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# PHYSICS

Student Book 2

Miles Hudson

SAMPLE

COPY

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# ABOUT THIS BOOK

This book is written for students following the Pearson Edexcel International Advanced Level (IAL) Physics specification. This book covers the second year of the International A Level course.

The book contains full coverage of IAL units (or exam papers) 4 and 5. Unit 4 in the specification has three topic areas; Unit 5 has four topic areas. The topics in this book, and their contents, fully match the specification. You can refer to the Assessment Overview on pages x–xi for further information. Students can prepare for the written Practical Skills Paper (Unit 6) with the support of the IAL Physics Lab Book (see pages viii and ix of this book).

Each Topic is divided into chapters and sections so that the content is presented in manageable chunks. Each section features a mix of learning and activities supported by features explained below.

## Learning objectives

Each chapter starts with a list of key learning objectives.

## Specification reference

The exact specification references covered in the section are listed.

## Exam hints

Tips on how to answer exam-style questions and guidance for exam preparation, including how to respond to **command words**. Content which you do not need to revise for your exams is indicated by red **Exam Hint: Extra content** boxes.

## Worked examples

These show you how to work through questions and set out calculations.

## 7A 2 ELECTRONS FROM ATOMS

SPECIFICATION  
REFERENCES  
4.5.113 4.5.117

### LEARNING OBJECTIVES

- Explain that electrons are released in thermionic emission.
- Describe how electrons can be accelerated by electric and magnetic fields.
- Explain why high energies are required to investigate the structure of nucleons.

### ELECTRON BEAMS

Free conduction electrons in metals need a particular amount of energy if they are to escape from the surface of the metal. This energy can be supplied by a beam of photons, as seen in the **photoelectric effect**. The electrons can also gain enough energy through heating of the metal. The release of electrons from the surface of a metal as it is heated is known as **thermionic emission**.

### LEARNING TIP

Students often confuse thermionic emission and the photoelectric effect. Whilst the two ideas have similarities, they are different and you must use the correct term with the correct situation.

If, when they escape, these electrons are in an electric field, they will be accelerated by the field, moving in the positive direction. The kinetic energy they gain will depend on the p.d.,  $V$ , that they move through, according to the equation:

$$E_k = eV$$

where  $e$  is the charge on an electron.

### WORKED EXAMPLE 1

How fast would an electron be moving if it was accelerated from rest through a p.d. of 2500 V?

$$E_k = eV = 1.6 \times 10^{-19} \times 2500 = 4 \times 10^{-16} \text{ J}$$

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

$$v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 4 \times 10^{-16}}{9.11 \times 10^{-31}}}$$

$$v = 2.96 \times 10^7 \text{ m s}^{-1}$$

Using thermionic emission to produce electrons, and applying an electric field to accelerate them, we can generate a beam of fast-moving electrons, known as a **cathode ray**. If this beam of electrons passes through a **deflecting** electric field or magnetic field, then the forces produced on the beam of electrons will cause it to deflect. As a fast-moving electron hits a screen that is painted with a particular chemical, the screen will fluoresce – it will emit light.

These are the principles by which cathode ray oscilloscopes (CROs) operate. The electron beam in a CRO is moved left and

right, and up and down, by passing the beam through horizontal and vertical electric fields. These are generated by electric plates so the strength and direction can be altered. The point on the screen which is emitting light can be changed quickly and easily.

### AN ELECTRON PROBE

Electron beams fired at a crystal will produce scattering patterns that can tell us about the structure of the crystal (Fig. A). In 1927, Davisson and Germer showed that an electron beam can produce a diffraction pattern. This was different to the patterns found by Geiger and Marsden in Rutherford's alpha particle scattering experiments. Davisson and Germer provided the experimental evidence to prove a theory that had been suggested three years earlier by the French physicist, Louis de Broglie. Light could be shown to behave as a wave sometimes, and at other times as a particle. He hypothesised that this might also be the case for electrons. His hypothesis was eventually accepted by particles. De Broglie had proposed that the wavelength,  $\lambda$ , of a particle could be calculated from its momentum ( $p$ ) using the expression:

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

where  $h$  is the Planck constant:

$$h = 6.63 \times 10^{-34} \text{ J s}$$

The Davisson-Germer experiment proved that the diffraction pattern obtained when a cathode ray hit a crystal could only be produced if the electrons in the beam had a wavelength that was the de Broglie wavelength. Because of this experimental confirmation, Louis de Broglie was awarded the 1929 Nobel Prize for Physics.

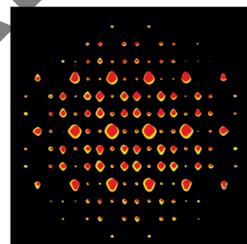


Fig. A Electron diffraction patterns can explore the molecular structure of crystals.

### PROBING MATTER

#### WORKED EXAMPLE 2

What is the wavelength of an electron in a beam which has been accelerated through 2000 V?

$$E_k = eV = 1.6 \times 10^{-19} \times 2000 = 3.2 \times 10^{-16} \text{ J}$$

$$E_k = \frac{1}{2}mv^2 = 3.2 \times 10^{-16} \text{ J}$$

$$v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 3.2 \times 10^{-16}}{9.11 \times 10^{-31}}} = 2.65 \times 10^7 \text{ m s}^{-1}$$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 2.65 \times 10^7}$$

$$\lambda = 2.75 \times 10^{-11} \text{ m}$$

### EXAM HINT

Many standard values, like the charge and mass of an electron and the Planck constant, are given in the data sheet in the exam.

### PRACTICAL SKILLS

#### Investigating electron diffraction

You may have the equipment to observe electron diffraction. By measuring the radius of the circular pattern for each accelerating voltage, you can perform a calculation to confirm de Broglie's hypothesis.

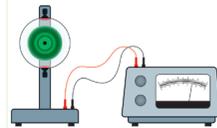


Fig. B Measuring electron diffraction caused by a very thin piece of carbon.  
Safety Note: The power supplies can give a severe electric shock and should be used with shielded connectors. Do not remove or attach connectors with the power switched on.

The idea of electrons acting as waves has enabled scientists to study the structure of crystals, the same way they do in X-ray crystallography. When waves pass through a gap which is about the same size as their wavelength, they are diffracted. In other words, they spread out. The degree of diffraction spreading

### 7A.2 ELECTRONS FROM ATOMS

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depends on the ratio of the size of the gap to the wavelength of the wave. If a beam of electrons is aimed at a crystal, the gaps between atoms in the crystal can act as a diffraction grating and the electron waves produce a diffraction pattern on a screen. Measuring the pattern allows the spacings between the atoms to be calculated.

Electron diffraction and alpha particle scattering both show the idea that we can study the structure of matter by probing it with beams of high energy particles. The more detail (or smaller scale) the structure to be investigated has, the higher energy the beam of particles needs to be. This means that very high energies are needed to investigate the structure of nucleons, as they are very, very small. Accelerating larger and larger particles to higher and higher energies has been the aim of particle physicists ever since Thomson discovered the electron in 1897.

### CHECKPOINT

#### SKILLS SELF-DIRECTION, ADAPTIVE LEARNING, INTERPRETATION, COMMUNICATION, ANALYSABILITY

- Calculate the de Broglie wavelengths for the following:
  - an electron travelling at 2% of the speed of light
  - an electron which has been accelerated through 1200 V
  - a proton with a momentum of  $5 \times 10^{-21} \text{ kg m s}^{-1}$
  - you running at 5 m s<sup>-1</sup>
- Why would de Broglie not have been awarded the Nobel Prize before the Davisson-Germer experiment?
- Calculate the speed at which an electron must travel if it is to be used to probe the structure of the nucleus. (It would need a de Broglie wavelength of about the size of the nucleus:  $\lambda = 5 \times 10^{-15} \text{ m}$ ) Comment on your answer.
- Carry out some research to find out how the direction of the electron beam in a cathode ray oscilloscope (CRO) can be changed in order to make any point on the screen light up. Show this in a diagram. Explain how such a CRO could be set up in a hospital to display the electrical impulses of a patient's heart.

### SUBJECT VOCABULARY

**photoelectric effect** when electrons are released from a metal surface because the metal is hit by electromagnetic radiation  
**thermionic emission** the release of electrons from a metal surface caused by heating of the metal  
**cathode ray** a beam of electrons

## Learning tips

These help you to focus your learning and avoid common errors.

## Subject vocabulary

Key terms are highlighted in blue in the text. Clear definitions are provided at the end of each section for easy reference, and are also collated in the **glossary** at the back of the book.

## Checkpoint

Questions at the end of each section check understanding of the key learning points. Certain questions allow you to develop **skills** which will be valuable for further study and in the workplace.

You should be able to put every stage of your learning in context, chapter by chapter.

- Links to other areas of Physics include previous knowledge that is built on in the chapter, and areas of knowledge and application that you will cover later in your course.
- Maths knowledge required is detailed in a handy checklist. If you need to practise the maths you need, you can use the **Maths Skills** reference at the back of the book as a starting point.

