Kinetic Theory and Ideal Gases

Q1.

A fine-beam tube is used for investigating properties of electrons.

An electron beam is produced inside a spherical glass bulb. The bulb contains neon gas at a very low pressure.

The neon gas is at a pressure of 1.25 Pa and a temperature of 25 °C.

Calculate the number *N* of neon atoms inside the bulb.

bulb diameter = 16.0 cm

(4)

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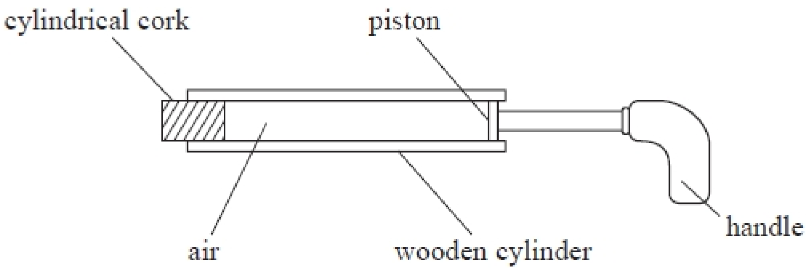
N = ...

(Total for question = 4 marks)

Q2.

The photographs show a wooden pop gun before and after the cork is popped.

The diagram shows a cross-section through the pop gun.



Initially the piston is at the right-hand end of the cylinder, as shown. Then the cork is pushed into the other end of the cylinder.

When the handle is pushed in, the pressure of the air in the cylinder increases. This exerts an additional force on the cork.

Once the additional force is sufficient to overcome the frictional force between the cork and the cylinder, the cork is pushed out.

Calculate the root mean square speed of the molecules of air in the cylinder before the handle is pushed in.

average mass of molecule of air = 4.8×10^{-26} kg
temperature of air = 19 °C

(2)

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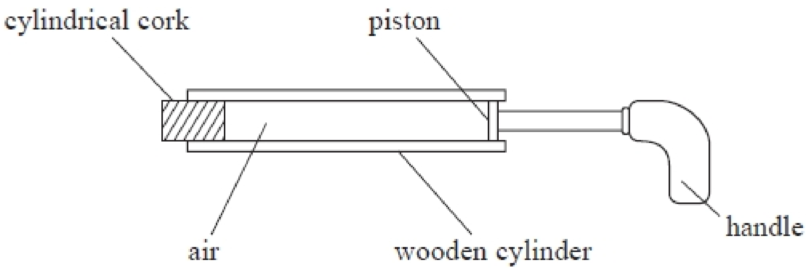
Root mean square speed = ...

(Total for question = 2 marks)

Q3.

The photographs show a wooden pop gun before and after the cork is popped.

The diagram shows a cross-section through the pop gun.



Initially the piston is at the right-hand end of the cylinder, as shown. Then the cork is pushed into the other end of the cylinder.

When the handle is pushed in, the pressure of the air in the cylinder increases. This exerts an additional force on the cork.

Once the additional force is sufficient to overcome the frictional force between the cork and the cylinder, the cork is pushed out.

Calculate the temperature of the gas in the cylinder at the instant the cork is expelled.

volume of air in the cylinder with the handle pulled out = 1.1×10^{-5} m^3
volume of air in the cylinder at the moment the cork is pushed out = 6.7×10^{-6} m^3
atmospheric pressure = 1.0×10^5 Pa
initial temperature of air = 19 °C

(2)

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Temperature = ...

(Total for question = 2 marks)

Q4.

