier bag?

A2 "If all the mobile phone chargers in the UK were unplugged when not in use, we could save enough energy to boil 1 000 000 kettles every year." Could this be true? If it is true, is it important?

A3 In his book *Sustainable Energy*, David MacKay says that trying to save energy by unplugging mobile phone chargers is like "trying to bail out the Titanic with a tea-spoon". How long would that take?

A4 What mass of plastic is used every year in the UK to hold bottled water?

A5 Make up your own estimation question and swap with another group. (You should have an answer, or at least a way of getting there.)

206092 AS Physics A-Level_CH1.indd 20 4/20/15 9:39 PM

Moving on: the start of the atomic age

In the first few years of the 20th century, the arguments over atomic reality were quickly forgotten. In 1897 the scientific debate was shifted by two discoveries: that of the electron (by J. J. Thomson in Cambridge) and radioactivity (by Henri Becquerel in Paris). These showed not only that the atom was real, but also that it had a structure and could be taken apart. The search to understand the composition of the atom had begun. But it was not until the 1950s that we could actually see images of atoms – search for 'field ion microscope'.

EXAM PRACTICE QUESTIONS

1. You have been asked to measure the thickness of a sheet of printed paper.
   a. Describe how you would do this as precisely as possible.
   b. Estimate the uncertainty of your reading.
   c. The average density of the paper is quoted as 120 g m^{-3}. How would you verify this?

2. The timing of races for a school sports day is done manually. Time keepers for the 100 m race stand at the finish line with stopwatches. They start their stopwatches when they hear the starting pistol and stop them as the runners cross the finish line.
   a. The physics teacher points out that the time keepers start their stopwatches some time after the runners have started because of the time taken for the sound of the pistol to reach them. Given that the speed of sound in air is around 340 $m\,s^{-1}$ calculate the size of this delay.
   b. Is this a systematic error or a or random error? Explain your answer.
   c. The time for the winner is given by the time keeper as 1[illegible].72 s. The physics teacher is critical of this. Explain why and rewrite the time in a way that can be justified scientifically.

3. An electric kettle is used to bring water to the boil. The temperature of the water is measured with an electronic thermometer every 30 s. The results are shown in Table Q1.
   a. A student has made a number of mistakes in recording the results. Suggest **two** corrections.
   b. Plot a graph of temperature (y-axis) against time (x-axis).

Time	Temperature
0	10
30	35.3
60	54.7
90	72.4
120	87
150	95
180	100.2
210	100.2

Table Q1

   c. Use the graph to calculate the greatest rate of increase of temperature.
   d. Explain the shape of the graph.

4. A metal cube of side length 4.0 cm is manufactured to a tolerance of ± 0.1 cm. Its volume will be:
   A (64.0 ± 0.1) cm^3
   B (64.0 ± 0.2) cm^3
   C (64 ± 5) cm^3
   D (64 ± 7.5) cm^3

5. The speed limit on British motorways is 70 mph. In SI units this would be written as:
   A 31.1 $m\,s^{-1}$
   B 1.87 $km\,min^{-1}$
   C 43.8 $km\,h^{-1}$
   D 43.8 $m\,s^{-1}$

6. Density is measured in kilograms per cubic metre. Water has a density of 1000 $kg\,m^{-3}$. What is the mass of 1 litre of water?
   A 100 kg
   B 10 kg
   C 1 kg
   D 100 g

7. Estimate the mass of a five-door family hatchback car. Which of these values is closest to the actual value?

A 100 kg
B 500 kg
C 1000 kg
D 5000 kg

8. Pressure is defined as the force on a certain area. Which of these would be the correct unit to measure pressure?

A pound per square inch
B kilogram per square metre
C newton per cubic metre
D newton per square metre

9. Estimate how many footballs you could fit into your (empty) classroom. Choose from:

A 300 000
B 30 000
C 3000
D 300

10. An experiment using polarised light requires a sugar solution of strength 100 g of sugar per litre of water. You are provided with a measuring cylinder of capacity 50 cm³, marked in cm³, and an electronic balance sensitive to 1 g. The maximum strength of your solution could be:

A 100.3 g cm^{-3}
B 100.2 g cm^{-3}
C 102 g cm^{-3}
D 103 g cm^{-3}

11. In an experiment a student measures the wavelength, λ, of different frequencies, f, of sound. The velocity of sound, v, is given by velocity = frequency × wavelength, $v = f \times \lambda$. To find a value for the velocity from the gradient of a graph, what should the student plot? Choose the correct row from Table Q2.

	y-axis	*x*-axis	Gradient
A	f	λ	v
B	λ	f	v
C	f	$\frac{1}{\lambda}$	v
D	$\frac{1}{\lambda}$	$\frac{1}{f}$	v

Table Q2

12. A student needs to measure the dimensions of a mobile phone as precisely as possible. Which of the rows in Table Q3 would be the most appropriate measuring devices?

	Length	Width	Thickness
A	Ruler	Vernier callipers	Micrometer
B	Ruler	Micrometer	Vernier callipers
C	Ruler	Vernier callipers	Micrometer
D	Micrometer	Micrometer	Vernier callipers

Table Q3

13. Two students are measuring the current through a circuit. Student A has a digital meter, which reads 0.1 A when the circuit is off. Student B has an analogue meter, which he views from an angle, leading to a parallax error. Which row in Table Q4 correctly describes the nature of these errors?

	Student A	Student B
A	Random	Random
B	Systematic	Random
C	Random	Systematic
D	Systematic	Systematic

Table Q4

14. Which row in Table Q5 correctly names the part of the micrometer in Figure Q1 and correctly identifies its function?

	Part	Name	Function
A	6	Spindle	To clamp the specimen tightly
B	7	Ratchet	To slip, rather than over-tighten and deform the specimen
C	4	Ratchet	To lock the jaws
D	1	Sleeve	To measure the specimen

Table Q5

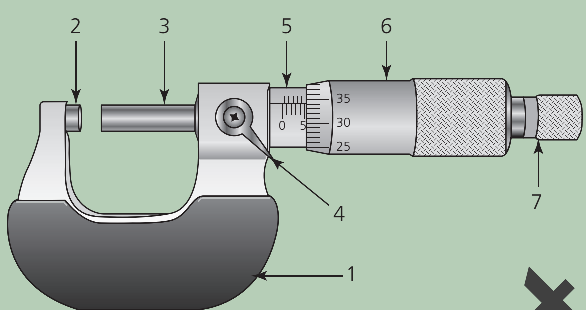


Figure Q1

15. The micrometer in Figure Q1 is reading:

A 5.34 mm

B 5.534 mm

C 5.84 cm

D 5.34 cm

16. A The micrometer like that in Figure Q1 has:

A A range of 25 cm and a resolution of 0.1 mm

B A range of 25 mm and a resolution of 0.01 mm

C A range of 25 mm and a resolution of 1 mm

D A range of 2.5 mm and a resolution of 0.01 mm

17. Vernier callipers are to be used to measure a short pipe.

Which of the following statements is **false**?

A Vernier callipers can be used to measure the internal and external diameter of the pipe.

B Vernier callipers have better resolution than a micrometer.

C Vernier callipers have a larger range than a micrometer.

D Vernier callipers can measure to the nearest 0.1 mm.

18. Look at the calliper scales in Figure Q2.

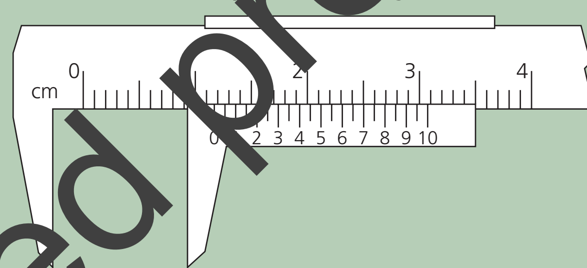


Figure Q2

What is the reading on the callipers?

A 1.07 cm

B 1.15 cm

C 7.25 cm

D 1.17 cm

206092 AS Physics A-Level_CH1.indd 23 4/20/15 9:39 PM

2 INSIDE THE ATOM

PRIOR KNOWLEDGE

You will be familiar with the nuclear atom and you probably know something about radioactivity. You should be aware of the forces between electric charges and know what the term potential difference means.

LEARNING OBJECTIVES

In this chapter you will learn more detail about the model of the atom and how this model evolved. You will learn more about nuclear decay and the four fundamental interactions will be introduced.

(Specification 3.2.1.1, 3.2.1.2 part, 3.2.1.4 part)

Modern physics is built on two outstandingly successful theories, quantum theory and general relativity. Quantum theory describes phenomena on the atomic and subatomic scale. It has been tested to extraordinary levels of precision. For example, electrons have a magnetic property due to their spin, called the magnetic moment. Quantum theory predicts its value to be 1.001 159 6[illegible]2 181 [illegible] (±8) (in certain units). Recent experimental measurements put this figure at 1.001 159 652 180 73 (±28). The uncertainty in brackets after these figures is in the least significant digit(s). The precision of agreement is better than 1 part in a trillion (10^{12}), like knowing the distance to the Moon to within the thickness of a human hair.

General relativity is used to explain behaviour on an astronomical scale. It also has been tested thoroughly and has come through unscathed (Figure 1). The theory, which predicts that clocks will run slower in a stronger gravitational field, is essential to the accuracy of navigation using the GPS system.

