11 Internal energy, absolute zero and change of state

Answers to exam practice questions

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1 In an ideal gas we assume that there are no inter-molecular forces (except during a collision) and so an ideal gas has no potential energy. The gas will have internal energy due to the random kinetic energy of the molecules. The answer is therefore C. [Total 1 mark]

2 When ice melts, it does so at a constant temperature (0°C) and so the kinetic energy of its molecules does not change. The volume decreases on melting and the potential energy (and hence the internal energy) increases. The answer is therefore D. [Total 1 mark]

3 Heat and work are both forms of energy and so are measured in J, the unit of energy. Power is the rate of doing work and is measured in J s\(^{-1}\) (= W). The answer is therefore C. [Total 1 mark]

4 a) \(-39°C = (-39 + 273) K = 234 K\)
   b) \(630 K = (630 - 273)°C = 357°C\)
   c) \(156 K = (156 - 273)°C = -117°C\)
   d) \(79°C = (79 + 273) K = 352 K\)
   e) \(54 K = (54 - 273)°C = -219°C\)
   f) \(-183°C = (-183 + 273) K = 90 K\)
   g) \(1083°C = (1083 + 273) K = 1356 K\)
   h) \(2853 K = (2853 - 273)°C = 2580°C\)

   [Total 4 marks]

5 The internal energy of a body is the energy that a body has due to the energy of the atoms or molecules that make up the body. These atoms or molecules have forces between them – bonds – which give them potential energy, and they are in continuous motion, which gives them kinetic energy. The potential energy of the bonds is like the energy stored in an elastic band when it is stretched. Any object in motion has kinetic energy – for example, when you kick a football, the energy from your foot gives the football kinetic energy. [2]

Heating is when energy is transferred between two objects due to a temperature difference. For example, if you put your cold hand on a warm radiator, energy is transferred from the radiator to your hand. This increases the internal kinetic energy of the molecules of your hand and so your hand warms up. [2]

If you rub your hands together you are doing work against the frictional forces between your hands. This work is transferred to the internal energy of the molecules of your hands and so your hands get warm. [2]

[Total 6 marks]
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**Tip:** Note that each of the three terms in *italics* here has been explained individually, with an everyday example given for each. This is essential if you want to get good marks in a question like this.

6 a) Force due to 5 kg mass = 5 kg × 9.8 N kg⁻¹ = 49 N

Frictional force due to bands = (49 – 16) N = 33 N

b) Work done against friction per revolution = force × distance moved

\[ \Delta W = F \Delta x = 33 \text{ N} \times 2\pi \times (29 \times 10^{-3}) \text{ m} = 3.01 \text{ J} = 3 \text{ J} \]

\[ \text{[2]} \]

c) Work done after 400 revolutions = 400 × 3.01 J = 1204 J

\[ \Delta W = mc \Delta \theta \implies c = \frac{\Delta W}{m \Delta \theta} = \frac{1204 \text{ J}}{0.197 \text{ kg} \times 14.5 \text{ K}} = 420 \text{ J kg}^{-1} \text{ K}^{-1} \]

\[ \text{[3]} \]

d) This is likely to be higher than the accepted value as some of the calculated 1200 J of energy will be transferred to the bands and to the surrounding air. The actual energy received by the cylinder will be less than this, so the specific heat capacity will really be less than that calculated. In other words, the experimental value will be too large.

\[ \text{[2]} \]

[Total 9 marks]

7 a) When a tray of water at room temperature is put into a freezer, where the temperature is typically −18°C, the temperature of the water will fall and the kinetic energy of its molecules will decrease, with little change in their potential energy. This continues until the water reaches 0°C, at which point the temperature, and hence the kinetic energy of the molecules, remains constant while the water changes from liquid to solid. A solid is more stable than a liquid and so the potential energy of the molecules has been reduced. Once the water has all changed into ice, the potential energy remains more or less constant while the kinetic energy of the molecules gets less and less as the ice cools from 0°C to −18°C.