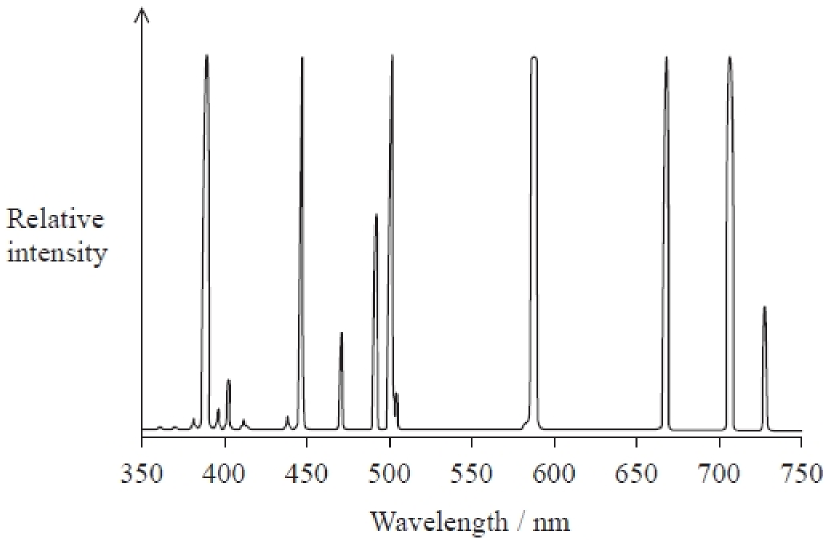
When a large potential difference is applied to a discharge tube, the gas in the discharge tube emits coloured light. When this light is passed through a diffraction grating, an emission spectrum which is made up of a series of lines of different wavelengths may be seen.

The photographs show the spectra produced from a tube containing hydrogen and a tube containing helium.

Hydrogen:

Helium:

The graph shows the relative intensities of different wavelengths of light in the spectrum of a sample of helium.



The graph shows that the lines are not at a single wavelength. This effect is known as thermal Doppler broadening and occurs because of the random motion of the helium atoms.

(i) Explain why the thermal motion of the helium atoms causes the broadening of the spectral lines.

(2)

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(ii) The width of a line may be used to determine the speed of the atoms in the gas and hence the temperature of the gas.

The spectral line with wavelength 587 nm for a particular tube containing helium has a width of 6×10^{-3} nm.

(1) Show that this corresponds to a speed, for a helium atom, of about 1500 m s^{-1}.

(2)

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(2) Assuming that this is the root mean square speed for the helium (He 4) atoms in the tube, calculate the temperature of the gas in the tube.

(3)

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Temperature = ...

(Total for question = 7 marks)

Q5.

The formulae sheet for this paper includes the equation

$$pV = \frac{1}{3}Nm\langle c^2 \rangle$$

Derive the equation $\frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$

(2)

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(Total for question = 2 marks)

Q6.

Our understanding of the atom has developed over time, from early models in which atoms were considered to be hard incompressible spheres, through to the nuclear model of the atom and the ladder model in which electrons exist in a discrete number of allowed energy states.

* The model of atoms as hard incompressible spheres, moving rapidly and randomly, can be used to explain why gases exert a pressure.

Explain, using ideas of momentum, why the pressure exerted by a gas increases as the temperature of the gas increases.

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(Total for question = 6 marks)

Q7.

Tomatoes can be made into a puree.

The puree is heated. When the puree boils, its temperature stays constant, even though the puree continues to be heated.

Explain this observation in terms of molecular energy changes.

(2)

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(Total for question = 2 marks)

Q8.

Barnard's star is a red dwarf star in the vicinity of the Sun. The wavelength of a line in the spectrum of light emitted from Barnard's star is measured to be 656.0 nm. The same light produced by a source in a laboratory has a wavelength of 656.2 nm.

Visible light from the star originates from the photosphere. In the photosphere of Barnard's star, hydrogen and helium atoms are at a temperature of 3100 K.

(i) Calculate the mean kinetic energy of an atom in the photosphere at a temperature of 3100 K.

(2)

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Mean kinetic energy = ...

(ii) Describe how these atoms emit visible light.

(2)

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(Total for question = 4 marks)

Q9.

Air is trapped in a glass tube. When the air is forced into a smaller volume at a constant temperature, the pressure increases.