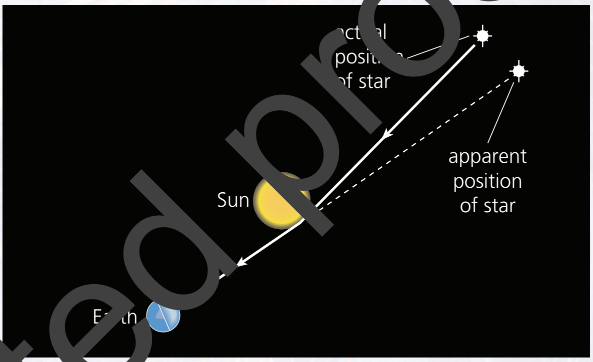


Figure 1 *General relativity predicts that light from a star will bend as it passes close to the Sun. The Sun's own light makes this impossible to detect, except during a solar eclipse. Arthur Eddington photographed the 1919 eclipse from the west coast of Africa. He sent this message to the mathematician Bertrand Russell: "Einstein's theory is completely confirmed. The predicted angular deflection was 1.72° and the observed angle 1.75° (±0.06")."*

Attempts to unite the two theories mathematically have so far failed. The most likely candidate for a unified 'Theory of Everything' is string theory (Figure 2). This has succeeded in explaining many of the phenomena observed by particle physicists. However, it does not make any unique new predictions that can be tested by experiment. This has led some to suggest that string theory is not science at all. Richard Feynman, the Nobel physicist whose work on quantum theory described the interaction between electrons and light, said,

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

Figure 2 (background) *String theory treats fundamental particles, such as electrons, as vibrating loops of energy.*

2.1 ATOMIC STRUCTURE

Before 1900, scientists considered the atom a fundamental particle – a particle without structure or constituent parts. A few suggested that there could be something inside the atom, which would help to explain atomic spectra (see Chapter 5), but nobody suspected that the atom itself could be taken apart. J. J. Thomson's discovery of the electron changed that – he realised that the electron was a part of the atom that had somehow broken free.

The electron

Physicists in the 19th century had two wonderful new pieces of technology: the vacuum pump and the induction coil. The vacuum pump could create a

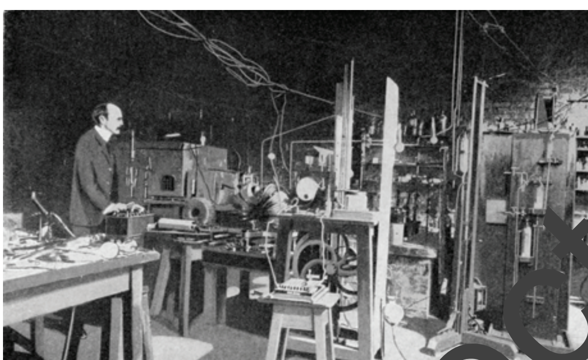


Figure 3 *Thomson at work in the Cavendish Laboratory, Cambridge*

very low pressure in a glass tube. The induction coil could generate a large potential difference (voltage) across electrodes placed in the tube. This technology led to the demonstration of radio waves by Hertz, the transmission of wireless telegraph signals by Marconi, the discovery of X-rays by Röntgen and the discovery of the first subatomic particle, the electron, by Thomson at the Cavendish Laboratory in Cambridge (Figure 3).

In Thomson's 'discharge tube' (Figure 4), a large potential difference was applied across two metal plates inside a partially evacuated glass tube. This caused a fluorescent glow from the tube.

Thomson was working on the hypothesis that **cathode rays** (Figure 5) were in fact a stream of electrically charged particles. He thought that these were emitted from the negatively charged plate (the cathode). A large potential difference accelerated particles; they travelled at high speed across the tube until they struck the coated glass, causing the glow. Thomson showed that he could deflect the beam with a magnet (Figure 6). He could also deflect the beam towards a positively charged plate. This proved that the cathode rays carried a negative electric charge.

Thomson's balancing act

Thomson knew that the cathode rays were associated with negative charge, but to prove that they were a stream of identical particles he needed to show that they had a unique mass and charge. Initially Thomson could not find either of these quantities separately but he was able to measure the charge-to-mass ratio for the cathode rays. This ratio is called the **specific charge**. For the electron written e/m, where e is the charge carried by the electron and m is its mass. Specific charge is measured in coulombs per kilogram, C kg^{-1}. A constant value of e/m would prove that cathode rays were in fact a stream of identical particles.

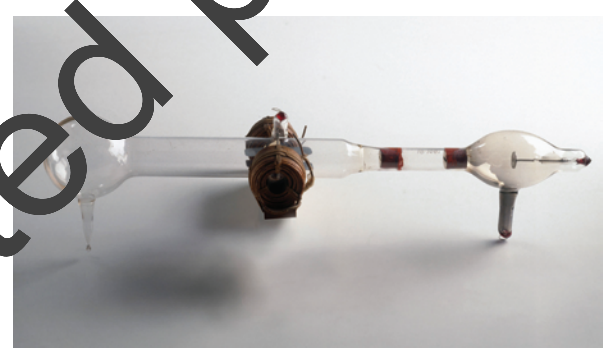


Figure 4 *Thomson discovered the electron using this discharge tube at the Cavendish Laboratory, in 1897. In the following year, there was a formal toast at the laboratory's annual dinner:* "The electron: may it never be of use to anybody."

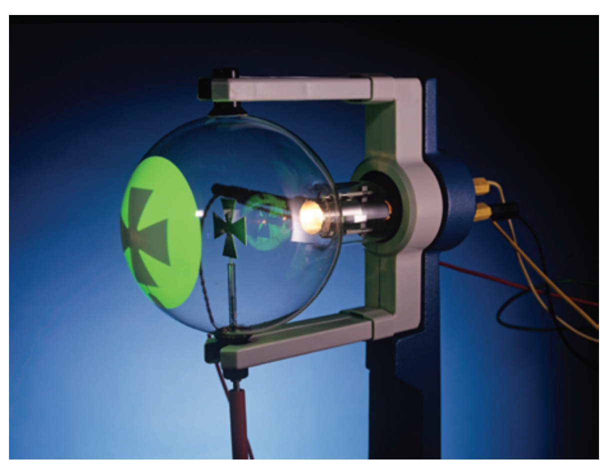


Figure 5 *Discharge tubes, or Crookes tubes, were the particle accelerators of their day. The fluorescence, first seen in the glass, became brighter with fluorescent coatings. This modern tube shows a metal object, a Maltese cross, casting a shadow by blocking the cathode rays.*

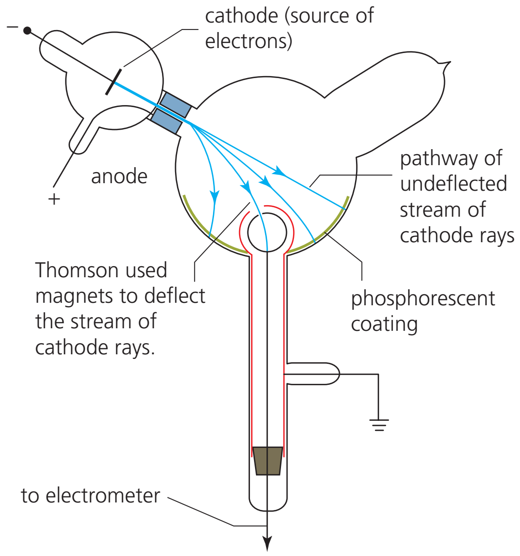


Figure 6 *One of Thomson's experimental set-ups*

QUESTIONS

1. **a.** Thomson repeated the experiment using different metals for the cathode. Why?

   b. Changing the metal made no difference to the path of the cathode rays. What does this suggest?

Thomson was able to find the specific charge of the electron using electric and magnetic fields at right angles to one another. His apparatus (Figure 6) had electric and magnetic fields arranged so that the forces from each field exactly cancelled out and so the cathode rays carried on in a straight line (Figure 7). By equating the forces from the two fields, Thomson was able to calculate a value for *e/m* (see Assignment 2).

Thomson then applied his method to the particles emitted by the photoelectric effect (see Chapter [illegible]) and found that they had the same value for *e/m* as cathode rays. In 1899, Thomson concluded that cathode rays were "a splitting up of the atom, a part of the mass of the atom getting free and becoming detached from the original atom". Thomson had discovered the electron.

Later, Thomson measured the electron's charge, by finding the velocity of falling charged water droplets, to be of the order of 10^{-19} C. He then arrived at a value for the mass of the electron of 3×10^{-29} kg. This is respectably close to the modern measurement of 9.109×10^{-31} kg.

Further experiments by Robert Millikan found a more accurate result for the charge on an electron. The currently accepted value is $e = -1.602\,176\,57 \times 10^{-19}$ C. The value of the specific charge of the electron is $e/m = -1.758\,820\,088(\pm 39) \times 10^{11}$ C kg. There is no evidence to suggest that the electron has any internal structure, or has any other constituents. It is still considered to be a fundamental particle.