## TOPIC 8 THERMODYNAMICS

### CHAPTER 8A HEAT AND TEMPERATURE

**When scuba divers need to return to the surface of the water in an emergency, they are trained to scream all the way up. This may sound a little strange, but the training is designed to ensure that they do not have to think about expelling the gas in their lungs, as this happens automatically when they scream. As the pressure decreases on their way to the surface, the air in their lungs expands. This could be very dangerous to their internal organs, particularly their lungs, and so the air must be expelled at least as fast as it expands. This is illustrated in a similar, although less extreme, scenario: the bubbles from a diver's normal exhaled breath will slowly get larger as they rise to the surface.**

**This chapter is all about the energy held by individual molecules, and how, on a large scale, this energy is responsible for many macroscopic effects, such as the pressure exerted by a gas on a diver's lungs. We will learn about a large number of rules governing the properties of gases, including their pressure, temperature, volume and quantity. There will be explained from first principles in terms of the molecules that make up the gas. In a more general sense, we will see how the energy possessed by a group of molecules leads to the temperature of a sample and the transfer of heat energy.**

**MATHS SKILLS FOR THIS CHAPTER**

- Recognising and use of appropriate units (e.g. converting between temperature scales)
- Finding arithmetic means (e.g. mean square speeds of gas molecules)
- Use of ratios (e.g. illustrating the gas laws)
- Estimating results (e.g. predicting the outcome on a gas of changes in its properties)
- Substituting numerical values into equations (e.g. calculations using the ideal gas equation)

**What prior knowledge do I need?**

- The pressure on a solid (Topic 16 (Book 1 (AS)))
- The kinetic energy equation (Topic 24 (Book 1 (AS)))
- The conservation of momentum and energy (Topics 16 and 17 (Book 1 (AS)))
- Collisions and Newton's laws of motion (Topic 24 (Book 1 (AS)))
- Density (Topic 24 (Book 1 (AS)))
- The potential divider (Topic 5A)
- Impulse and momentum change

**What will I study in this chapter?**

- The difference between heat and temperature
- Scales of temperature
- The ideal gas equation
- Bubbles on a diver
- Internal energy and the distribution of energy through a gas sample

**What will I study later?**

- Topic 9A
  - Nuclear fusion energy release
- Topic 10A
  - Simple harmonic motion
  - Resonance and damping in molecular energy transport
- Topic 11B
  - The importance of fluid pressure in stars and stellar development
  - The emission of stellar radiation following black body curves

## 6C THINKING BIGGER

### METAL DETECTIVES

Using a process involving electromagnetic induction to detect metal objects was first proposed by Alexander Graham Bell, also the inventor of the telephone. Today metal detectors are used by a variety of people in many different industries. For example, for finding underground water pipes, and by archaeologists looking for old metal objects.

**SKILLS** CRITICAL THINKING, PROBLEM SOLVING, INTERPRETING, EVALUATING, COMMUNICATIONS, EXAMINATION PROCEDURE



Fig 6C.1 Archaeologists can find buried ancient objects using electromagnetic induction.

#### SCIENTIFIC PAPER

### METAL DETECTORS: BASICS AND THEORY

Metal detectors work on the principle of transmitting a magnetic field and analysing a return signal from the target and environment. The transmitted magnetic field varies in time, usually at rates of early high pitched audio signals. The magnetic transmitter is in the form of a transmit coil with a varying electric current flowing through it produced by transmit electronics. The receiver is in the form of a receive coil connected to receive and signal processing electronics. The transmit coil and receive coil are sometimes the same coil. The coils are within a coil housing which is usually simply called the 'coil', and all the electronics are within the electronics housing attached to the coil via an electric cable and commonly called the 'control box'.

This changing transmitted magnetic field causes electric currents to flow in metal targets. These electric currents are called eddy currents, which in turn generate a weak magnetic field, but their generated magnetic field is different from the transmitted magnetic field in shape and strength. It is the altered shape of this regenerated magnetic field that metal detectors use to detect metal targets. (The different 'shape' may be in the form of a time delay.)

The regenerated magnetic field from the eddy currents causes an alternating voltage signal at the receive coil. This is amplified by the electronics because relatively deep buried targets produce signals in the receive coil which can be millions of times weaker than the signal in the transmit coil, and so need to be amplified to a reasonable level for the electronics to be able to process.

- In summary:
1. Transmit signal from the electronics causes transmit electric current in transmit coil.
  2. Electrical current in the transmit coil causes a transmitted magnetic field.
  3. Transmitted magnetic field causes electrical currents to flow in metal targets (called eddy currents).
  4. Eddy currents generate a magnetic field. This field is altered compared to the transmitted field.
  5. Receive coil detects the magnetic field generated by eddy currents as a very small voltage.
  6. Signal from receive coil is amplified by receive electronics, then processed to extract signal from the target, rather than signals from other environment magnetic sources such as Earth's magnetic field.

From a paper written by Bruce Candy, Chief Scientist, Minidetect Electronics, a manufacturer of metal detectors.

[https://www.minidetect.com/\\_files/ugd/1943METAL\\_DETECTOR\\_BASICS\\_AND\\_THEORY.pdf](https://www.minidetect.com/_files/ugd/1943METAL_DETECTOR_BASICS_AND_THEORY.pdf)

#### ELECTROMAGNETIC EFFECTS

#### THINKING BIGGER

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##### SCIENCE COMMUNICATION

The extract consists of information from a technical paper written for a metal detector manufacturer's customers.

1. Why is there no obvious commercial bias in the text?

2. Discuss the level of scientific detail included in the extract, and the level of language used, particularly considering the intended audience.

##### INTERPRETATION NOTE

Although this is a technical paper, it is presented in a brochure-style format for Minidetect's customers.

##### PHYSICS IN DETAIL

Now we will look at the physics in detail. Some of these questions will link to topics elsewhere in this book, so you may need to combine concepts from other areas of physics to work out the answers.

3. Explain how a metal detector functions, including reference to Faraday's law and Lenz's law.

4. (a) Explain how the operation of the metal detector is similar to that of a transformer.  
(b) Explain how the metal detector is different from a transformer.

5. Why does the signal from the receive coil need to be amplified electronically?

6. If the target metal has a lower resistivity, it produces a stronger electromagnetic field. Explain why a gold-sounding ring might be rejected as not a naturally occurring nugget of a similar size.

##### CRITICAL THINKING

Consider how the transformer in the previous question is similar to the primary coil and how compare with the structure of this device.

##### ACTIVITY

Imagine you work for Minidetect, and have been asked to prepare a presentation about the portable metal detectors to a group of amateur treasure hunters. Prepare the part of the presentation which explains why some objects are more likely to be detected than others. It should cover the shape, proximity and resistivity. Diagrams should be included in your presentation.

##### THINKING BIGGER TIP

Do not attempt to teach International A Level Physics to the treasure hunters. Your presentation should explain the principles without overcomplicated detail.

### Thinking Bigger

At the end of each topic, there is an opportunity to read and work with real-life research and writing about science.

The activities help you to read authentic material that's relevant to your course, analyse how scientists write, think critically and consider how different aspects of your learning piece together.

These Thinking Bigger activities focus on **key transferable skills**, which are an important basis for key academic qualities.

## 8A EXAM PRACTICE

(Note: In questions marked with an asterisk (\*), marks will be awarded for your ability to structure your answer logically, following the points that you make and related or follow on from each other.)

1. If a fixed mass of gas in a weather balloon moves to a new situation where the temperature is halved, and the pressure is also halved, what would happen to the volume of the balloon?
- A It would stay the same.
  - B It would become a quarter of its original value.
  - C It would halve.
  - D It would double.

(Total for Question 1 = 1 mark)

2. How much energy is needed to melt 100 kg of lead at 600 K? Specific latent heat of fusion of lead = 23 kJ/kg.  
Melting point of lead = 927 °C.
- A 2.3 J
  - B 23 J
  - C 2300 J
  - D 2300 J

(Total for Question 2 = 1 mark)

3. The molar mass of oxygen molecules is 32 g. Assuming oxygen behaves as an ideal gas, what is the root-mean-square speed of oxygen molecules in a sample kept at 15 °C?
- A 21 m s<sup>-1</sup>
  - B 150 m s<sup>-1</sup>
  - C 470 m s<sup>-1</sup>
  - D 440 000 m s<sup>-1</sup>

(Total for Question 3 = 1 mark)

4. (a) A typical aerosol can is able to withstand pressures up to 12 atmospheres before exploding. A 3.0 × 10<sup>-2</sup> m<sup>3</sup> aerosol contains 3.0 × 10<sup>23</sup> molecules of gas as a propellant. Show that the pressure would reach 12 atmospheres at a temperature of about 900 K.  
1 atmosphere = 1.0 × 10<sup>5</sup> Pa. [2]
- (b) Some aerosol cans contain a liquid propellant. The propellant exists inside the can as a liquid and a vapour. Explain what happens when such an aerosol can is heated to about 900 K. [3]

(Total for Question 4 = 5 marks)

5. When your diaphragm contracts, the pressure in the chest cavity is lowered below atmospheric pressure and air is forced into your lungs.



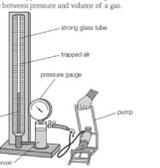
- (a) The diaphragm contracts and the lung capacity increases by 20%. State two assumptions you would need to make to calculate the new pressure in the lungs if the initial pressure is 1.0 atm. [2]

- (b) (i) The volume of air inhaled in a typical breath is 2.5 × 10<sup>-2</sup> m<sup>3</sup> and an adult takes about 23 breaths per minute. Show that the mass of air taken into the lungs each second is about 1 × 10<sup>-2</sup> kg. [2]

- (ii) Body temperature is 37 °C and the temperature outside the body is 20 °C. Calculate the rate at which energy is used to warm air to body temperature. Specific heat capacity of air = 1900 J kg<sup>-1</sup> °C<sup>-1</sup>. [2]

(Total for Question 5 = 6 marks)

6. A student uses the apparatus above to investigate the relationship between pressure and volume of a gas.



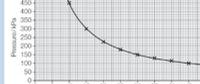
- (a) Draw the electrical circuit he should use. [1]

#### HEAT AND TEMPERATURE

#### EXAM PRACTICE

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Air is trapped in a glass tube of uniform cross-sectional area. As the pressure of the trapped air is increased, the length of trapped air decreases. The student collects data and plots the following graph.