Which of the following statements about air molecules is a reason why the pressure the trapped air exerts on the tube increases?

☐ **A** The molecules have a greater mean kinetic energy.

☐ **B** The molecules make more frequent collisions with each other.

☐ **C** The molecules make more frequent collisions with the walls of the tube.

☐ **D** The molecules experience a greater change in momentum when they collide with the tube.

(Total for question = 1 mark)

Q10.

A sample of an ideal gas has pressure *p*, volume *V* and absolute temperature *T*.

The volume of the gas is decreased to $\frac{2}{3}V$ and the temperature increased to $\frac{6}{5}T$.

Which of the following is the new pressure of the gas?

☐ **A** $\frac{5}{9}p$

☐ **B** $\frac{4}{5}p$

☐ **C** $\frac{5}{4}p$

☐ **D** $\frac{9}{5}p$

(Total for question = 1 mark)

Q11.

At the Culham Centre for Fusion Energy (CCFE) experiments are carried out to investigate nuclear fusion and the properties of plasmas. A plasma consists of ionised gas, containing positive ions and electrons.

In a plasma experiment 5.0 mg of deuterium, an isotope of hydrogen, occupies a volume of 98 m^3. The temperature of deuterium is raised to 1.3×10^8 K. In this experiment, the deuterium behaves as an ideal gas.

(i) Calculate the pressure due to the deuterium ions.

mass of deuterium ion = 3.3×10^{-27} kg

(3)

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Pressure = ...

(ii) Calculate the root mean square speed of the deuterium ions at this temperature.

(2)

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Root mean square speed = ...

(iii) The temperature of the plasma is monitored using the Doppler effect. Light from a laser is directed into the plasma and the wavelength of the light reflected is measured.

The Doppler shift observed when light is reflected by a deuterium ion is twice the Doppler shift that would be observed for a source of light moving at the same speed as the deuterium ion.

Calculate the maximum wavelength of light that would be detected after reflection from a deuterium ion moving at 1.5 × 106 m s^{-1}.

wavelength of laser light = 1064 nm

(3)

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Maximum wavelength detected = ...

(Total for question = 8 marks)

Q12.

For an ideal gas $pV = NkT$ and $pV = \frac{1}{3}Nm <c^2>$.

Use these relationships to show that the mean kinetic energy of a gas molecule is proportional to the absolute temperature.

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(Total for question = 2 marks)

Q13.

The molecules in a sample of gas have a mass of 5.0×10^{-26} kg.

Calculate the root-mean-square speed of gas molecules in the gas at 25 °C.

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Root-mean-square speed = ...

(Total for question = 3 marks)

Q14.

An electric drinks cooler is an appliance consisting of a thermally insulated compartment and a heat pump that transfers heat from the inside of the cooler to the room in which the cooler is placed.

This maintains the temperature of the inside of the cooler below the temperature of the room.

(Source: http://www.americanas.com.br/produto/110863245/adega-de-vinhos-easycooler-12 garrafas)

On closing the door of the cooler, warm air at atmospheric pressure and at a temperature of 22.5°C is trapped inside. After a time, the internal temperature stabilises at 3.3°C.

A student notices that the door is difficult to open and concludes that this is because the air inside has cooled down and reduced the pressure.

Carry out a calculation to assess the validity of the student's conclusion.

atmospheric pressure = 102 kPa

area of door = 0.15 m^2

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(Total for question = 7 marks)

Q15.

A gas cylinder of volume 0.052 m^3 contains oxygen gas at a temperature of 22°C and a pressure of 2.0×10^5 Pa.
Some of the oxygen in the cylinder is used and the gas pressure falls to 1.6×10^5 Pa.
The temperature remains constant.

Calculate the number of molecules removed from the cylinder

(3)

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Number of molecules removed = ...

(Total for question = 3 marks)

Q16.