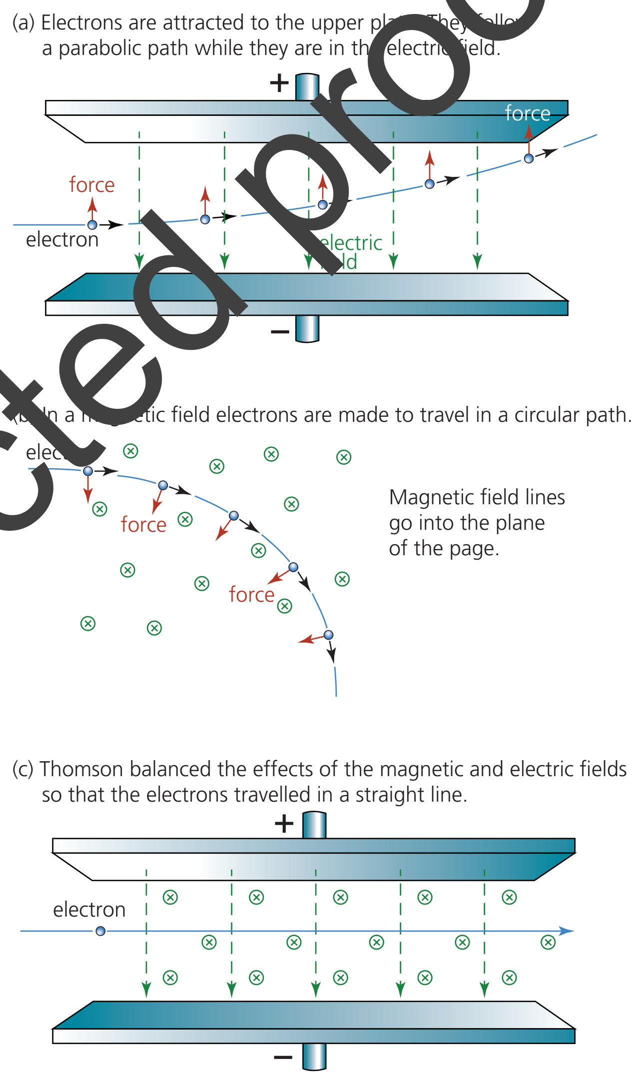
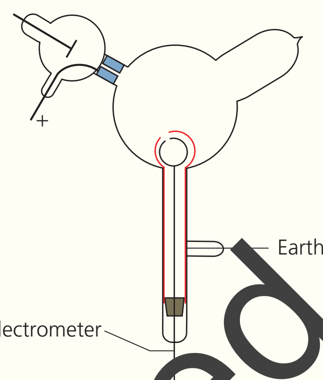


Figure 7 *Electric deflection (a) and magnetic deflection (b) of cathode rays could be balanced (c).*

CATHODE RAYS

BY J. J. THOMSON, M.A., F.R.S.,
Cavendish Professor of Experimental Physics, Cambridge.

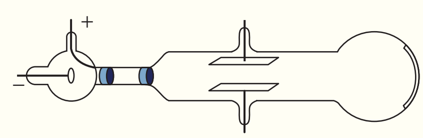
THE EXPERIMENTS discussed in this paper were undertaken in the hope of gaining some information as to the nature of cathode rays . . . According to the almost unanimous opinion of German physicists they are due to some process in the aether[1] . . . another view of these rays is that . . . they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity . . . The following experiments were carried out to test some of the consequences of the electrified-particle theory.



Two coaxial cylinders with slits in them are placed in a bulb connected with a discharge tube; the cathode rays . . . do not fall upon the cylinders unless they are deflected by a magnet. The outer cylinder is connected with the Earth, the inner with the electrometer. When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer . . . was small and irregular; when, however, the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer. I was surprised at the magnitude of the charge . . . Thus this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays.

[Thomson goes on to discuss the effect of an electric field on cathode rays . . .]

Deflexion of the Cathode Rays by an Electrostatic Field



At high exhaustions (a strong vacuum or low pressure) the rays were deflected when the two aluminium plates were connected with the terminals of a battery of small storage-cells; the rays were depressed when the upper plate was connected with the negative pole of the battery, the lower with the positive, and raised when the upper plate was connected with the positive, the lower with the negative pole. The deflexion was proportional to the difference of potential between the plates, and I could detect the deflexion when the potential difference was as small as two volts. It was only when the vacuum was a good one that the deflexion took place.

Figure 8 *Article in* The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, *October 1897*

[1] The aether was thought to be an invisible substance that filled the vacuum.

ASSIGNMENT 1: UNDERSTANDING THOMSON'S EXPERIMENTS

(PS 1.2, PS 2.1)

J. J. Thomson was awarded the 1905 Nobel Prize for Physics "for his theoretical and experimental investigations on the conduction of electricity by gases". Read the extract from J. J. Thomson's paper *Cathode Rays* in Figure 8. You may need to do some brief internet searches to help you to answer the questions below.

A1 In Thomson's first experiment (detail shown in Figure 6), how were the cathode rays deflected? How could Thomson see what path they took? What did he use to detect the cathode rays?

A2 How did Thomson's view of cathode rays differ from that of the 'German physicists' that he mentions?

A3 In the second experiment described by Thomson he says that a good vacuum (low pressure) is needed to see the cathode rays. What does this suggest about cathode rays?

A4 Thomson says that the deflection is proportional to the difference in the potential of the (horizontal) plates. What does this suggest about cathode rays?

A5 The Crookes tube apparatus had been around for at least 40 years before J. J. Thomson used a version of it to identify the electron. Why did it take so long?

ASSIGNMENT 2: MEASURING THE SPECIFIC CHARGE (*e/m*) OF THE ELECTRON

(MS 2.3, PS 1.2, PS 2.4, PS 3.2, PS 3.3, PS 4.1)

It is possible to carry out or observe a modern version of Thomson's experiment using the apparatus in Figure A1. If you are not able to see this first-hand, there are simulations on the internet. Your aim in this assignment is to understand how the apparatus works and to get a value for *e/m*, known as the specific charge.

Figure A1 A school deflection tube

You should be able to vary three independent factors:

- The accelerating voltage, V_a. Increasing this makes the electrons travel faster (see Figure A2).
- The deflecting voltage, V_d. Increasing this increases the force on the electron as it passes between the plates.
- The current in the magnetic field coils, I. Increasing this makes the magnetic field stronger and so increases the force on the electron.

Start with $I = 0$ and $V_d = 0$. The beam should be straight.

Keeping V_a constant:

1 Vary V_d while $I = 0$

2 Vary I, while $V_d = 0$

3 Find a pair of non-zero values for V_d and I so that the beam is straight.

When the beam is straight, the electric force due to the deflection plates balances the force due to the magnetic field. By equating these forces, you can find the ratio *e/m*. It is given by:

$$e/m = \frac{V_d^2}{2V_a B^2 d^2}$$

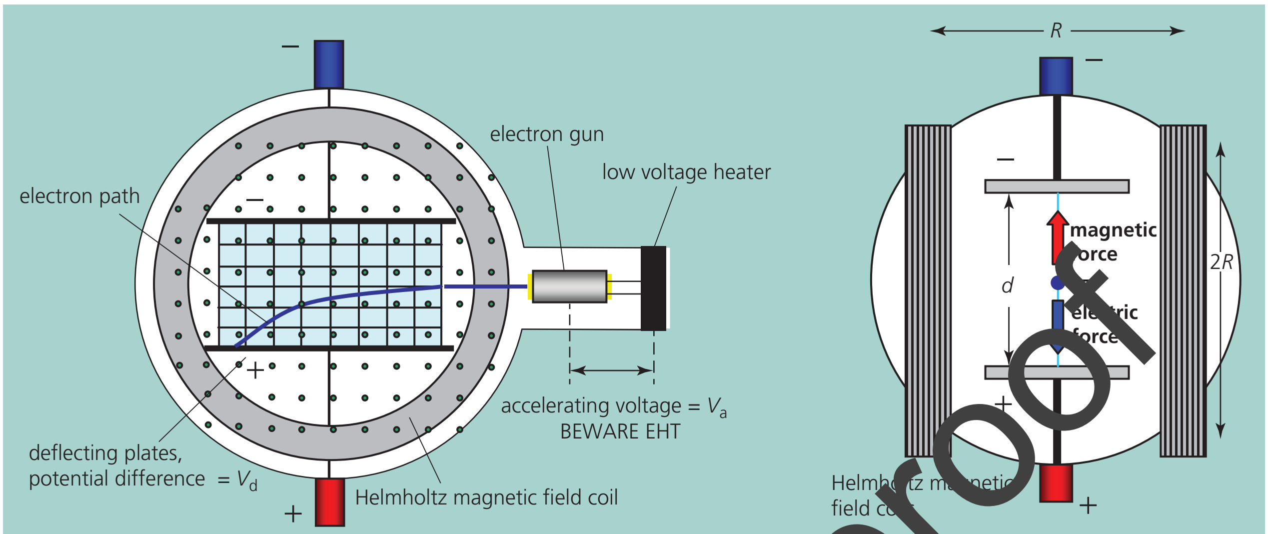


Figure A2 Details of the deflection tube

You should have values for V_a and V_d.

d is the distance (m) between the deflection plates.

B is the magnetic flux density between the coils.

For Helmholtz coils the magnetic flux density is:

$$B = \frac{8\mu_0 NI}{5R\sqrt{5}}$$

where

R is the average radius of the coils = separation between the coils

N is the number of turns in each coil

I is the current through the coils

$\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} = permeability of free space

A1 What shape is the path of the cathode rays when there is a potential difference across the horizontal plates? What shape is the path when there is only a magnetic field?

A2 What factors did Thomson need to control in his experiment?

A3 Use the formula for e/m on the previous page to calculate a value for e/m. Compare this with the accepted value.

A4 How might the precision and accuracy of the school experiment be improved?

The plum pudding atom

Physicists construct models that describe some aspect of the real world, such as the kinetic theory of gases, or the Big Bang model for the beginning of the Universe. Naturally, physicists began to suggest models for the atom.

A first thought (Thomson's) was that atoms were made entirely of electrons. He suggested that a hydrogen atom might consist of around 1000 electrons. However, there had to be some positive charge to cancel out the negative charge carried by all those electrons. This was necessary or else electrostatic repulsion would push apart the whole atom. How much mass did this positive charge have and where was it? Thomson's plum pudding model (Figure 9) pictured the atom as a uniform, positively charged cloud with tiny electrons embedded in it, like plums in a pudding.