b) Energy removed to cool water from 20°C to 0°C:

\[ \Delta E = mc \Delta \theta = 0.200 \text{ kg} \times 4.2 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \times (20 – 0) \text{ K} = 16 800 \text{ J} \]

Energy removed to change this water into ice:

\[ \Delta E = L \Delta m = 3.3 \times 10^5 \text{ J kg}^{-1} \times 0.200 \text{ kg} = 66 000 \text{ J} \]

Energy removed to cool this ice from 0°C to −18°C:

\[ \Delta E = mc \Delta \theta = 0.200 \text{ kg} \times 2.1 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \times (0 – (−18)) \text{ K} = 7 560 \text{ J} \]

Total energy removed = (16 800 + 66 000 + 7560) J = 90 kJ

\[ \text{[1]} \]

[Total 8 marks]

8 a) i) Energy needed to raise temperature of water from 20°C to boiling point, 100°C:

\[ \Delta E = mc \Delta \theta = 1.0 \text{ kg} \times 4.2 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \times (100 – 20) \text{ K} = 3.36 \times 10^5 \text{ J} \]

Energy needed to change this boiling water into steam:

\[ \Delta E = L \Delta m = 2.3 \times 10^6 \text{ J kg}^{-1} \times 1.0 \text{ kg} = 2.3 \times 10^6 \text{ J} \]

Total energy needed = (3.36 × 10⁵ + 2.3 × 10⁶) J = 2.636 × 10⁶ J

\[ \text{[1]} \]

© Tim Akrill and Graham George 2015
Kettle is supplying energy at the rate of 2.4 kW = 2400 J s⁻¹

So time to boil dry would be \( \frac{2.636 \times 10^6 \text{ J}}{2400 \text{ J s}^{-1}} = 1098 \text{ s} = 18.3 \text{ minutes} \) [2]

ii) Before drawing the graph we must do a calculation. From the above, the energy to heat the water from 20°C to 100°C was \( 3.36 \times 10^5 \text{ J} \).

This would take \( \frac{33600 \text{ J}}{2400 \text{ J s}^{-1}} = 140 \text{ s} = 2.3 \text{ minutes} \) [1]

We can now plot a graph like the one below.

The line is horizontal at a constant volume of 1.0 litres whilst the temperature of the water rises from 20°C to 100°C in 2.3 minutes. The line then slopes downwards at a constant rate until all the water has boiled away after 18.3 minutes. [2]

b) i) Your graph should look like the one below. [2]

ii) We must first calculate the resistance that would give an output p.d. of 3.0 V when the thermistor is at 0°C. From the graph, the resistance of the thermistor at 0°C is 32 kΩ.

We can use the formula \( \frac{V_{\text{in}}}{V_{\text{out}}} = V_{\text{in}} \times \frac{R_1}{R_2 + R_2} \) and rearrange to give

\[
\frac{V_{\text{in}}}{V_{\text{out}}} = \frac{R_1 + R_2}{R_2} \Rightarrow \frac{9 \text{ V}}{3 \text{ V}} = 3 = \frac{R_1 + R_2}{R_2} \Rightarrow 3R_2 = R_1 + R_2 \Rightarrow 2R_2 = R_1
\]
As \( R_1 = 32 \, \text{k}\Omega \Rightarrow R_2 = 16 \, \text{k}\Omega \)  \[2\]
The most suitable resistor would therefore be the 15 k\(\Omega\) resistor.  \[1\]

This is rather a long-winded way of calculating the required resistance. As the numbers are simple, you should be able to spot that if the output is 3 V, then 6 V must be dropped across the thermistor. The ratio of the voltage across the output to that across the thermistor is then 1:2. The output resistance must therefore be half that of the thermistor resistance, giving an output resistance of \( \frac{1}{2} \times 32 \, \text{k}\Omega = 16 \, \text{k}\Omega \).