- (a) State the variables that should be controlled in this investigation. [2]

- (b) Theory suggests that, for the air trapped in the tube, the pressure is inversely proportional to the volume *V*. Use the graph to show that this relationship is correct. State an assumption that you are making. [4]

- (c) On the day that the investigation was carried out, the temperature in the laboratory was 20 °C. Calculate the number of air molecules trapped in the tube; cross-sectional area of tube = 7.5 × 10<sup>-4</sup> m<sup>2</sup>. [3]

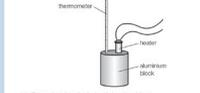
- (d) Show how the graph would change if [1]

- (i) the air molecules in the tube were replaced by the same number of molecules of hydrogen gas, [1]

- (ii) the temperature of the laboratory was much higher. [2]

(Total for Question 6 = 12 marks)

7. A student wants to determine the specific heat capacity of aluminium. He heats a block of aluminium by supplying electrical energy a heater that is inserted into the block, as shown.



- (a) Draw the electrical circuit he should use. [1]

- (b) He writes the following plan:

1. Heat the aluminium block in a water bath.  
2. Turn on the electric heater.  
3. Measure the temperature of the block at the start.  
4. Turn off the heater and measure the temperature.  
5. Use the specific heat capacity of aluminium to calculate the total energy by the mass and temperature rise.

Write an improved plan that includes details of the method to be used and any precautions needed to produce an accurate value for the specific heat capacity of aluminium. (Total for Question 7 = 7 marks)

8. The picture shows an inflatable globe. This is a flexible plastic sphere on which a map of the world is printed. It is inflated by blowing air in like a balloon.



When fully inflated the globe has a volume of 8.55 × 10<sup>-2</sup> m<sup>3</sup>. At a temperature of 22 °C the pressure exerted by the air in the globe is 1.05 × 10<sup>5</sup> Pa.

- (a) On average there are 1.25 × 10<sup>24</sup> molecules in each breath of air that we take. Show that the number of breaths needed to fully inflate the globe is about 140. [3]

- (b) The fully inflated globe is left outside and its temperature rises from 22 °C to 30 °C. The volume of the globe remains constant. Calculate the new pressure exerted by the air in the globe. [2]

- (c) Including ideas of momentum, explain why the pressure exerted by the air in the globe increases. [4]

(Total for Question 8 = 9 marks)

# PRACTICAL SKILLS

Practical work is central to the study of physics. The second year of the Pearson Edexcel International Advanced Level (IAL) Physics course includes eight Core Practicals that link theoretical knowledge and understanding to practical scenarios.

Your knowledge and understanding of practical skills and activities will be assessed in all exam papers for the IAL Physics qualification.

- Papers 4 and 5 will include questions based on practical activities, including novel scenarios.
- Paper 6 will test your ability to plan practical work, including risk management and selection of apparatus.

In order to develop practical skills, you should carry out a range of practical experiments related to the topics covered in your course. Further suggestions in addition to the Core Practicals are included below.

STUDENT BOOK TOPIC	IAL CORE PRACTICALS	
<b>TOPIC 5</b> <b>FURTHER MECHANICS</b>	<b>CP9</b> Investigate the relationship between the force exerted on an object and its change of momentum	<b>UNIT 4 (TOPICS 5 TO 7)</b> <b>FURTHER MECHANICS, FIELDS AND PARTICLES</b>  Possible further practicals include: <ul style="list-style-type: none"> <li>• investigating the effect of mass, velocity and radius of orbit on centripetal force</li> <li>• using a coulomb meter to measure charge stored</li> <li>• using an electronic balance to measure the force between two charges</li> </ul>
	<b>CP10</b> Use ICT to analyse collisions between small spheres	
<b>TOPIC 6</b> <b>ELECTRIC AND MAGNETIC FIELDS</b>	<b>CP11</b> Use an oscilloscope or data logger to display and analyse the potential difference (p.d.) across a capacitor as it charges and discharges through a resistor	
<b>TOPIC 8</b> <b>THERMODYNAMICS</b>	<b>CP12</b> Calibrate a thermistor in a potential divider circuit as a thermostat	<b>UNIT 5 (TOPICS 8 TO 11)</b> <b>THERMODYNAMICS, RADIATION, OSCILLATIONS AND COSMOLOGY</b>  Possible further practicals include: <ul style="list-style-type: none"> <li>• investigating the relationship between the volume and temperature of a fixed mass of gas</li> <li>• measuring the half-life of a radioactive material, measuring gravitational field strength using a simple pendulum and measuring a spring constant from simple harmonic motion</li> </ul>
	<b>CP13</b> Determine the specific latent heat of a phase change	
	<b>CP14</b> Investigate the relationship between pressure and volume of a gas at fixed temperature	
<b>TOPIC 9</b> <b>NUCLEAR DECAY</b>	<b>CP15</b> Investigate the absorption of gamma radiation by lead	
<b>TOPIC 10</b> <b>OSCILLATIONS</b>	<b>CP16</b> Determine the value of an unknown mass using the resonant frequencies of the oscillation of known masses	

In the **Student Book**, the Core Practical specification and Lab Book references are supplied in the relevant sections.

**Practical Skills**  
Practical skills boxes explain techniques or apparatus used in the Core Practicals, and also detail useful skills and knowledge gained in other related investigations.

**5A 2 MORE COLLISIONS** 4.3.81 4.3.82 4.3.83 4.3.84 CP9 CP10  
CP9 LAB BOOK PAGE 36 CP10 LAB BOOK PAGE 41

**LEARNING OBJECTIVES**

- Apply the conservation of linear momentum to situations in two dimensions.
- Analyse collisions in two dimensions.
- Calculate impulses and changes in momentum.

So far, we have only considered the conservation of linear momentum in one-dimensional collisions, where all objects move forwards and/or backwards along the same straight line. This is an unusual situation, and we need to be able to work with more complex movements. Luckily, momentum is conserved in each dimension separately. So, we resolve vector movements entering a collision into components in each dimension and then calculate following the conservation of momentum in each dimension. After this, we can recombine component vectors to give us an overall vector after a collision. A real world example, as in **fig B**, will illustrate this best.

**IMPULSE**

The product of a force applied for a known time ( $F \times \Delta t$ ) is known as the **impulse**, and this is equal to the change in momentum:

$$\text{impulse (Ns)} = \text{force (N)} \times \text{time (s)}$$

$$= \text{change in momentum (kg m s}^{-1}\text{)}$$

$$\text{impulse} = F \times \Delta t = \Delta p$$

To stop something moving, we need to remove all of its momentum. This idea allows us to calculate the impulse needed to stop an object moving. If we know how long a force is applied, we could work out the size of that force.

**WORKED EXAMPLE 1**

What is the impulse needed to accelerate a 1000 kg car from rest to 25 m s<sup>-1</sup>?

$$p = m \times v$$

At the start, the car is at rest, so has no momentum. Therefore the change in momentum will equal its final momentum:

$$\Delta p = 1000 \times 25$$

impulse =  $F \times \Delta t = \Delta p$

$$F = 25\,000 \text{ kg m s}^{-1}$$

If the car needed to stop in 3.8 seconds, what force would the brakes need to apply?

At the end, the car is at rest, so has no momentum. Therefore the change in momentum will equal its initial momentum:

$$F = m \Delta v$$

$$m \Delta v = 25\,000 \text{ kg m s}^{-1}$$

$$F = \frac{25\,000}{3.8}$$

$$F = 6600 \text{ N to 2 significant figures (sf)}$$

**COLLISION VECTORS**

Momentum is a vector quantity. As with all vectors, we can resolve momentum into a right-angle pair of vector components. And we can add components together in two dimensions to find a resultant vector. A spacecraft is moving through empty space at 8 m s<sup>-1</sup>. A meteoroid, travelling at 15 m s<sup>-1</sup>, comes from behind and at an angle of 45° to the line of movement of the rocket, strikes into the rocket and becomes embedded in it. The rocket has a mass of 350 kg and the meteorite mass is 20 kg. We can calculate the velocity of the rocket (**fig B**) after the collision.

**PRACTICAL SKILLS CP9**

**Investigating impulse**

**motion sensor**

**fig A** Measuring how impulse changes the momentum of a trolley

In **Book 1, Section 1C.1**, we saw how you can investigate the change in momentum over time for a trolley that is subject to a constant accelerating force. Using the same apparatus, you could again record how different forces acting over different time periods cause the trolley to accelerate to different velocities. From these results, you can calculate the impulse applied in each case. As  $I = F \Delta t = \Delta p = \Delta mv$ , a graph of impulse on the y-axis against change in velocity on the x-axis should give a straight best fit line through the origin. This straight line verifies the impulse equation, and the gradient of it will give the mass of the accelerating trolley and weights.

**Safety Note:** Put a 'catch box' full of soft material under the hanging masses to stop them falling on to feet and use an end stop to prevent the trolley falling off the runway.

**EXAM HINT**

Make sure you have a good understanding of this practical as your understanding of the experimental method may be assessed in your exams.

**CORE PRACTICAL 9:**  
**INVESTIGATE THE RELATIONSHIP BETWEEN THE FORCE EXERTED ON AN OBJECT AND ITS CHANGE OF MOMENTUM** SPECIFICATION REFERENCE  
4.3.82

**Procedure**

- Secure the bench pulley to one end of the runway. This end of the runway should project over the end of a bench, so that the string connecting the mass hanger and the trolley passes over the pulley. The mass hanger will fall to the floor as the trolley moves along the runway. The runway should be tilted to compensate for friction.
- Place the slotted mass hanger on the floor and move the trolley backwards along the runway until the string becomes tight, with the mass still on the floor. Place the light gate so it is positioned in the middle of the interrupt card on the trolley. There should be enough space on the ramp to allow the trolley to continue so that it clears the light gate before hitting the pulley.
- Move the trolley further backwards until the mass hanger is touching the pulley. Put the five 10g masses on the trolley so that they will not slide off. This is the start position for the experiment.
- Record the total hanging mass,  $m$ . Release the trolley and use the stop clock to measure the time,  $T$ , it takes for the trolley to move from the start position to the light gate – this should be when the mass hanger hits the floor. Record the time reading,  $t$ , on the light gate. Repeat your measurements twice more and calculate mean values for  $T$  and  $t$ . Then estimate  $\Delta t$  and  $\Delta v$ , the uncertainties in these values.
- Move one 10g mass from the trolley to the hanger and repeat step 4. Repeat this process, moving one 10g mass at a time and recording  $m$ ,  $T$  and  $t$ , until all of the masses are on the hanger.
- Measure the combined mass,  $M$ , of the trolley, string, slotted masses and hanger.
- Measure the distance,  $d$ , travelled by the trolley. This should be the same as the distance fallen by the mass hanger.
- Record the length,  $L$ , of the card.
- You can develop the investigation further by taking more readings after adding an additional mass, for example, 200g, to the mass of the trolley.