The plum pudding model did not stand the test of time, though. Its fate was finally decided by experiments carried out at Manchester University in 1909.

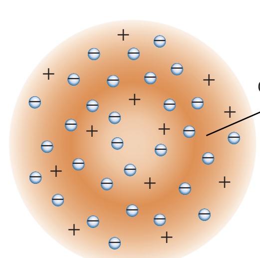


Figure 9 The plum pudding model. The term 'pudding' is rather misleading; the low density of the positive part of the atom makes it more like a cloud than a pudding.

KEY IDEAS

- The electron is a fundamental particle.
- The electron has a mass of 9.1×10^{-31} kg and carries a negative charge of 1.6×10^{-19} C.
- The charge-to-mass ratio, or specific charge, is very high for the electron: $e/m = -1.8 \times 10^{11}\ \mathrm{C\ kg^{-1}}$
- The plum pudding model represented atoms as tiny electrons embedded in a positively charged background of uniform density.

2.2 THE DISCOVERY OF THE NUCLEUS

The first steps in nuclear physics were taken early in 1909. Hans Geiger and his research student Ernest Marsden were conducting an experiment to investigate the scattering of alpha particles as they collided with gold atoms (Figure 10). The experiment was overseen by Ernest Rutherford. He had shown (see section 2.4) that an alpha particle is a tightly bound group of two neutrons and two protons – a helium nucleus – that is emitted at high velocity from some radioactive isotopes.

Geiger and Marsden used radium as the source of the alpha particles, which were beamed towards a thin gold foil. The alpha particles, after passing through the foil, hit a zinc sulfide screen. When each particle hit the screen there was a flash of light (scintillation). In hours of painstaking observations, they recorded the number of scintillations, and hence alpha particles deflected at each angle. Rutherford suggested that they should look for alpha particles reflected from the metal surface. To their great surprise, a small fraction of the alpha particles, about 1 in 8000, bounced back from the gold foil.

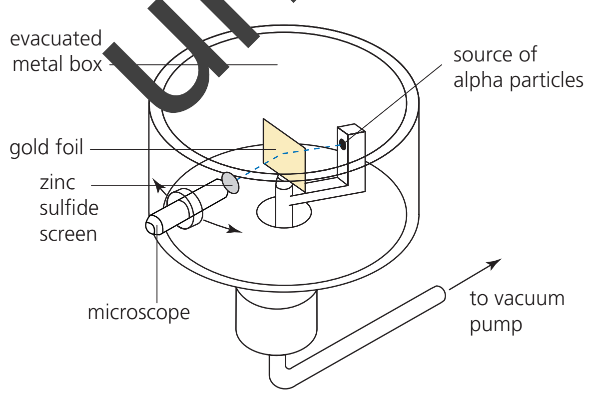


Figure 10 *Geiger and Marsden's experimental set up*

Alpha particles have a positive charge, known to be twice the magnitude of the charge on the electron. They are also relatively heavy, about 8000 times as massive as an electron. An alpha particle travelling at 10 000 km s^{-1} should not have been bounced back by a gold atom that consisted of a few tiny electrons stuck into a positive 'pudding'. Rutherford was amazed. He said later, "It was quite the most incredible event that has ever happened to me. It was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you."

The plum pudding model of the atom had to go. Rutherford deduced from the scattering results that all the positive charge, and almost all the mass, of an atom must be concentrated in the centre of the atom. He called this the **nucleus**.

Rutherford suggested that the electrons carried all the negative charge and that they orbited the nucleus through empty space, a relatively long way from the nucleus. Most of the alpha particles passed through the gold foil with small or zero deflections; the particles were simply too far away from the nucleus of a gold atom to be affected by it. Very occasionally, an alpha particle passed so close to a gold nucleus that it would be repelled by the positive charge and suffer a large deflection (Figure 11).

Rutherford used the results of these scattering experiments to calculate the size of the **nuclear atom**. The nucleus has a radius of the order of 10^{-15} m, compared with the radius of the atom, which is of the order of 10^{-10} m. Rutherford's model of the atom is often pictured as a miniature solar system: the electrons orbit the nucleus rather like planets orbiting the Sun. This image does not really reflect the true scale of the atom. Picture the atom scaled up, so that the nucleus is the size of the Sun; the electrons would orbit ten times further from the nucleus than Pluto is from the Sun. The atom is almost all empty space with an extremely small, dense nucleus.

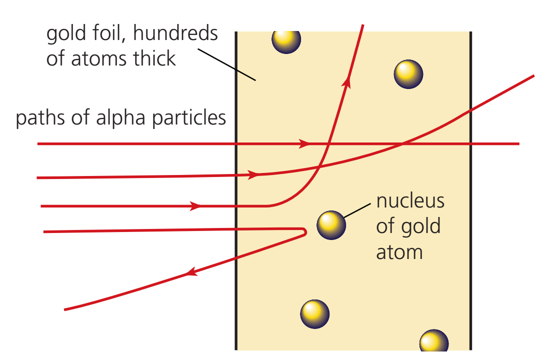


Figure 11 *Rutherford scattering*

QUESTIONS

2. In the film *The Men Who Stare at Goats*, General Hopwood tries to run through a wall. Scientists had told him that the atoms in his body and those in the wall are almost all empty space. This is true. Explain to the general why he still cannot run through a wall.
3. If the atomic nucleus were the size of a football placed on the centre circle at Wembley stadium, where might you find the electron's orbit?

2.3 INSIDE THE NUCLEUS

Rutherford's model of the nuclear atom has a positively charged nucleus orbited by negatively charged electrons. The particles that carry the positive charge in the nucleus are protons. The number of protons is the **proton number**, or the atomic number, and its symbol is *Z*. In a neutral atom – an atom that carries no overall charge – the number of protons in the nucleus is equal to the number of electrons orbiting the nucleus, since these have equal but opposite charge. The atomic number of an atom is therefore also the number of electrons in the neutral atom. The atomic number for each element indicates its place in the Periodic Table. Hydrogen, with $Z = 1$, has one proton in its nucleus and one electron in orbit. Helium, with $Z = 2$, has two protons and two electrons, and so on through the Periodic Table, to the heaviest naturally occurring atom, uranium, which has 92 protons and 92 electrons.

The strong nuclear force

A nucleus composed entirely of positive charges would not hold together. Positive charges repel each other. At the very small separations inside the nucleus, the electrostatic forces pushing the protons apart are very large. There must be another force, acting inside the nucleus, that holds the nucleus together. This force is the **strong nuclear force** or strong interaction.

The strong nuclear force has a very short range; it has little effect at separations greater than about 3 fm (3×10^{-15} m). When two protons are 3 fm apart or closer, the strong interaction acts as an attractive force, pulling the protons closer together. This happens until the separation is about 0.5 fm. Closer than this, the strong interaction becomes highly repulsive (Figure 12). The overall effect of the force is to pull the nucleus together, but the repulsive action prevents it from collapsing to a point.

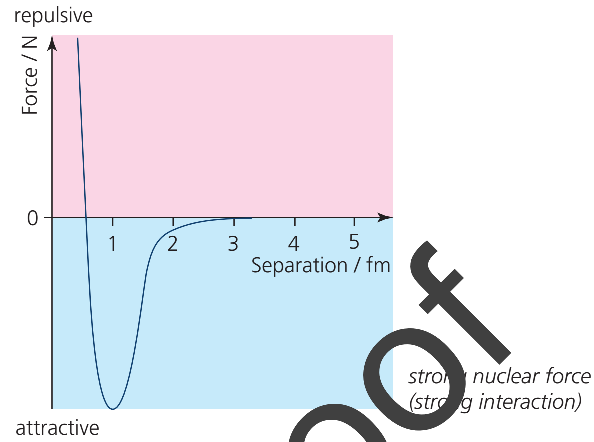


Figure 12 *The strong nuclear force versus distance between two protons*

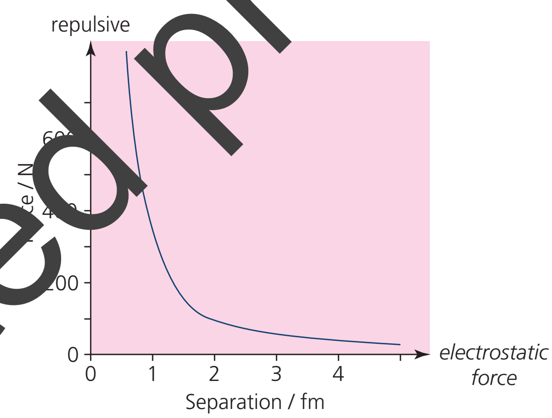


Figure 13 *The electrostatic force versus distance between two protons*

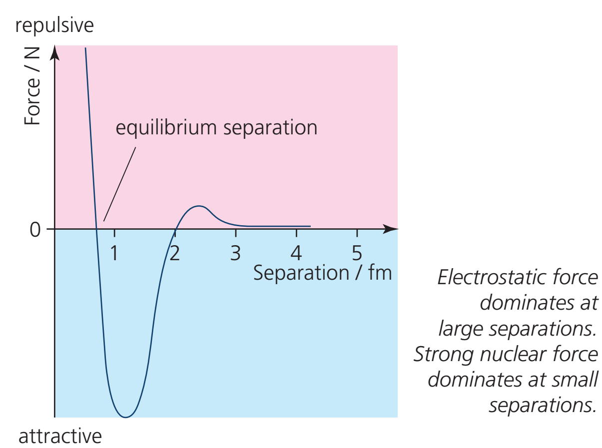


Figure 14 *The combined effect of the electrostatic and the strong nuclear force versus distance between two protons*

At distances of less than about 2 fm, the strong nuclear attraction between two protons is larger than the electrostatic repulsion (Figure 13) so the nucleus is held together (Figure 14).