When the absolute temperature of an ideal gas is doubled, the internal energy of the gas changes by a factor of

☐ **A** 1

☐ **B** √2

☐ **C** 2

☐ **D** 4

(Total for question = 1 mark)

Mark Scheme - Kinetic Theory and Ideal Gases

Q1.

Question Number	Acceptable answers	Additional guidance	Mark
	• Use of $V = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3$ (1) • Use of $pV = NkT$ (1) • Conversion of temperature to kelvin (1) • $N = 6.5 \times 10^{17}$ (1)	Example of calculation: $V = \frac{4}{3}\pi(0.080\text{ m})^3 = 2.14 \times 10^{-3}\text{ m}^3$ $N = \frac{1.25\text{ Pa} \times 2.14 \times 10^{-3}\text{ m}^3}{1.38 \times 10^{-23}\text{ N m K}^{-1} \times (273 + 25)\text{K}}$ $= 6.50 \times 10^{17}$	4

Q2.

Question Number	Acceptable answers	Additional guidance	Mark
	• Use of $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ (1) • $\sqrt{\langle c^2 \rangle} = 500\text{ m s}^{-1}$ (1)	Example of calculation $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ $\frac{1}{2} \times 4.8 \times 10^{-26}\text{ kg} \times \langle c^2 \rangle = 3/2 \times 1.38 \times 10^{-23}\text{ J K}^{-1} \times 292\text{ K}$ $\langle c^2 \rangle = 2.52 \times 10^5\text{ m}^2\text{ s}^{-2}$ $\sqrt{\langle c^2 \rangle} = 502\text{ m s}^{-1}$	2

Q3.

Question Number	Acceptable answers	Additional guidance	Mark
	• Use of $pV = NkT$ (1) • = 349 K (= 76 °C) (ecf from (a)) (1)	Example of calculation pV/T = constant $T = 1.957 \times 10^5\text{ Pa} \times 6.7 \times 10^{-6}\text{ m}^3 \times 292\text{ K} /$ $1.0 \times 10^5\text{ Pa} \times 1.1 \times 10^{-5}\text{ m}^3$ = 349 K = 76 °C	2

Q4.

Question Number	Acceptable answers		Additional guidance	Mark
(i)	An answer that makes reference to the following: • because the helium atoms are moving, there is a change in frequency/ wavelength of the emitted light • for particles moving away from the observer there will be an decrease in frequency and for particles moving towards the observer there will be an increase in frequency OR for particles moving away from the observer there will be an increase in wavelength and for particles moving towards the observer there will be an decrease in wavelength	(1) (1) (1)		**(2)**

Question Number	Acceptable answers	Additional guidance	Mark
(ii)(1)	• use of $v/c = \Delta\lambda/\lambda$ • $v = 1530\ \text{m s}^{-1}$	Example of calculation: $v\ /\ 3 \times 10^{8}\ \text{m s}^{-1} = 3 \times 10^{-3}\ \text{nm} / 587\ \text{nm}$ $v = 1530\ \text{m s}^{-1}$	**(2)**

Question Number	Acceptable answers	Additional guidance	Mark
(ii)(2)	• mass of helium atom = 4u • use of $\frac{1}{2} m \langle c^2 \rangle = 3/2\ kT$ • $T = 375$ K	Example of calculation: Mass of He atom = $4 \times 1.66 \times 10^{-27}\ \text{kg} = 6.64 \times 10^{-27}\ \text{kg}$ $\frac{1}{2}\ 6.64 \times 10^{-27}\ \text{kg} \times (1530\ \text{m s}^{-1})^2 = 3/2 \times 1.38 \times 10^{-23}\ \text{J K}^{-1} \times T$ $T = 375$ K	**(3)**

Q5.

Question Number	Acceptable answers	Additional guidance	Mark
	• Equate $pV = NkT$ and $pV = \frac{1}{3}Nm < c^2 >$ • Suitable algebra		2

Q6.