**Learning tip**

- Choose a suitable scale for your graph so that your plot fills the whole page – you do not need to include the origin. This will make it easier to draw the last two gradient lines.

**Objectives**

- To determine the momentum change of a trolley when a force acts on it, as a function of time

**Equipment**

- five slotted masses (10g) and hanger
- light gate and recorder
- stop clock
- metre rule
- dynamics trolley or airtrack vehicle
- runway or air track
- bench pulley
- string

**Safety**

- Runways and trolleys are very heavy and need to be placed so they will not slide off the benches.
- Air track blowers should be on the floor with the hose secured so that it cannot come loose and blow dust and dirt into people's faces.
- If large masses are used a catch box is needed in the drop zone to keep feet clear.

**CORE PRACTICAL 9:**  
**INVESTIGATE THE RELATIONSHIP BETWEEN THE FORCE EXERTED ON AN OBJECT AND ITS CHANGE OF MOMENTUM** SPECIFICATION REFERENCE  
4.3.82

- Find the gradient of your line of best fit and compare it with your value for  $\frac{M}{g}$ .
- You can take the uncertainty in  $T$  and  $t$  as half the range of repeated readings. You need not work out the uncertainty for every value of  $T$  and  $t$ , but take typical values, neither the largest nor the smallest.
  - Calculate  $\Delta v$ , the actual uncertainty in  $v$ , from the equation  $\Delta v = v \left( \frac{\Delta t}{t} \right)$ . Use a mid-range value for  $v$ .
  - Calculate  $\Delta(mT)$  by multiplying a mid-range value for  $m$  (for example, 30g) by  $\Delta T$ .
  - Use these actual uncertainties to draw error bars in both directions to form error boxes on your graph. Draw one line that is steeper than the line of best fit (LoBF) and one line that is less steep than the LoBF. Both of these lines should pass through the error boxes. Find the gradient of each new line.

The difference between the two gradients of the lines gives you the uncertainty in your gradient and this uncertainty is based on your readings.

Your value for  $\frac{M}{g}$  should lie between these two values if Newton's second law is operating.

This Student Book is accompanied by a **Lab Book**, which includes instructions and writing frames for the Core Practicals for students to record their results and reflect on their work. Practical skills checklists, practice questions and answers are also provided. The Lab Book records can be used as preparation and revision for the Practical Skills Papers.

# ASSESSMENT OVERVIEW

The following tables give an overview of the assessment for the second year of the Pearson Edexcel International Advanced Level course in Physics. You should study this information closely to help ensure that you are fully prepared for this course and know exactly what to expect in each part of the exam. More information about this qualification, and about the question types in the different papers, can be found on page 210 of this book.

PAPER / UNIT 4	PERCENTAGE OF IA2	PERCENTAGE OF IAL	MARK	TIME	AVAILABILITY
<b>FURTHER MECHANICS, FIELDS AND PARTICLES</b> Written exam paper Paper code WPH14/01 Externally set and marked by Pearson Edexcel Single tier of entry	40%	20%	90	1 hour 45 minutes	January, June and October First assessment: January 2020
PAPER / UNIT 5	PERCENTAGE OF IA2	PERCENTAGE OF IAL	MARK	TIME	AVAILABILITY
<b>THERMODYNAMICS, RADIATION, OSCILLATIONS AND COSMOLOGY</b> Written exam paper Paper code WPH15/01 Externally set and marked by Pearson Edexcel Single tier of entry	40%	20%	90	1 hour 45 minutes	January, June and October First assessment: June 2020
PAPER / UNIT 6	PERCENTAGE OF IA2	PERCENTAGE OF IAL	MARK	TIME	AVAILABILITY
<b>PRACTICAL SKILLS IN PHYSICS II</b> Written exam paper Paper code WPH16/01 Externally set and marked by Pearson Edexcel Single tier of entry	20%	10%	50	1 hour 20 minutes	January, June and October First assessment: June 2020

## ASSESSMENT OBJECTIVES AND WEIGHTINGS

ASSESSMENT OBJECTIVE	DESCRIPTION	% IN IAS	% IN IA2	% IN IAL
A01	Demonstrate knowledge and understanding of science	34–36	29–31	32–34
A02	(a) Application of knowledge and understanding of science in familiar and unfamiliar contexts	34–36 9–11	33–36 14–16	34–36 11–14
	(b) Analysis and evaluation of scientific information to make judgments and reach conclusions			
A03	Experimental skills in science, including analysis and evaluation of data and methods	20	20	20

## RELATIONSHIP OF ASSESSMENT OBJECTIVES TO UNITS

UNIT NUMBER	ASSESSMENT OBJECTIVE (%)			
	A01	A02 (A)	A02 (B)	A03
UNIT 1	17–18	17–18	4.5–5.5	0
UNIT 2	17–18	17–18	4.5–5.5	0
UNIT 3	0	0	0	20
<b>TOTAL FOR INTERNATIONAL ADVANCED SUBSIDIARY</b>	<b>33–36</b>	<b>34–36</b>	<b>9–11</b>	<b>20</b>

UNIT NUMBER	ASSESSMENT OBJECTIVE (%)			
	A01	A02 (A)	A02 (B)	A03
UNIT 1	8.5–9.0	8.5–9.0	2.25–2.75	0
UNIT 2	8.5–9.0	8.5–9.0	2.25–2.75	0
UNIT 3	0	0	0	10
UNIT 4	7.3–7.8	8.4–8.9	3.6–4.0	0
UNIT 5	7.3–7.8	8.4–8.9	3.6–4.0	0
UNIT 6	0	0	0	10
<b>TOTAL FOR INTERNATIONAL ADVANCED LEVEL</b>	<b>32–34</b>	<b>34–36</b>	<b>11–14</b>	<b>20</b>

# TOPIC 5 FURTHER MECHANICS

CHAPTER

## 5A

# FURTHER MOMENTUM

Acceleration can be considered as a change in momentum per unit mass. It can often be more exciting than basic calculations such as calculating the changing speed of a car.

Curling is a game which originated in Scotland. It is now an established sport which is popular in Canada and Japan. The sport uses the ideas of conservation of momentum and elastic collisions. Players deliberately collide the stones to deflect their opponents' stones, and to ensure their own stone finishes in a winning position. Also, the friction with the ice causes a change in momentum to slow the stone to a stop.

In this chapter, you will learn about the way forces can change the momentum of an object over time. The chapter will also cover how kinetic energy changes in different types of collisions, whilst momentum is conserved. All of this will be extended to events happening in two dimensions, so vector addition and the resolving of vectors will be revisited in order to make the necessary calculations.

### MATHS SKILLS FOR THIS CHAPTER

- Use of trigonometric functions (*e.g. finding components of momentum vectors*)
- Use of Pythagoras' theorem (*e.g. finding velocity as a vector sum*)
- Changing the subject of an equation (*e.g. rearranging the impulse equation*)
- Substituting numerical values into algebraic equations (*e.g. finding the velocity after a collision*)
- Visualising and representing 2D forms (*e.g. drawing a 2D momentum diagram for a collision between meteors*)

## What prior knowledge do I need?

### Topic 1A (Book 1: IAS)

- How to add forces as vectors
- How to resolve vectors
- Newton's laws of motion

### Topic 1B (Book 1: IAS)

- How to calculate kinetic energy
- Conservation of energy

### Topic 1C (Book 1: IAS)

- How to calculate the momentum of an object
- Conservation of linear momentum in collisions

## What will I study in this chapter?

- The impulse equation and its connection with Newton's second law of motion
- The relationship between the force on an object and its change in momentum
- Conservation of linear momentum in two dimensions
- How to analyse collisions in 2D
- The difference between an elastic and an inelastic collision
- The equation for the kinetic energy of a non-relativistic particle, in terms of its momentum

## What will I study later?

### Topics 6A and 6B

- How electrical and magnetic fields affect the momentum of charged particles

### Topic 7A

- The de Broglie wavelength for a particle and its connection with the momentum of the particle
- Large-angle alpha particle scattering indicating the structure of the atom, with the scattering dependent on momentum conservation

### Topic 7B

- How the momentum affects the size of a circle in which a charged particle is trapped by a magnetic field
- How conservation of momentum affects the creation and detection of new particles

## LEARNING OBJECTIVES

- Explain the difference between elastic and inelastic collisions.
- Make calculations based on the conservation of linear momentum to determine energy changes in collisions.
- Derive and use the equation for the kinetic energy of a non-relativistic particle.

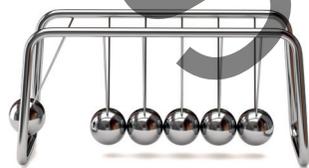
We have seen in **Book 1, Chapter 1C** that linear momentum is always conserved in any collision between objects, and this is responsible for Newton's third law of motion. We also learned that Newton's second law of motion expresses the concept that a force is equivalent to the rate of change of momentum. **Book 1, Chapter 1A** explained how forces can do work, which results in energy transfer. So, does the kinetic energy change in a collision?