The neutron

For larger nuclei, there is still a problem. The strong nuclear force acts over a much shorter range than electrostatic repulsion. It is just not possible to get all of the protons close enough together for the strong nuclear force to overcome the electrostatic repulsion. There must be some other particle, or particles, in the nucleus that help to glue it together. The particle is the neutron; it adds extra strong nuclear force, without any electrostatic repulsion. The strong nuclear force between two neutrons, or between a neutron and a proton, acts in the same way as it does between two protons (see Figure 12).

The neutron is a particle with a mass of similar value to that of the proton (Figure 15), but the neutron carries no electric charge (Table 1). It does exert a strong nuclear attraction on protons and on other neutrons. The number of neutrons in a nucleus is known as the **neutron number**, *N*.

Protons and neutrons are the only particles in the nucleus. They are referred to as **nucleons**. The strong nuclear force acts between *any* pair of nucleons, whether that is two protons, two neutrons or a proton and a neutron. Electrostatic repulsion acts only between two protons, because of their positive charge.

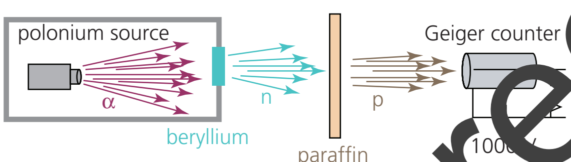


Figure 15 *Chadwick discovered the neutron in 1932. Neutrons are hard to detect, so his ingenious experiment allowed neutrons to collide with protons, which were detected. He was also able to show that neutrons and protons have a very similar mass.*

QUESTIONS

4. Work out the specific charge (charge-to-mass ratio) of the proton. Use the data in Table 1.

Building nuclei

The simplest atom of all is hydrogen. It has one proton in its nucleus and no neutrons. It has only one electron orbiting the nucleus. The most common form of helium has two protons and two neutrons in its nucleus and, therefore, there are two electrons in orbit around it (Figure 16).

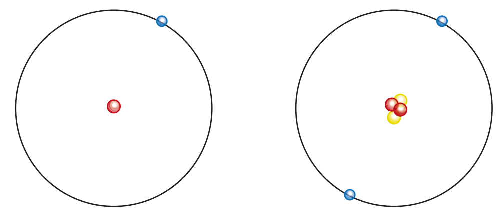


Figure 16 *Hydrogen and helium atoms*

The total number of nucleons in the nucleus of an atom is referred to as its **nucleon number**, or mass number, *A*. This is the number of protons plus the number of neutrons, so $A = Z + N$.

The nuclear composition of an atom can be described using symbols. The most common form of carbon has six protons and six neutrons in its nucleus. It can be written ${}^{12}_{6}C$. The upper number is the nucleon (mass) number, *A*; the lower number is the proton (atomic) number, *Z*.

In general, an element X with an atomic number *Z* and nucleon number *A* is written as ${}^{A}_{Z}X$. Using this system, hydrogen is represented as ${}^{1}_{1}H$, and helium is represented as ${}^{4}_{2}He$. The nucleon number is also the atomic mass number. The atomic mass number is always an exact integer, since it counts the number of nucleons in the nucleus. The **relative atomic mass** of an element is slightly different. It is found by comparing the mass of the atom to that of the most common form of carbon atom, ${}^{12}_{6}C$, whose mass is 19.93×10^{-27} kg. This atom is defined as having a mass of exactly 12 'units'. This 'unit' is known as the unified **atomic mass unit**, u, and has the value 1.661×10^{-27} kg.

The mass of an atom, in atomic mass units, is not exactly equal to the nucleon number. This difference,

	Proton	Neutron	Electron
Symbol	${}^{1}_{1}p$	${}^{1}_{0}n$	${}^{0}_{-1}e$
Charge / C	$+1.602 \times 10^{-19}$	0	-1.602×10^{-19}
Mass / kg	1.6726×10^{-27}	1.6749×10^{-27}	9.1094×10^{-31}

Table 1 *Proton, neutron and electron data*

Element	Symbol	Proton number, *Z*	Neutron number, *N*	Nucleon number, *A*	Atomic mass / u
Hydrogen	H	1	0	1	1.0078
Helium	He	2	2	4	4.0026
Lithium	Li	3	4	7	7.016
Beryllium	Be	4	5	9	9.012
Boron	B	5	6	11	11.009

Table 2 *The first five elements in the Periodic Table*

and its implications, is for discussion in Book 2. However, the relative atomic mass of hydrogen is 1.0078 u, which is almost the same as its nucleon number, 1. Similarly, helium, with nucleon number 4, has a relative atomic mass of 4.0026 u. Indeed *all* nuclei have relative atomic masses that are very close to their nucleon numbers (see Table 2). To an accuracy of three significant figures the mass of the proton, the mass of a hydrogen atom and the mass of a neutron are all equivalent to 1 atomic mass unit.

All nuclei carry a net positive charge equal to their proton number multiplied by the proton charge. We can calculate the specific charge of a nucleus, in C kg^{-1}, as follows:

$$\text{specific charge} = \text{proton number} \times \frac{1.602 \times 10^{-19}}{\text{nuclear mass}}$$

where the nuclear mass is *approximately* equal to nucleon number × 1.66 × 10^{-27} kg.

For example, to a first approximation the specific charge of an uranium-238 nucleus, $^{238}_{92}U$, is:

$$\frac{92 \times 1.602 \times 10^{-19}}{238 \times 1.661 \times 10^{-27}} = 3.728 \times 10^{7}\ \text{C kg}^{-1}$$

(Using a more precise value for the nuclear mass of uranium-238, 238.05076 u, would make only a very small difference to this result.)

Isotopes

Elements can exist in more than one atomic form. Though the simplest atom, hydrogen, usually has only one proton as its nucleus, some hydrogen atoms have one or two neutrons in their nucleus. These different forms of hydrogen are **isotopes** (Figure 17).

The different isotopes of an element are chemically identical. This is because their atoms have the same number of electrons. Isotopes also have the same number of protons in their nucleus. The difference between the isotopes of an element is simply the number of neutrons that they have. This makes some isotopes heavier than others. The most common form of carbon has six protons and six neutrons in its nucleus; this isotope is carbon-12. Carbon-13 has six protons and seven neutrons; carbon-14 has six protons and eight neutrons (see Table 3).

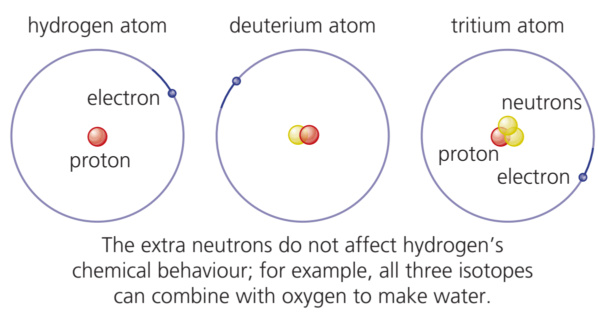


Figure 17 *Hydrogen isotopes*

Isotope	Proton number, *Z*	Number of electrons	Neutron number, *N*	Nucleon number, *A*	% abundance
Carbon-12	6	6	6	12	98.89
Carbon-13	6	6	7	13	1.11
Carbon-14	6	6	8	14	< 0.001

Table 3 *Isotopes of carbon*

QUESTIONS

5. An isotope of uranium, atomic number 92, has 235 nucleons in its nucleus. How many protons, neutrons and electrons are there in a neutral atom of uranium-235?
6. Uranium-238, ${}^{238}_{92}U$, is another isotope of uranium. How does it differ from uranium-235?
7. Calculate the specific charge of each of the nuclei in Table 2.
8. The lighter elements, like carbon and oxygen, tend to have equal numbers of protons and neutrons in their nuclei. In heavier elements, there are always more neutrons. Explain why this is so.
9. List the properties of the strong nuclear force.

KEY IDEAS

- The diameter of a nucleus is of the order of 10^{-15} m. The diameter of an atom is 100 000 times larger.
- The nucleus contains two different particles of approximately equal mass, the neutron and the proton.
- Protons are positively charged. Neutrons are uncharged.
- Protons and neutrons are affected equally by the short-range strong nuclear force. This is a short-range force of attraction, up to a distance of about 3 fm, but is highly repulsive at distances closer than about 0.5 fm. This holds the nucleus together.
- The proton number, Z, is the number of protons in a nucleus. The nucleon number, A, gives the total number of nucleons in a nucleus. The nucleus of element X can be represented by ${}^{A}_{Z}X$.
- Isotopes of an element have the same number of protons and electrons. They are chemically identical. Different isotopes have different numbers of neutrons in their nuclei.

2.4 RADIOACTIVITY

The discovery of radioactivity owed something to chance. In 1896, Henri Becquerel was researching the action of light on fluorescent materials. He was investigating the possibility that light might cause these fluorescent materials to emit X-rays and so darken photographic plates. Becquerel's technique was to wrap the unexposed film in black paper and place a thin copper cross between the film and the fluorescent material that he was investigating. He would then expose the fluorescent material, one of which was uranium salts, to sunlight. For some weeks, his experiments had produced only negative results and, when the skies turned overcast, he put all the apparatus, uranium salts, screen and film, into a dark cupboard to await sunnier weather. After four days of continuous cloud cover, Becquerel grew tired of waiting and decided to develop the film anyway. To his astonishment, the photographic plate had darkened strongly, with the image of the copper cross standing out white against a dark background.