Question Number	Acceptable Answer	Additional Guidance	Mark
*	This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully sustained reasoning. Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The table shows how the marks should be awarded for indicative content and structure and lines of reasoning.	IC3 and IC4 must include a mention of the walls/container	6

Number of indicative marking points seen in answer	Number of marks awarded for indicative marking points
6	4
5–4	3
3–2	2
1	1
0	0

	Number of marks awarded for structure of answer and sustained line of reasoning
Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout	2
Answer is partially structured with some linkages and lines of reasoning	1
Answer has no linkages between points and is unstructured	0

IC Points	IC Mark	Max linkage mark avail.	Max final mark
6	4	2	6
5	3	2	5
4	3	1	4
3	2	1	3
2	2	0	2
1	1	0	1
0	0	0	0

	Indicative content: 1. As the temperature of the gas increases the (average) speed/E_k of the atoms increases 2. Greater speed/E_k so the momentum of the atoms increases 3. The rate/frequency of collision of atoms with the container walls increases **Or** the time between collisions with the walls decreases 4. The rate of change of momentum at the walls increases 5. Rate of change of momentum is equal to the force 6. Pressure is $\frac{\text{force}}{\text{area}}$ and the force (on the walls) is greater		

Q7.

Question Number	Acceptable answers	Additional guidance	Mark
	An explanation that makes reference to: • the temperature is constant when the puree boils because the average kinetic energy of the molecules in the puree is constant. **(1)** • when boiling occurs, the thermal energy supplied increases the potential energy of the molecules causing the molecules to move further apart (producing steam) **(1) OR** when boiling occurs, the thermal energy supplied increases the potential energy of the molecules breaking molecular bonds. **(1)**		2

Q8.

Question Number	Acceptable Answer	Additional Guidance	Mark
(i)	• Use of $\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$ **(1)** • mean kinetic energy $= 6.4\times10^{-20}$ J **(1)**	<u>Example of calculation:</u> $\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$ $= \frac{3}{2}\times1.38\times10^{-23}\,\text{J K}^{-1}\times3100\,\text{K} = 6.42\times10^{-20}$ J	2

Question Number	Acceptable Answer	Additional Guidance	Mark
(ii)	• There are electron transitions between energy levels in the atoms, **(1)** • When electrons return to a lower level they emit energy in the form of photons **(1)**		2

Q9.

Question Number	Answers	Mark
	The only correct answer is C ***A*** *is incorrect because the mean kinetic energy is constant at constant temperature* ***B*** *is incorrect because collisions between molecules do not increase the force on the walls of the container* ***D*** *is incorrect because the momentum change depends upon the root mean square speed of the molecules*	1

Q10.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is **D** because pressure is proportional to absolute temperature and inversely proportional to volume, so the effect of the volume change is to increase the pressure by 3/2 and the effect of the temperature change is to increase the pressure by 6/5, and 18/10 = 9/5 A is not correct because a pressure of 5/9 p would depend on pressure being proportional to volume and inversely proportional to absolute temperature rather than being proportional to absolute temperature and inversely proportional to volume B is not correct because this assumes that pressure is proportional to both volume and absolute temperature, giving an answer of 4/5 p, instead of assuming that pressure is proportional to absolute temperature and inversely proportional to volume C is not correct because this assumes that pressure is inversely proportional to both volume and absolute temperature, giving an answer of 5/4 p, instead of assuming that pressure is proportional to absolute temperature and inversely proportional to volume		1

Q11.