▲ **fig A** Damaging a car uses energy. What can we say about the conservation of kinetic energy in a car crash?

## ELASTIC COLLISIONS

In a collision between one pool ball and another, the first one often stops completely and the second then moves away from the collision. As both pool balls have the same mass, the principle of conservation of momentum tells us that the velocity of the second ball must be identical to the initial velocity of the first. This means that the kinetic energy of this system of two balls before and after the collision must be the same. A collision in which kinetic energy is conserved is called an **elastic collision**. In general, these are rare. A Newton's cradle is an example that is nearly perfectly elastic (a tiny amount of energy is lost as heat and sound). A collision caused by non-contact forces, such as alpha particles being scattered by a nucleus (see **Section 7A.1**), is perfectly elastic.



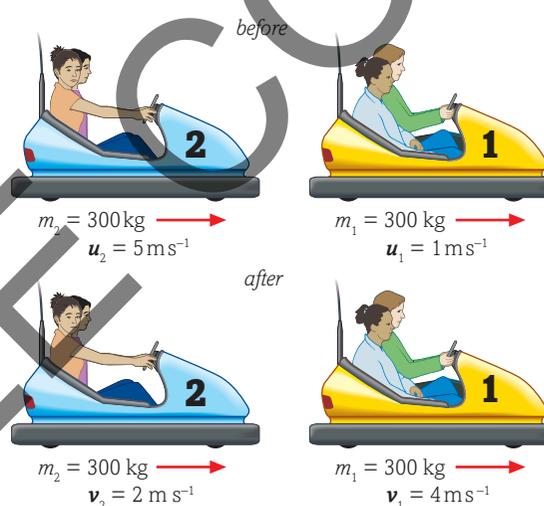
▲ **fig B** Newton's cradle maintains kinetic energy, as well as conserving momentum in its collisions.

## INELASTIC COLLISIONS

In a crash between two bumper cars, the total momentum after the collision must be identical to the total momentum before

the collision. However, if we calculate the total kinetic energy before and after, we find that the total is reduced by the collision. Some of the kinetic energy is transferred into other forms such as heat and sound. A collision in which total kinetic energy is not conserved is called an **inelastic collision**.

## INELASTIC COLLISION EXAMPLE



▲ **fig C** The fun of inelastic collisions.

If you calculate the total momentum before and after the collision in **fig C**, you will see that it is conserved. However, what happens to the kinetic energy?

*Before collision:*

$$E_{k1} = \frac{1}{2} m_1 u_1^2 = \frac{1}{2} \times (300) \times 1^2 = 150 \text{ J}$$

$$E_{k2} = \frac{1}{2} m_2 u_2^2 = \frac{1}{2} \times (300) \times 5^2 = 3750 \text{ J}$$

$$\text{Total kinetic energy} = 3900 \text{ J}$$

*After collision:*

$$E_{k1} = \frac{1}{2} m_1 v_1^2 = \frac{1}{2} \times (300) \times 4^2 = 2400 \text{ J}$$

$$E_{k2} = \frac{1}{2} m_2 v_2^2 = \frac{1}{2} \times (300) \times 2^2 = 600 \text{ J}$$

$$\text{Total kinetic energy} = 3000 \text{ J}$$

Loss in kinetic energy = 900 J. This is an inelastic collision.

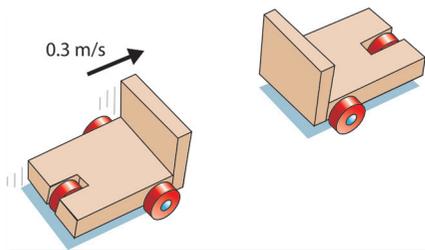
This 'lost' energy has been transferred to heat and sound energy.

## LEARNING TIP

When you are deciding whether a collision is elastic or inelastic, you must only consider the conservation of *kinetic* energy. Total energy in all forms must always be conserved.

**PRACTICAL SKILLS**

**Investigating elastic and inelastic collisions**



**▲ fig D** Crash testing the elasticity of collisions.

You can investigate elastic and inelastic collisions in the school laboratory. If you cause head-on collisions, and record the mass and velocity of each trolley before and after the collisions, you then calculate the momentum at each stage. This should be conserved. You can also then calculate kinetic energy before and after the collisions. Real cars are designed with crumple zones to absorb as much kinetic energy as possible when they crash. This reduces the energy available to cause injury to the passengers. What is the best design for a crumple zone on your experimental trolleys which will absorb kinetic energy?

**!** Safety Note: Carry and place heavy runways so they cannot fall. Use end-stops to prevent the trolleys falling off the ends of the runway.

**PARTICLE MOMENTUM**

We know that the formula for calculating kinetic energy is  $E_k = \frac{1}{2}mv^2$  and that the formula for momentum is  $p = mv$ . We can combine these to get an equation that gives kinetic energy in terms of the momentum and mass.

$$E_k = \frac{1}{2}mv^2 \quad \text{and} \quad v = \frac{p}{m}$$

$$E_k = \frac{1}{2}m\left(\frac{p}{m}\right)^2$$

$$\therefore E_k = \frac{1}{2} \frac{p^2}{m}$$

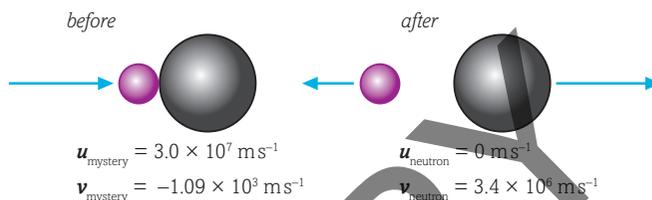
$$\therefore E_k = \frac{p^2}{2m}$$

This formula is particularly useful for calculations involving the kinetic energy of subatomic particles travelling at non-relativistic speeds – that is, much slower than the speed of light.

**PARTICLE COLLISIONS**

In experiments to determine the nature of fundamental particles, physicists detect the movements of many unknown particles. The Large Hadron Collider experiment at CERN, underground near Geneva in Switzerland, produces 600 million particle interactions in its detector every second. The conservation of momentum allows the mass of these particles to be calculated, which helps to identify them. This can be done by colliding the particles produced in the experiment with known particles in the detector.

For example, the detector registers an elastic collision with one of its neutrons which changes the neutron's velocity from stationary to  $3.4 \times 10^6 \text{ m s}^{-1}$ . The collision was 'head-on' with an unknown particle, which was initially moving at 10% of the speed of light, and leaves the collision in the opposite direction at  $1.09 \times 10^3 \text{ m s}^{-1}$ . What is the mass of the mystery particle? The mass of a neutron is  $1.67 \times 10^{-27} \text{ kg}$ .



**▲ fig E** Discovering mystery particles from their momentum and collisions.

*Before collision:*

$$p_{\text{mystery}} = m_{\text{mystery}} \times 3 \times 10^7 = p_{\text{total before}} \quad (p_n = \text{zero})$$

*After collision:*

$$p_{\text{total after}} = (m_{\text{mystery}} \times v_{\text{mystery}}) + (m_n \times v_n)$$

$$= (m_{\text{mystery}} \times -1.09 \times 10^3) + (1.67 \times 10^{-27} \times 3.4 \times 10^6)$$

$$= p_{\text{total before}} = m_{\text{mystery}} \times 3 \times 10^7$$

So:

$$(m_{\text{mystery}} \times -1.09 \times 10^3) + (1.67 \times 10^{-27} \times 3.4 \times 10^6) = m_{\text{mystery}} \times 3 \times 10^7$$

$$(1.67 \times 10^{-27} \times 3.4 \times 10^6) = (m_{\text{mystery}} \times 3 \times 10^7) - (m_{\text{mystery}} \times -1.09 \times 10^3)$$

$$5.678 \times 10^{-21} = (m_{\text{mystery}} \times 30\,001\,090)$$

So:

$$m_{\text{mystery}} = \frac{5.678 \times 10^{-21}}{30\,001\,090} = 1.89 \times 10^{-28} \text{ kg}$$

This is approximately 207 times the mass of an electron, and so this can be identified as a particle called a muon, which is known to have this mass.

**CHECKPOINT**

**SKILLS ANALYSIS**

- An alpha particle consists of two protons and two neutrons. Calculate the kinetic energy of an alpha particle which has a momentum of  $1.08 \times 10^{-19} \text{ kg m s}^{-1}$ :  
(a) in joules (b) in electron volts (c) in MeV.  
(mass of neutron = mass of proton =  $1.67 \times 10^{-27} \text{ kg}$ )
- A bowling ball travelling at  $5 \text{ m s}^{-1}$  strikes the only standing pin straight on. The pin flies backward at  $7 \text{ m s}^{-1}$ . Calculate:  
(a) the velocity of the bowling ball after the collision  
(b) the loss of kinetic energy in this collision.  
(mass of bowling ball =  $6.35 \text{ kg}$ ; mass of pin =  $1 \text{ kg}$ )
- In a particle collision experiment, a mystery particle collides with a stationary neutron and sets the neutron into motion with a velocity of  $1.5 \times 10^7 \text{ m s}^{-1}$ . The mystery particle arrived at a velocity of 1% of the speed of light, and recoiled after collision with a velocity of  $7.5 \times 10^5 \text{ m s}^{-1}$  in the opposite direction. Calculate the mass of the mystery particle, and identify it.