Becquerel reported that he had discovered a natural radiation that could penetrate paper. He also found that these rays could cause a gas, like air, to conduct electricity. Later, scientists found that this process, known as **ionisation**, occurs because the rays can knock an electron completely out of its atom. This turns a neutral atom into an **ion pair**: a negatively charged electron and the positively charged ion it has left behind. The electron, and the positive ion, are free to move so that the gas becomes an electrical conductor. Radioactive sources can be detected through this effect, for example by causing an electroscope to be discharged (Figure 18).

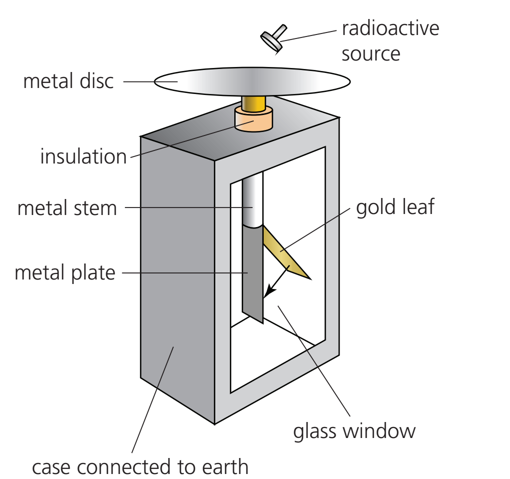


Figure 18 *The ions created by the radioactive source discharge a charged electroscope.*

Marie Curie and her husband Pierre took Becquerel's work further. They discovered other materials, thorium and radium, which also gave off ionising rays. In 1903, the Nobel Prize for Physics was awarded jointly to Becquerel and the Curies for the discovery of radioactivity.

Activity of a radioactive source

Radiation that can ionise gases and cause skin burns must carry a significant amount of energy. This energy comes from changes within the nuclei of the atoms of the radioactive source.

Isotopes, such as radium-226, that emit ionising radiation are **radioisotopes**. Their nuclei are unstable, which means that they are likely to **decay** to a lower energy state at some time in the future. They emit radiation in the process. Sometimes this decay changes the original (parent) nucleus to a different element altogether. This new (daughter) nucleus may be stable, or it may be a new radioisotope – which will in turn decay and emit more radiation.

Radioactive decay is a random event. It is impossible to predict exactly when any particular unstable nucleus will decay, just as when throwing a die you cannot predict when you will get a six. It is possible, though, to calculate the probability that it will decay in a certain time. This will be discussed in Book 2.

The nuclei of some radioisotopes are more likely to decay in a given time than those of other radioisotopes. This means that these radioisotopes emit more radiation in a given time. They are more active. The **activity**, A, of a radioisotope is defined as the number of nuclei that decay in one second; this is equal to the number of emissions per second. Activity is measured in the unit becquerel. If a source has an activity of 1 becquerel, 1 Bq, then on average one of its nuclei decays every second. This is an extremely small unit and activities of kilobecquerel, kBq, or megabecquerel, MBq, are much more likely.

Although the becquerel is the SI unit of activity, an older unit, still commonly used, is the curie, Ci. One curie is the number of disintegrations per second in one gram of radium – 266 – this is equivalent to 3.7×10^{10} Bq.

Alpha, beta and gamma rays

It quickly became clear that the rays emanating from radioactive elements were not all the same. Rutherford realised that there were at least two different sorts of rays. One type, which he called alpha (α) radiation, was easily absorbed by materials in its path. The other type, which was more penetrating, he named beta (β) radiation. A third type of very penetrating radiation became known as gamma (γ) rays.

Alpha, beta and gamma rays all cause ionisation. This is how they are detected. Photographic film, Geiger counters and cloud chambers all detect the ionisation caused by radiation. Cloud chambers (Figure 19) reveal the tracks left by radiation (Figure 20) and were very important in the early days of particle physics. Cloud chambers were replaced by bubble chambers and later spark chambers.

A cloud chamber contains a gas, often air, and a highly saturated vapour. Ionising particles such as beta particles ionise the air as they pass through the chamber. The ions produced act as sites for the vapour to condense around. The liquid droplets that form along the trails of ionised air are just big enough to see and photograph.

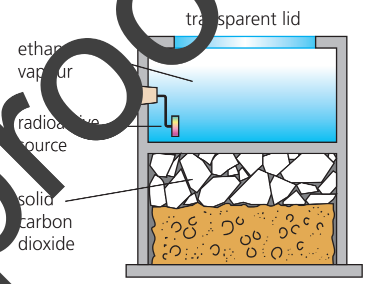


Figure 19 *Radiation is detected by the ionisation that it causes.*

Alpha radiation

Rutherford passed alpha radiation through strong electric and magnetic fields. He showed that it consists of particles that carry a positive charge equal in magnitude to $2e$, where e is the charge on the electron. He also found that the alpha particles have a short range in air, only a few centimetres. Thin sheets of paper could also stop alpha particles. It took an ingenious experiment, completed in 1908, to show what an alpha particle actually is (see Figure 21).

Alpha particles are actually helium nuclei. They are a tightly bound group of two protons and two neutrons, with a charge of $+2e$ and a mass of about 8000 times that of the electron. This combination of relatively large mass and strong electric field makes them highly ionising. When alpha particles pass through a material, they have frequent collisions with atoms. The alpha's large kinetic energy means that it can easily knock an atomic electron out of its orbit. The alpha's large momentum means that it is hardly deflected by the collision. An alpha particle will

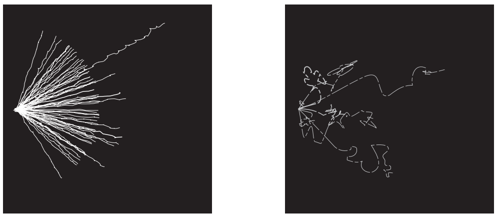


Figure 20 *Tracks of alpha radiation (left) and beta radiation (right) in a cloud chamber*

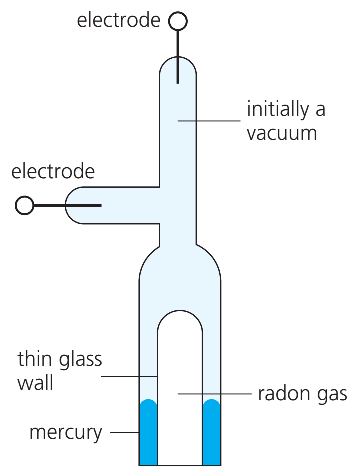
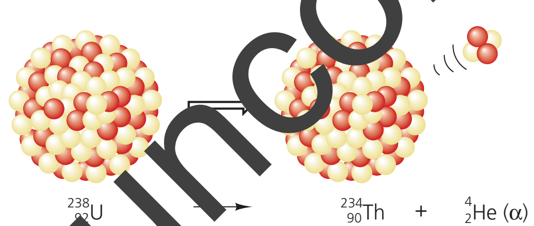


Figure 21 *Ernest Rutherford and Thomas Royds sealed some radon gas in a thin walled glass tube. The glass was thin enough to allow alpha particles to pass through it, but strong enough to withstand atmospheric pressure. The outer tube was evacuated. After a few days, they raised the level of mercury, to compress any gas that might have collected in the tube. They passed a spark between the electrodes and observed the spectrum. This showed that there was helium gas in the outer tube. Rutherford and Royds concluded from their experiment that alpha particles were doubly charged helium atoms.*

undergo thousands of collisions in a short distance until it comes to a halt. After some time it will collect two electrons to become a neutral helium atom.

Decay by alpha emission tends to occur in large unstable nuclei. Inside the nucleus, a stable group of two neutrons and two protons forms. This is expelled from the nucleus at high speed. The emitting, parent, nucleus is transformed into a new daughter nucleus. An example is shown in Figure 22.



A uranium-238 nucleus is made up of 92 protons and 146 neutrons. It decays to thorium-234 (90 protons and 144 neutrons) by emitting an alpha particle (2 protons and 2 neutrons)

Figure 22 *Alpha emission from uranium-238*

The total number of nucleons (protons and neutrons) is not changed by a radioactive decay. The total charge also stays unchanged, so the sum of the proton numbers must be the same before and after any emission.

In alpha decay, the nucleon number, *A*, is reduced by 4 and the proton number, *Z*, is reduced by 2. In a nuclear decay equation, using X as the symbol for the parent radioisotope and Y for the daughter, the alpha decay can be written:

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

An example of an alpha emitter is radium-226. Radium-226 decays into radon, Rn, gas. This decay can be written:

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

QUESTIONS

10. When scientists first discovered alpha rays, they thought that they had no charge: the rays did not appear to be deflected by electric or magnetic fields. Explain what you think the problem might have been with these early experiments.

11. An alpha particle travelling through air leaves a trail of ionised atoms and molecules in its wake. Calculate the specific charge of a doubly ionised oxygen atom – that is, an $^{16}_{8}O$ atom that has lost *two* electrons. You may assume that the mass of the orbital electrons is negligible compared with the mass of the nucleus.

12. The electronvolt (eV) is a unit of energy (see Chapter 3). An alpha particle is emitted with an energy of around 5 MeV. It takes 10 eV, roughly, to ionise an atom. Estimate how many ion pairs an alpha particle will create before it comes to a stop.

13. Radioisotopes that emit only alpha particles are considered not hazardous, as long as they are kept at least five centimetres from the body. However, they are extremely dangerous if they come into contact with the body, for example if someone swallows or breathes in the isotope. Explain why this is.