Question Number	Acceptable answers		Additional guidance	Mark
(i)	• Use total mass / mass of D ion • Use of $pV = NkT$ • $p = 2.8 \times 10^4$ Pa	(1) (1) (1)	Example of calculation $N = 5.0 \times 10^{-6}$ kg / 3.3×10^{-27} kg $= 1.5 \times 10^{21}$ $p = 1.5 \times 10^{21} \times 1.38 \times 10^{-23}$ J K^{-1} × 130 000 000 K / 98 m^3 $= 2.77 \times 10^4$ Pa	3
(ii)	• Use of $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ Or $pV = 1/3\,(Nm\langle c^2 \rangle)$ (ecf for N and p from (i)) • $\sqrt{\langle c^2 \rangle} = 1.3 \times 10^6$ m s^{-1}	(1) (1)	Example of calculation $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ $\frac{1}{2} \times (3.3 \times 10^{-27}$ kg$) \times \langle c^2 \rangle = 3/2 \times 1.38 \times 10^{-23}$ J K^{-1} × 130 000 000 K $\langle c^2 \rangle = 1.6 \times 10^{12}$ m^2 s^{-2} $\sqrt{\langle c^2 \rangle} = 1.28 \times 10^6$ m s^{-1}	2
(iii)	• Use of $\Delta\lambda / \lambda = v/c$ to determine $\Delta\lambda$ • Adds shift to original wavelength • 1.075×10^{-6} m	(1) (1) (1)	Example of calculation $\Delta\lambda / 1.064 \times 10^{-6}$ m $= 15 \times 10^6$ m s^{-1}/3.00×10^8 m s^{-1} $\Delta\lambda = 5.3 \times 10^{-9}$ m $\lambda + 2\Delta\lambda = 1.075 \times 10^{-6}$ m	3

Q12.

Question Number	Acceptable answers		Additional guidance	Mark
	• Equates right hand sides • Final E_k formula ($\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$) and k is constant	(1) (1)		2

Q13.

Question Number	Acceptable answers		Additional guidance	Mark
	• Use of $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ • with T in Kelvin • $\sqrt{\langle c^2 \rangle} = 497$ m s^{-1}	(1) (1) (1)	Example of calculation $\frac{1}{2} m \langle c^2 \rangle = 3/2\, kT$ $\frac{1}{2} \times 5.0 \times 10^{-26}$ kg $\times \langle c^2 \rangle = 3/2 \times 1.38 \times 10^{-23}$ J K^{-1} × 298 K $\langle c^2 \rangle = 247\,000$ m^2 s^{-2} $\sqrt{\langle c^2 \rangle} = 497$ m s^{-1}	3

Q14.

Question Number	Acceptable answers	Additional guidance	Mark
	• Use of $pV = NkT$ **(1)** • Conversion of temperature to Kelvin **(1)** • $p = 95.4$ kPa **(1)** • Calculation of excess pressure **(1)** • Use of $p = F/A$ **(1)** • $\Delta F = 995$ N **(1)** • Sensible comment, e.g. this is a large force so could make the door hard to open **(1)**	Example of calculation: $\frac{p_1}{T_1} = \frac{p_2}{T_2}$ $p_2 = p_1 \times \frac{T_2}{T_1} = 102 \times 10^3\,\text{Pa} \times \frac{(273+3.3)\text{K}}{(273+22.5)\text{K}}$ $= 95.37 \times 10^3\,\text{Pa}$ $\Delta p = (102 - 95.37)\,\text{kPa} = 6.63\,\text{kPa}$ $\Delta F = A\Delta p = 0.15\,\text{m}^2 \times 6.63 \times 10^3\,\text{Pa} = 994.5\text{N}$	7

Q15.

Question Number	Answer	Mark
	Use of $pV = NkT$ (1) Temperature conversion (1) $\Delta N = 5.1 \times 10^{23}$ (1) [allow use of $pV = nRT$ and use of $N = n \times N_A$ for mp1] Example of calculation: $\Delta N = \frac{V\Delta p}{kT} = \frac{0.052\,\text{m}^3 \times (2.0\times10^5 - 1.6\times10^5)\,\text{Pa}}{1.38\times10^{-23}\,\text{J K}^{-1}(273+22)\text{K}} = 5.11\times10^{23}$	3
	Total for Question	**3**

Q16.

Question Number	Answer	Mark
	C	**1**