**SUBJECT VOCABULARY**

**elastic collision** a collision in which total kinetic energy is conserved  
**inelastic collision** a collision in which total kinetic energy is not conserved

# 5A 2 MORE COLLISIONS

SPECIFICATION  
REFERENCE

4.3.81 4.3.82 4.3.83 4.3.84 CP9 CP10

CP9 LAB BOOK PAGE 36 CP10 LAB BOOK PAGE 41

## LEARNING OBJECTIVES

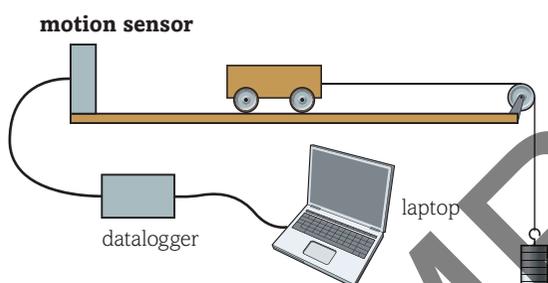
- Apply the conservation of linear momentum to situations in two dimensions.
- Analyse collisions in two dimensions.
- Calculate impulses and changes in momentum.

So far, we have only considered the conservation of linear momentum in one-dimensional collisions, where all objects move forwards and/or backwards along the *same* straight line. This is an unusual situation, and we need to be able to work with more complex movements. Helpfully, momentum is conserved in each dimension separately. So, we resolve vector movements entering a collision into components in each dimension and then calculate following the conservation of momentum in each dimension. After this, we can recombine component vectors to give us an overall vector after a collision. A real world example, as in **fig B**, will illustrate this best.

## PRACTICAL SKILLS

CP9

### Investigating impulse



**fig A** Measuring how impulse changes the momentum of a trolley

In **Book 1, Section 1C.1**, we saw how you can investigate the change in momentum over time for a trolley that is subject to a constant accelerating force. Using the same apparatus, you could again record how different forces acting over different time periods cause the trolley to accelerate to different velocities. From these results, you can calculate the impulse applied in each case. As  $I = F\Delta t = \Delta p = \Delta mv$ , a graph of impulse on the y-axis against change in velocity on the x-axis should give a straight best fit line through the origin. This straight line verifies the impulse equation, and the gradient of it will give the mass of the accelerating trolley and weights.



**Safety Note:** Put a 'catch box' full of soft material under the hanging masses to stop them falling on to feet and use an end stop to prevent the trolley falling off the runway.

## EXAM HINT

Make sure you have a good understanding of this practical as your understanding of the experimental method may be assessed in your exams.

## IMPULSE

The product of a force applied for a known time ( $F \times \Delta t$ ) is known as the **impulse**, and this is equal to the change in momentum:

$$\begin{aligned} \text{impulse (Ns)} &= \text{force (N)} \times \text{time (s)} \\ &= \text{change in momentum (kg m s}^{-1}\text{)} \end{aligned}$$

$$\text{impulse} = F \times \Delta t = \Delta p$$

To stop something moving, we need to remove all of its momentum. This idea allows us to calculate the impulse needed to stop an object moving. If we know how long a force is applied, we could work out the size of that force.

## WORKED EXAMPLE 1

What is the impulse needed to accelerate a 1000 kg car from rest to  $25 \text{ m s}^{-1}$ ?

$$p = m \times v$$

At the start, the car is at rest, so has no momentum. Therefore the change in momentum will equal its final momentum:

$$\Delta p = 1000 \times 25$$

$$\text{impulse} = F \times \Delta t = \Delta p$$

$$I = 25\,000 \text{ kg m s}^{-1}$$

If the car needed to stop in 3.8 seconds, what force would the brakes need to apply?

At the end, the car is at rest, so has no momentum. Therefore the change in momentum will equal its initial momentum:

$$Ft = m\Delta v$$

$$m\Delta v = 25\,000 \text{ kg m s}^{-1}$$

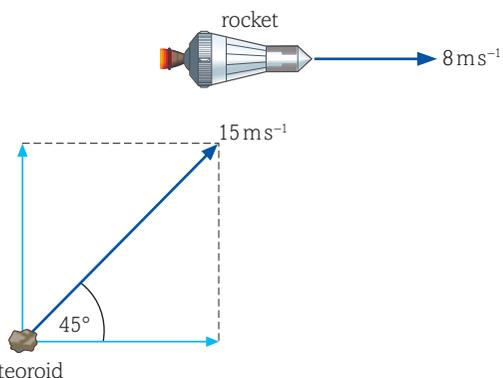
$$F = \frac{m\Delta v}{t}$$

$$F = \frac{25\,000}{3.8}$$

$$F = 6600 \text{ N to 2 significant figures (sf)}$$

## COLLISION VECTORS

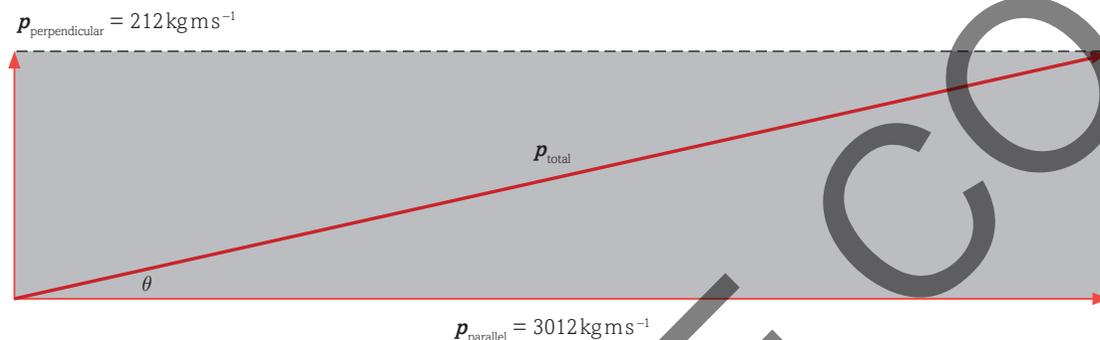
Momentum is a vector quantity. As with all vectors, we can resolve momentum into a right-angle pair of vector components. And we can add components together in two dimensions to find an overall vector. A spacecraft is moving through empty space at  $8 \text{ m s}^{-1}$ . A meteoroid, travelling at  $15 \text{ m s}^{-1}$ , comes from behind and at an angle of  $45^\circ$  to the line of movement of the rocket, crashes into the rocket and becomes embedded in it. The rocket has a mass of 350 kg and the meteorite mass is 20 kg. We can calculate the velocity of the rocket (**fig B**) after the collision.



▲ **fig B** A collision in two dimensions.

After collision:

Vector sum of momenta (**fig C**):



▲ **fig C** Vector sum of total momentum in two dimensions.

$$p_{\text{total}} = \sqrt{(3012^2 + 212^2)} = 3019 \text{ kg m s}^{-1}$$

$$v_{\text{after}} = \frac{p_{\text{total}}}{(m_{\text{rocket}} + m_{\text{meteorite}})} = \frac{3019}{(350 + 20)} = 8.16 \text{ m s}^{-1}$$

Angle of momentum (i.e. direction of velocity) after collision:

$$\theta = \tan^{-1} \left( \frac{212}{3012} \right) = 4.0^\circ$$

So, the spacecraft with embedded meteorite carries on at  $8.16 \text{ m s}^{-1}$  at an angle of  $4.0^\circ$  off the original direction of motion.

Before collision:

Parallel to rocket motion:

$$v_{\text{meteorite}} = 15 \cos 45^\circ = 10.6 \text{ m s}^{-1}$$

$$p_{\text{meteorite}} = 20 \times 10.6 = 212 \text{ kg m s}^{-1}$$

$$p_{\text{rocket}} = 350 \times 8 = 2800 \text{ kg m s}^{-1}$$

$$p_{\text{parallel}} = 2800 + 212 = 3012 \text{ kg m s}^{-1}$$

Perpendicular to rocket motion:

$$v_{\text{meteorite}} = 15 \sin 45^\circ = 10.6 \text{ m s}^{-1}$$

$$p_{\text{meteorite}} = 20 \times 10.6 = 212 \text{ kg m s}^{-1}$$

$$p_{\text{rocket}} = 350 \times 0 = 0 \text{ kg m s}^{-1}$$

$$p_{\text{perpendicular}} = 0 + 212 = 212 \text{ kg m s}^{-1}$$

**EXAM HINT**

Collision and momentum exam questions often ask **Show that ...** In 'show that' questions, you must state the equations you use. Then substitute in values and calculate a final answer that rounds to the approximate value in the question. Give the answer to 1 significant figure more than given in the question to prove you have calculated it yourself, and that it matches with the number in the question.

For example, for the calculation on the left, for an exam question could be 'Show that the total momentum after the collision is  $3020 \text{ kg m s}^{-1}$ .' Our calculations would show:

$$\text{momentum} = 3019 \text{ kg m s}^{-1}$$

We should then conclude the answer with:

$$p_{\text{total}} = 3019 = 3020 \text{ kg m s}^{-1} \text{ (3sf)}$$

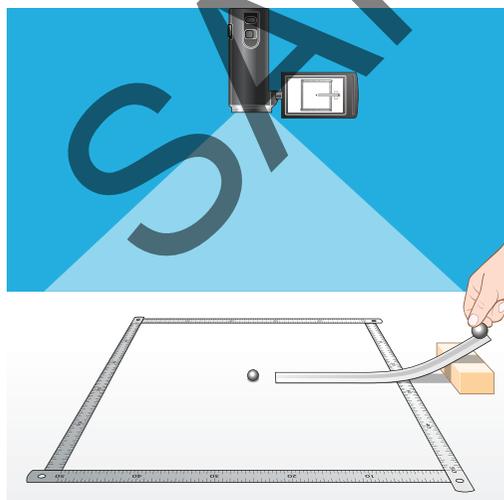
**EXAM HINT**

Make sure you have a good understanding of this practical as your understanding of the experimental method may be assessed in your exams.

**PRACTICAL SKILLS**

CP10

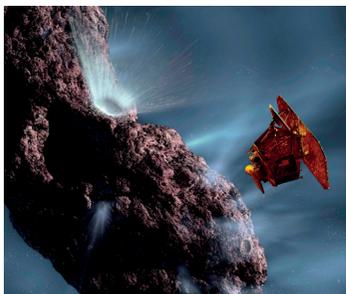
**Investigating 2D collisions**



▲ **fig D** Video analysis of collisions in 2D.