14. The radioisotope americium-241 ($^{241}_{95}Am$) is used in smoke detectors (Figure 23). It decays by alpha emission to neptunium (Np). Write an equation describing this nuclear decay.

Figure 23 *There is a small amount of a radioactive isotope in a smoke detector. This causes the air inside to be ionised. A small electric current flows across an air gap. When large smoke particles enter, they interfere with the current, causing the alarm to sound.*

Beta radiation

Beta particles are much more penetrating than alpha particles. They have a range in air of up to several metres and can pass through thin sheets of an absorber such as plastic or paper. A magnetic field will deflect beta particles much more easily than alpha particles and in the opposite direction. Beta particles are also deflected by an electric field and in a way that shows them to be negatively charged (Figure 24).

Experiments using magnetic fields showed that beta particles have exactly the same charge-to-mass ratio as electrons. In fact, beta particles *are* electrons, even though they come from the nucleus. Beta decay occurs in an unstable nucleus when one of the neutrons decays into a proton and an electron. The proton remains in the nucleus but the electron is emitted at very high speed, often over 90% of the speed of light. Beta decay leaves the nucleon number of the radioisotope unchanged: there is now a proton instead of a neutron. This extra proton makes the proton number increase by one. Beta decay could therefore be written:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$$

However, we now know that this decay equation is incomplete. A particle called an antineutrino is also emitted. This will be discussed in Chapter 3.

Beta particles cause ionisation by colliding with atomic electrons. Because the beta particle and the electron have the same mass, the beta particle may be widely deflected by a collision. Not all collisions will cause ionisation; some may 'excite' the atomic electron to a higher energy level. Other collisions may just deflect the beta particle with no change in its kinetic energy. The beta particle has a much less densely ionising track than an alpha particle and its path will be more tortuous (see Figure 20), especially as it begins to slow down.

Some nuclei decay by emitting positively charged beta particles. These have exactly the same mass and other properties as a negative beta particle, but their charge is positive. There is more about these positive electrons (positrons) in Chapter 3.

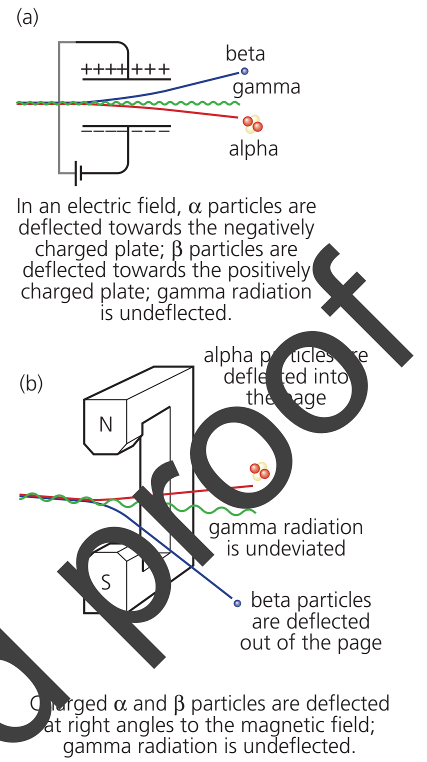


Figure 24 *The effect of electric and magnetic fields on alpha, beta (β^-) and gamma rays*

QUESTIONS

15. The isotope carbon-14 is a beta emitter that decays into nitrogen, N. Write an equation to represent the decay.

16. The cloud chamber pictures in Figure 20 show the tracks left by alpha particles and beta particles. Explain the difference in the tracks.

17. The isotope magnesium-23 ($^{23}_{12}Mg$) decays by positive beta emission to sodium (Na). Write an equation to represent the decay. State the difference between the parent nuclei and the daughter nuclei.

Gamma radiation

Soon after the discovery of radioactivity, it was realised that at least part of the radiation was very penetrating indeed. In 1900, Paul Villard discovered that some rays could pass through thick sheets of metal and still have the ability to blacken photographic plates. He also discovered that electric or magnetic fields could not deflect the radiation (Figure 24). Villard had discovered gamma radiation.

Gamma radiation is high-energy electromagnetic radiation. It has no charge and no mass. Gamma rays can cause ionisation (Figure 25). However, the probability of interaction with an electron is lower than that for alpha or beta particles and so gamma radiation is much less densely ionising.

Gamma emission changes the energy of the parent nucleus, but does not change its nuclear composition.

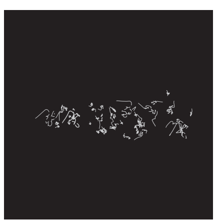


Figure 25 *This cloud chamber photograph shows the ionisation caused by a gamma ray. Most of the tracks are made by secondary electrons, knocked out of their atoms by the gamma ray.*

KEY IDEAS

- Some nuclei are unstable. These nuclei decay, emitting ionising radiation in the process. Radioactive decay may change the nucleus to one of a different isotope.
- Unstable nuclei can emit alpha, beta or gamma rays, or a combination of these.
- An alpha particle is a helium nucleus. An alpha decay can be written:

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

- A beta particle is a high-energy electron emitted from the nucleus. A beta decay can be written:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e $$

plus an antineutrino (see Chapter 3).

- Gamma radiation is high-energy, penetrating electromagnetic radiation.
- During gamma decay the nucleus loses energy, but does not change to a different isotope.

2.5 FUNDAMENTAL INTERACTIONS

Figure 26 *Although gravity is the dominant force on the scale of planets and stars, within the nucleus it is the weakest of the four fundamental forces.*

The search inside the atom revealed two new forces. The strong nuclear force, which acts to hold nuclei together, has been discussed earlier (section 2.3). A second new force, known as the weak interaction or weak nuclear force, was needed to explain some kinds of radioactive decay.

Scientists now believe that there are only four fundamental forces (Table 4 and Figure 26).

Force	Relative strength (within the nucleus)	Range
Strong nuclear	1	10^{-15} m
Weak interaction	10^{-5}	10^{-18} m
Electromagnetic	10^{-2}	infinite
Gravity	10^{-39}	infinite

Table 4 *The four fundamental forces*

The **electromagnetic force** holds atoms together. It ties electrons into orbits and binds atoms into molecules. This force acts between all charged particles. Electromagnetic forces have an infinite range, though the strength of the interaction decreases with distance. Because there are two charges, positive and negative, the electromagnetic force can be either attractive or repulsive. Two similar charges repel each other. Two particles carrying opposite charges will attract each other.

Electromagnetism is responsible for the everyday forces between objects. Contact forces, friction, air resistance and tension are all electromagnetic in origin (Figure 27).

Figure 27 Most of the forces acting on the water-skier are electromagnetic. The tension in the tow rope, the drag from the air and water and the buoyancy from the water are all due to the interaction between charged particles.

Gravity is the other force that has a noticeable impact on our lives. Every mass in the Universe attracts every other mass because gravity is always an attractive force and it has infinite range (Figure 28). The strength of the attraction between two objects depends on their masses and on the distance between them. On the atomic and nuclear scale, the effect of gravity is negligible.

The **strong nuclear force** acts inside protons and neutrons and holds them together. The attraction also acts between nucleons and it is this force that holds the nucleus together. Although it is the strongest of the four forces, it has no effect outside the nucleus. This is because its range is so short, $\approx 10^{-15}$ fm.

The **weak interaction** exerts its influence on all particles. Despite its name, the weak interaction is significantly stronger than gravity, but it only acts over an extremely short range, $\approx 10^{-18}$ m. The weak interaction is responsible for beta radiation and plays an important role in nuclear reactions.

Figure 28 Because there is no negative mass, nothing can be shielded from the effects of gravity. The only way to leave Earth is by expending a lot of energy.

Without the weak interaction there would be no nuclear fusion, the process that powers the Sun (Figure 29). Nuclear fusion begins when two protons join together (fuse) to form a deuterium nucleus, a positron (a positive electron), e^+, and an electron-neutrino, ν_e (see Chapter 3).

$$ {}^{1}_{1}p + {}^{1}_{1}p + \rightarrow {}^{2}_{1}H + {}^{0}_{+1}e + \nu_e $$

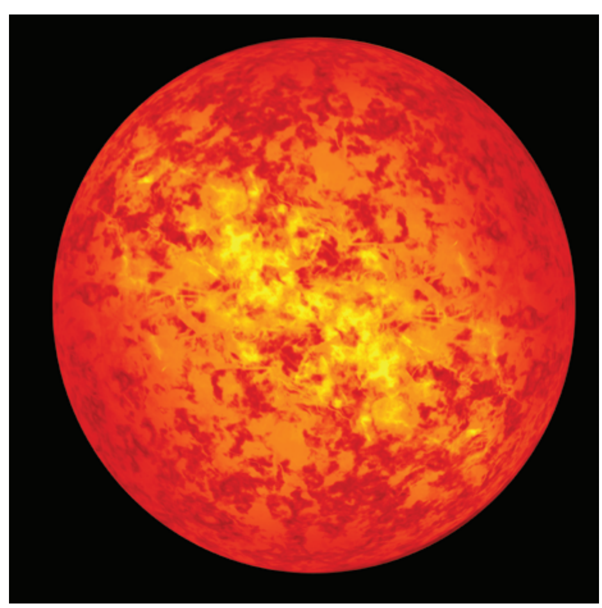


Figure 29 Deep inside the Sun, nuclear fusion is gradually converting hydrogen to helium.