You can investigate two-dimensional collisions in the school laboratory. We saw in **Book 1, Section 1A.2** that by analysing video footage of an object's movement, frame by frame, we can calculate any changes in velocity. With measurement scales in two dimensions, the components of velocity in each dimension can be isolated. This means that separate calculations can be made in each dimension, in order to verify the conservation of momentum in 2D.

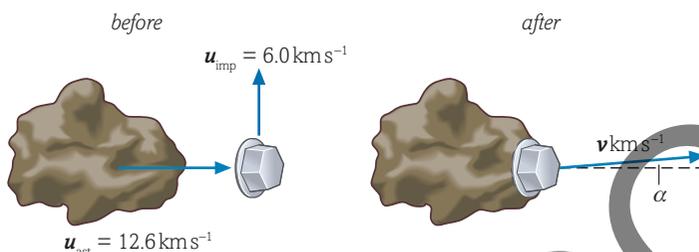
**! Safety Note:** Use a heavy stand and a clamp to secure the camera so that it cannot fall over.



▲ **fig E** The comet Tempel 1 was hit by NASA's Deep Impact probe.

## DEEP SPACE COLLISION

On 4 July 2005, NASA's Deep Impact mission succeeded in crashing a spacecraft into a comet called Tempel 1 (**fig E**). For that mission, the impactor spacecraft had a mass of 370 kg compared with the comet's mass of  $7.2 \times 10^{13}$  kg, so there would have been an insignificant change in the comet's trajectory. Deep Impact was purely intended to study the comet's composition. However, there is an asteroid named Apophis which has a small chance of colliding with Earth in 2035, 2036, or maybe 2037, and there have been some calls for a mission to crash a spacecraft into Apophis in order to move it out of the crash line. The mass of this asteroid is  $6.1 \times 10^{10}$  kg and it is travelling at  $12.6 \text{ km s}^{-1}$ . It has been claimed that a collision by a 4000 kg impactor craft travelling at  $6 \text{ km s}^{-1}$  could change the path of this asteroid enough to ensure it would not hit Earth. If this impactor collided with Apophis at right angles, we can calculate the change in angle of the asteroid (**fig F**).

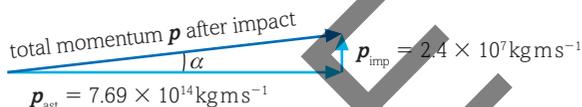


▲ **fig F** Could we hit an asteroid hard enough to save Earth from Asteroid Impact Hazards?

Before collision:

$$p_{\text{ast}} = m_{\text{ast}} u_{\text{ast}} = 6.1 \times 10^{10} \times 12.6 \times 10^3 = 7.69 \times 10^{14} \text{ kg m s}^{-1}$$

$$p_{\text{imp}} = m_{\text{imp}} u_{\text{imp}} = 4 \times 10^3 \times 6 \times 10^3 = 2.4 \times 10^7 \text{ kg m s}^{-1}$$



▲ **fig G** The vector sum of momentum components after asteroid impact.

The momentum of the combined object after the impactor embeds in the asteroid is the vector sum of the two initial momenta, which are at right angles to each other.

After collision:

$$p_{\text{after}} = \sqrt{(p_{\text{ast}})^2 + (p_{\text{imp}})^2} = \sqrt{((7.69 \times 10^{14})^2 + (2.4 \times 10^7)^2)}$$

$$= 7.69 \times 10^{14} \text{ kg m s}^{-1}$$

$$\therefore v_{\text{after}} = \frac{p_{\text{after}}}{m_{\text{total}}} = \frac{7.69 \times 10^{14}}{(6.1 \times 10^{10} + 4 \times 10^3)}$$

$$= 12.6 \text{ km s}^{-1} \text{ (3 significant figures)}$$

There is no significant change in the magnitude of the asteroid's velocity. Is there a significant change in its direction?

Angle of momentum after:

$$\alpha = \tan^{-1} \left( \frac{2.4 \times 10^7}{7.69 \times 10^{14}} \right) = 1.79 \times 10^{-6} \text{ }^\circ$$

Although less than two microdegrees sounds like an insignificantly small angle, this would represent a change in position of nearly 30 km as Apophis crosses the Earth's orbit from one side of the Sun to the other. This might be just enough to prevent a collision with Earth that would have a hundred times more energy than all the explosives used in the Second World War.

### DID YOU KNOW?

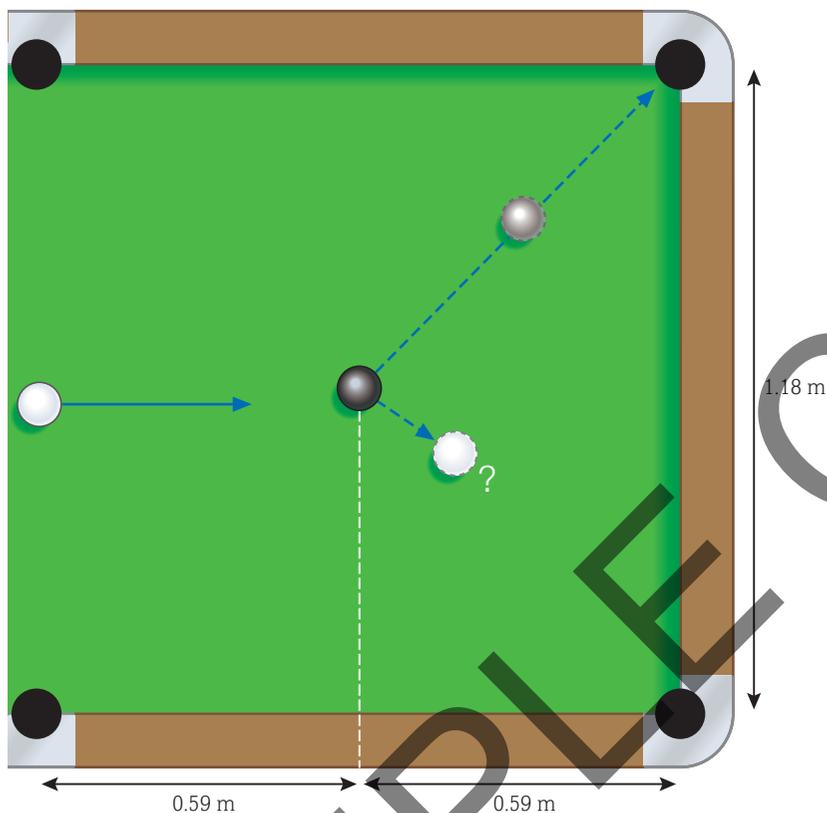
Archer fish catch insect prey by squirting water droplets into the air to knock the insects off leaves above the surface.

Calculations of the mass and velocity of the water droplet, and its impact time, show that the impact force can be ten times stronger than the insect's grip on the leaf.

## CHECKPOINT

- What is the impulse needed to stop a car that has a momentum of  $22\,000\text{ kg m s}^{-1}$ ?
  - If the car brakes could apply a force of  $6800\text{ N}$ , how long would it take to bring the car to a stop?
- In a pool shot, the cue ball has a mass of  $0.17\text{ kg}$ . It travels at  $6.00\text{ m s}^{-1}$  and hits the stationary black ball in the middle of one end of the table. The black ball, also of mass  $0.17\text{ kg}$ , travels away at  $45^\circ$  and  $4.24\text{ m s}^{-1}$ , ending up in the corner pocket.
    - By resolving the components of the black ball's momentum, find out what happens to the cue ball.
    - Is this an elastic or inelastic collision?

SKILLS CRITICAL THINKING



▲ **fig H** 2D momentum calculations can be very important in winning at pool.

- Calculate how fast the impactor spacecraft in **fig F** would have to be travelling if it is to alter the Apophis asteroid's trajectory by one degree. Comment on the answer.
- For the experimental set up shown in **fig D**, suggest two improvements that could be made in order to improve the accuracy of the resolved vectors that would be observable on the video stills.

SKILLS INNOVATION

## SUBJECT VOCABULARY

**impulse** force acting for a certain time causing a change in an object's momentum

$$\text{impulse} = F \times \Delta t$$

# 5A THINKING BIGGER

## ASTEROIDS

SKILLS

CRITICAL THINKING, PROBLEM SOLVING, ANALYSIS, INTERPRETATION, ADAPTIVE LEARNING

This poster from the Planetary Society explains the preparations needed for an asteroid impact with the Earth.

### PUBLIC INFORMATION POSTER

## DEFENDING EARTH

With advanced planning and preparation, we could prevent a disastrous impact from an asteroid or comet. The Planetary Society breaks it down into these five steps for saving the world.

### 1. Find

Astronomers use ground- and space-based telescopes to spot NEOs and have found 90% of the largest ones. Infrared imaging also helps find objects that are too dark to see from their reflected light.

### 2. Track

If we find a near-Earth object, how do we know if it will hit Earth? We need to map its orbit by taking repeated observations. A number of missions, observatories, and systems track the orbits of NEOs, and more are in development.

### 3. Characterize

By characterizing the spin rate, composition, and physical properties of potentially hazardous NEOs, we can better know how to deflect them. Awardees of The Planetary Society's Shoemaker NEO Grant Program are making tremendous contributions in this area.

### 4. Deflect

There is a variety of possible techniques for deflecting a potential impact, but all need more development and testing:

**Slow gravity tractor:** A massive spacecraft follows next to the near-Earth object and uses the spacecraft's gravity to pull the object off its collision course.

**Kinetic impactor:** A swarm of spacecraft slam into the object to knock it off course.

**Laser ablation:** A spacecraft uses lasers to vaporize rock on the object, creating jets that push it off course. The Planetary Society is researching this technique with the University of Strathclyde through their Laser Bees project.

### 5. Coordinate and Educate

An asteroid impact is a worldwide issue that requires immense advance coordination and education. The Planetary Society is taking an active role by working with governments around the world, hosting conferences, doing public outreach, and supporting volunteer efforts.

**What about the nuclear option?** Detonating nuclear devices on or beside an asteroid may be the only viable technique we have today for deflecting an asteroid. But this comes with challenges, including political opposition and the danger of fragment impacts.

  
Find out more at  
[planetary.org/defense](http://planetary.org/defense)

## SCIENCE COMMUNICATION

The poster was produced by the Planetary Society. It aims to explain the issues connected with a possible asteroid collision with the Earth.

- Discuss the tone and level of vocabulary and level of scientific detail in the poster. Who is the intended audience?
  - Discuss which of the images are the most useful to support the text, and which do not add so much.
- Explain which of the five sections on the poster explains the most scientific ideas. Why do you think this section has the most scientific ideas?

### INTERPRETATION NOTE

Consider which sections of the poster describe science that has been tested the most. Which sections are well understood? Which need more research?

## PHYSICS IN DETAIL

Now we will look at the physics in detail. Some of these questions will link to topics elsewhere in this book, so you may need to combine concepts from different areas of physics to work out the answers.

- Look at section 1. *Find* in the poster. What is a NEO?
  - Explain two of the difficulties in finding NEOs.
- Consider an asteroid 1000 km in diameter, with a structure of iron and rock. The overall density of such asteroids is about  $2000 \text{ kg m}^{-3}$ .
  - Estimate the volume of the asteroid. Why is your answer an estimate and not the exact answer?
  - Calculate an estimate for its mass.
  - Imagine the asteroid travelled directly towards the Earth at  $10\,000 \text{ m s}^{-1}$  and collided and embedded into the surface of the Earth. Calculate the change in speed of the Earth. The mass of the Earth is  $5.97 \times 10^{24} \text{ kg}$ .
- A Planetary Society scientist suggests we try to blow the asteroid apart with a nuclear explosion (as in 4. *Deflect*) before it hits the Earth. If the bomb can be set off 24 hours before collision with the Earth, and can split the asteroid into two equal pieces, calculate the force that the nuclear explosion, lasting for 2 seconds, would need to apply to send the two parts off course enough to save the Earth. The Earth's radius is 6400 km.

### PHYSICS TIP

Think about what would determine the motion of the broken pieces after the explosion. Consider conservation of momentum.

## ACTIVITY

Write a short talk for a member of the Planetary Society to give to a school age audience explaining the physics of the 'kinetic impactor' deflection method. This talk could be a part of the activities in 5. *Coordinate and Educate*.

### THINKING BIGGER TIP

You may need to do some further research about the 'kinetic impactor' idea. Concentrate on the conservation of momentum and the vector additions involved.

# 5A EXAM PRACTICE

[Note: In questions marked with an asterisk (\*), marks will be awarded for your ability to structure your answer logically, showing how the points that you make are related or follow on from each other.]

1 An inelastic collision:

- A conserves momentum but not kinetic energy
- B conserves momentum and kinetic energy
- C need not conserve energy
- D need not conserve momentum.

[1]

**(Total for Question 1 = 1 mark)**

2 A tennis ball travelling with the momentum of  $4.2 \text{ kg m s}^{-1}$  is hit by a tennis racquet. The force of  $56 \text{ N}$  from the racquet causes the tennis ball to travel back in the opposite direction with the momentum of  $5.8 \text{ kg m s}^{-1}$ . How long is the ball in contact with the racquet?

- A 0.029 s
- B 0.10 s
- C 0.18 s
- D 5.6 s

[1]

**(Total for Question 2 = 1 mark)**

3 In order to calculate the kinetic energy of a non-relativistic particle, we would need to know its:

- A mass only
- B mass and momentum
- C acceleration and momentum
- D velocity and acceleration.

[1]

**(Total for Question 3 = 1 mark)**

4 In an experiment to accelerate a trolley along a runway, a light gate measured the time the trolley took to pass through it. There were five repeats of the same acceleration test and it took the following readings:

0.87 s, 0.89 s, 0.65 s, 0.76 s, 0.77 s

Which of these is the correct percentage error for this set of time readings?

- A 0.12%
- B 0.15%
- C 15%
- D 30%

[1]

**(Total for Question 4 = 1 mark)**

5 A spacecraft called Deep Space 1, mass  $486 \text{ kg}$ , uses an 'ion-drive' engine. This type of engine is designed to be used in deep space.

The following statement appeared in a website:

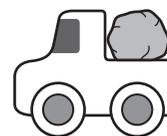
The ion propulsion system on Deep Space 1 expels  $0.13 \text{ kg}$  of xenon propellant each day. The xenon ions are expelled from the spacecraft at a speed of  $30 \text{ km s}^{-1}$ . The speed of the spacecraft is predicted to initially increase by about  $8 \text{ m s}^{-1}$  each day.

Use a calculation to comment on the prediction made in this statement.

[4]

**(Total for Question 5 = 4 marks)**

- 6 (a) Explain what is meant by the principle of conservation of momentum. [2]
- (b) The picture shows a toy car initially at rest with a piece of modelling clay attached to it.

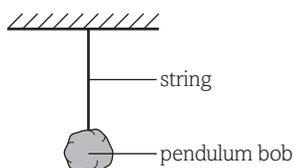


A student carries out an experiment to find the speed of a pellet fired from an air rifle. The pellet is fired horizontally into the modelling clay. The pellet remains in the modelling clay as the car moves forward. The motion of the car is filmed for analysis.

The car travels a distance of  $69 \text{ cm}$  before coming to rest after a time of  $1.3 \text{ s}$ .

- (i) Show that the speed of the car immediately after being struck by the pellet was about  $1 \text{ m s}^{-1}$ . [2]
- (ii) State an assumption you made in order to apply the equation you used. [1]
- (iii) Show that the speed of the pellet just before it collides with the car is about  $120 \text{ m s}^{-1}$   
mass of car and modelling clay =  $97.31 \text{ g}$   
mass of pellet =  $0.84 \text{ g}$  [3]
- (c) The modelling clay is removed and is replaced by a metal plate of the same mass. The metal plate is fixed to the back of the car. The experiment is repeated but this time the pellet bounces backwards.
- \* (i) Explain why the speed of the toy car will now be greater than in the original experiment. [3]
- (ii) The film of this experiment shows that the pellet bounces back at an angle of  $72^\circ$  to the horizontal. Explain why the car would move even faster if the pellet bounced directly backwards at the same speed. [1]

- (d) The student tests the result of the first experiment by firing a pellet into a pendulum with a bob made of modelling clay. They calculate the energy transferred.



The student's data and calculations are shown:

*Data:*

*mass of pellet = 0.84 g*

*mass of pendulum and pellet = 71.6 g*

*change in vertical height of pendulum = 22.6 cm*

*Calculations:*

*change in gravitational potential energy of pendulum and pellet*

$$= 71.6 \times 10^{-3} \text{ kg} \times 9.81 \text{ N kg}^{-1} \times 0.226 \text{ m} = 0.16 \text{ J}$$

*therefore kinetic energy of pendulum and pellet immediately after collision = 0.16 J*

*therefore kinetic energy of pellet immediately before collision = 0.16 J*

*therefore speed of pellet before collision = 19.5 m s<sup>-1</sup>*

There are no mathematical errors but the student's answer for the speed is too small.

Explain which of the statements in the calculations are correct and which are not. [4]

**(Total for Question 6 = 16 marks)**

- 7** James Chadwick is credited with 'discovering' the neutron in 1932.

Beryllium was bombarded with alpha particles, knocking neutrons out of the beryllium atoms. Chadwick placed various targets between the beryllium and a detector. Hydrogen and nitrogen atoms were knocked out of the targets by the neutrons and the kinetic energies of these atoms were measured by the detector.

- (a) The maximum energy of a nitrogen atom was found to be 1.2 MeV.

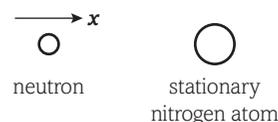
Show that the maximum velocity of the atom is about  $4 \times 10^6 \text{ m s}^{-1}$ .

mass of nitrogen atom =  $14u$ ,

where  $u = 1.66 \times 10^{-27} \text{ kg}$

[3]

- (b) The mass of a neutron is  $Nu$  (where  $N$  is the relative mass of the neutron) and its initial velocity is  $\mathbf{x}$ . The nitrogen atom, mass  $14u$ , is initially stationary and is then knocked out of the target with a velocity,  $\mathbf{y}$ , by a collision with a neutron.



- (i) Show that the velocity,  $\mathbf{z}$ , of the neutron after the collision can be written as

$$\mathbf{z} = \frac{N\mathbf{x} - 14\mathbf{y}}{N} \quad [3]$$

- (ii) The collision between this neutron and the nitrogen atom is elastic. What is meant by an elastic collision? [1]

- (iii) Explain why the kinetic energy  $E_k$  of the nitrogen atom is given by

$$E_k = \frac{Nu(\mathbf{x}^2 - \mathbf{z}^2)}{2} \quad [2]$$

- (c) The two equations in (b) can be combined and  $\mathbf{z}$  can be eliminated to give

$$\mathbf{y} = \frac{2N\mathbf{x}}{N + 14}$$

- (i) The maximum velocity of hydrogen atoms displaced by neutrons in the same experiment was  $3.0 \times 10^7 \text{ m s}^{-1}$ . The mass of a hydrogen atom is  $1u$ . Show that the relative mass  $N$  of the neutron is 1. [3]

- (ii) This equation cannot be applied to all collisions in this experiment. Explain why. [1]

**(Total for Question 7 = 13 marks)**