The probability of this reaction occurring is incredibly small, only 1 in every 10^{31} collisions between protons will result in fusion. This makes winning the National Lottery, with odds of around 1 in 10^{7}, look like a racing certainty! Even though a typical proton in the Sun undergoes 10^{14} collisions every second, it will take an average of 10 billion years before it eventually reacts in this way with another proton. Without this highly improbable reaction, there would be no sunshine and no life on Earth.

QUESTIONS

18. Which forces act on a proton in a nucleus of carbon? Which forces act on a neutron in the same nucleus?

19. Uranium atoms, which have 92 protons, are the largest that occur naturally. There are no naturally occurring elements with larger atoms and more protons. Why not?

20. Is the weak interaction badly named? Explain your answer.

21. Speculate on what atoms, nuclei and even the Universe would be like, if:

a. gravity was much stronger

b. the strong force was not as strong

c. the weak interaction was much weaker or much stronger and longer range?

KEY IDEAS

- There are four fundamental interactions between particles: electromagnetic, gravitational, strong and weak.
- The strong interaction is short range (about 10^{-15} m) and acts inside the nucleus, holding nucleons together.
- The weak interaction is even shorter range (about 10^{-18} m) and is responsible for some forms of radioactivity.
- The electromagnetic force acts on charged particles and is responsible for holding atoms and molecules together.
- Gravity is also a fundamental force, but it is insignificant within the atom.

Moving on: Grand Unification Theories

In 1850, the renowned British scientist Michael Faraday carried out experiments to prove that the forces of magnetism and electricity were different aspects of the same force (Figure 30). Over a hundred years later, in 1967, Pakistani physicist Abdus Salaam and Americans Steven Weinberg and Sheldon Glashow put forward a theory that linked the weak interaction with the electromagnetic force. The theory predicted the existence of three new particles, the W^+, W^- and Z^0 particles. In 1983, these particles were discovered by Carlo Rubbia's team at CERN in Geneva. The results were in such good agreement with the theory that the 'electroweak theory' is now widely accepted.

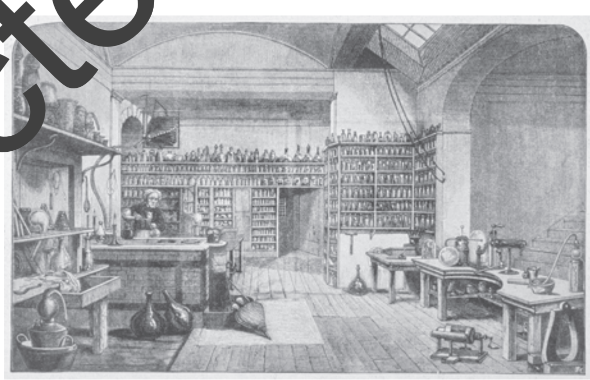


Figure 30 *Michael Faraday felt that the different forces could be unified. After linking electricity and magnetism, Faraday tried to link gravity into the scheme but was unsuccessful. Nobody has succeeded in this since.*

Grand Unification Theories (GUTs) link the electroweak and strong interactions together. Most of these predict that the proton is not stable at all, but will decay with a mean lifetime of 10^{30} years. These decays are difficult to detect because the lifetime of the Universe so far is only 10^{10} years. Physicists are looking in huge tanks containing about 8000 tonnes of water, trying to catch the 1 proton per day which should decay. The results so far are inconclusive.

EXAM PRACTICE QUESTIONS

1. a. The nucleus of a particular atom has a nucleon number of 14 and a proton number of 6.
   i. State what is meant by nucleon number and proton number.
   ii. Calculate the number of neutrons in the nucleus of this atom.
   iii. Calculate the specific charge of the nucleus.

   b. The specific charge of the nucleus of another isotope of the element is $4.8 \times 10^{7}\ \mathrm{C\,kg^{-1}}$.
   i. State what is meant by an isotope.
   ii. Calculate the number of neutrons in this isotope.

   AQA June 2012 Unit 1 Q2

2. An atom of calcium, $^{48}_{20}\mathrm{Ca}$, is ionised by removing two electrons.
   a. State the number of protons, neutrons and electrons in the ion formed.
   b. Calculate the charge of the ion.
   c. Calculate the specific charge of the ion.

   AQA June 201[illegible] Unit 1 Q1

3. Tritium and deuterium are isotopes of hydrogen.
   a. State one difference between an atom of tritium and an atom of deuterium.
   b. State one similarity between an atom of tritium and an atom of deuterium.

4. a. An atom of the radioisotope radium-226 is represented by the symbol $^{226}_{88}\mathrm{Ra}$. Determine the number of protons, the number of neutrons and the number of electrons in a neutral atom of radium.
   b. Radium-226 emits ionising radiation. Explain what *ionising* means.
   c. Radium-226 is an alpha particle emitter; it decays to radon, Rn. Write out and complete this equation that describes the decay:

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{?}_{?}\mathrm{Rn} + ?$$

5. At room temperature, radium is a silvery, solid, metal. Radon is a gas. Both are alpha particle emitters. Explain why radon usually presents more of a hazard to human health.

6. Describe how you could demonstrate in the lab that alpha particles have a short range in air.

7. Rutherford was awarded the Nobel Prize for Chemistry in 1908 for his work on 'The chemical nature of the alpha particles from radioactive substances'. Read this extract from his Nobel acceptance speech and answer the following questions.

   "Shortly after the discovery of the radiating power of uranium by the photographic method Becquerel showed that the radiation from uranium…possessed the property of discharging an electrified body. In a detailed investigation of this property, I examined the effect on the rate of discharge by placing successive layers of thin aluminium foil over the surface of a layer of uranium oxide and was led to the conclusion that two types of radiation of very different penetrating power were present. The conclusions at that period were summed up as follows:

   "These experiments show that the uranium, radiation is complex and that there are present at least two distinct types of radiation – one that is very readily absorbed, which will be termed for convenience the α-radiation, and the other of a more penetrative character, which will be termed the β-radiation." When other radioactive substances were discovered, it was seen that the types of radiation present were analogous to the β- and α-rays of uranium and when a still more penetrating type of radiation from radium was discovered by Villard, the term γ-rays was applied to them…"

206092 AS Physics A-Level_CH2.indd 41 4/20/15 9:44 PM

a. In his experiments described in this extract, Rutherford could only identify two distinct types of radiation, although he was aware that there could be more. Suggest a reason why he was only able to identify two types.

b. Later in the speech, Rutherford describes how he showed that alpha and beta radiation carry opposite charges. Explain, briefly, how you would do that.

c. How could you show that α rays from one substance were the same as α rays from another?

d. The bulk of Rutherford's paper describes how he determined the nature of alpha particles. Read his concluding paragraph, which follows here. Explain what Rutherford got right, and what we now know is wrong, with his ideas.

"*Considering the evidence together, we conclude that the α-particle is a projected atom of helium, which has, or in some way during its flight acquires, two unit charges of positive electricity. It is somewhat unexpected that the atom of a monatomic gas like helium should carry a double charge. It must not however be forgotten that the α-particle is released at a high speed as a result of an intense atomic explosion, and plunges through the molecules of matter in its path. Such conditions are exceptionally favourable to the release of loosely attached electrons from the atomic system. If the α-particle can lose two electrons in this way, the double positive charge is explained.*"

8. Describe an experiment that you could carry out in the lab to demonstrate that the radiation from a sample of uranium contained three distinct types of radiation. Identify the potential hazards in carrying out the experiment and explain what steps you would take to reduce these hazards.

9. Select the correct description.
Thomson is credited with the discovery of the electron because he showed that cathode rays were a stream of particles:

A that were all negatively charged

B that all had the same mass

C that all had the same charge

D that all had the same specific charge.

10. Rutherford's scattering experiment used alpha particles to probe thin gold foil. Which of these conclusions did he make?

A Gold atoms are positively charged.

B The mass and positive charge of the atom are concentrated in a small region of the atom.

C The mass and the positive charge of a gold atom are uniformly distributed.

D There are large gaps between atoms.

11. Which of these statements about heavy nuclei is **false**?

A Very heavy nuclei have more neutrons than protons.

B Very heavy nuclei are denser that lighter nuclei.

C Very heavy nuclei are more likely to be alpha emitters than lighter nuclei.

D Very heavy nuclei are larger than light nuclei.

12. The fundamental forces operate at different ranges. Which of these represents the correct order, from shortest range to longest range?

A weak interaction – strong interaction – electromagnetic interaction

B strong interaction – electromagnetic interaction – weak interaction

C electromagnetic interaction – weak interaction – strong interaction

D weak interaction – gravity – strong interaction

13. The specific charge on a particle is measured as $+48 \times 10^6$ C kg^{-1}. Which of the following is it likely to be?

    A a carbon-12 ion

    B an electron

    C an alpha particle

    D a beta particle

14. Which of these statements about the strong nuclear force is always false?

    A It acts between a neutron and a proton.

    B It acts between two protons.

    C It holds the nucleus of an atom together.

    D It holds electrons in their orbits in atoms.

Stretch and challenge

15. The radius of a nucleus, r, is related to its nucleon number, A, by

$$r = r_0 A^{\frac{1}{3}}$$

where r_0 is a constant.

Table Q1 gives the values of the nuclear radius for some isotopes.

Isotope	Radius r / 10^{-15} m
carbon-12	2.66
silicon-28	3.43
iron-56	4.35
tin-120	5.49
lead-208	6.66

Table Q1

a. Plot a straight-line graph to confirm that

$$r \propto A^{\frac{1}{3}}$$

using the data in Table Q1. From your graph, obtain a value for r_0 and estimate the uncertainty in this value.

b. Taking the mass of one nucleon as 1.67×10^{-27} kg, estimate the density of nuclear matter. State any assumption that you have made.