iii) The purpose of the potentiometer is to ‘fine tune’ the output resistance to the exact value required for the output voltage to be 3.0 V when the thermistor is at 0°C.  \[1\]

iv) The circuit can be calibrated by putting the thermistor in a funnel of melting ice and adjusting the output voltage to be exactly 3.0 V by varying the resistance of the potentiometer.  \[2\]

[Total 16 marks]

9 a) Absolute zero is the lowest temperature that can theoretically be reached. In terms of the kinetic theory, it is the temperature at which the molecules of matter have their lowest possible average kinetic energy. In a simplified model, the molecules are considered to have no kinetic energy at absolute zero: in other words, they have no random movement. In practice, quantum mechanics requires that they have a minimum kinetic energy, called the zero-point energy.  \[2\]

b) Kammerlingh Onnes' achievement of preparing liquid helium led initially to experimental work in low temperature physics, in particular, in superconductivity and superfluidity. This gave rise to the development of quantum mechanics to explain these phenomena. In turn, quantum mechanics has contributed to today's technology, such as computers and MRI scanners.  \[2\]

c) A superconductor is a material that at low temperatures has no electrical resistance. This means that once a current is created in it, the charge will continue to flow, even if the source of the current (e.g. battery) is removed.  \[2\]

d) Practical use of superconductors is now being made in creating very powerful electromagnets. These are used, for example, in particle physics, such as the Large Hadron Collider (LHC) at CERN, in MRI scanners and magnetic levitating trains. Research is being undertaken in the application of superconductors in the generation and transmission of electricity and in high-powered computers.  \[2\]

[Total 8 marks]
11 a) Efficiency $= \frac{T_1 - T_2}{T_1} \times 100\%$ where the temperatures are in kelvin, K.

$T_1 = 600°C = (600 + 273) K = 873 K$

$\Rightarrow 46\% = \frac{(873 - T_2) K}{873 K} \times 100\%$

$\Rightarrow 46 \times 873 \times 100 = (873 - T_2)$

$\Rightarrow 873 - T_2 = 402$

$\Rightarrow T_2 = (873 - 402) K = 471 K = 198°C = 200°C$

b) $T_1 = 700°C = (700 + 273) K = 973 K$, and $T_2 = 471 K$ as found in part (a).

Efficiency $= \frac{T_1 - T_2}{T_1} \times 100\%$

$= \frac{(973 - 471) K}{973 K} \times 100\% = 52\%$

So the manufacturer’s claim that an efficiency of 50 % will be achieved with a steam temperature of 700°C is valid.

c) The remaining 50 % or so of the energy could be used as a piped hot water supply to the district surrounding the power station for use in houses and factories. This is called a combined heat and power (CHP) system. In some power stations, this energy is recycled to heat the steam before it enters the turbine.

[Total 8 marks]

Stretch and challenge

11 a) i) The atoms in a metal are arranged in a regular pattern called a lattice. The atoms in the lattice are held in position by the interatomic bonds, rather like springs (see Figure 11.1 on page 197 of your textbook). This enables the atoms to vibrate about their mean positions. The energy of these lattice vibrations is dependent on the temperature.

In a metal, the outer electrons are only loosely bound to the atom and can move randomly from atom to atom. At any one time there is, on average, about one electron per atom that is not attached to a particular atom. As this is the mechanism by which metals conduct electricity, these electrons are called conduction electrons.

ii) When an electric field is applied to a metal, the conduction electrons experience a force, which causes them to drift in the direction of the applied field. The moving electrons experience an equal and opposite force due to the positive lattice ions – electrical resistance – and so the electrons drift at a constant speed – electric current.

[Total 8 marks]
b) In the equation  
\[ c = \alpha T^3 + \gamma T \]
the units must be the same on both sides of the equation. As the units of \( c \) are J kg\(^{-1}\) K\(^{-1}\), the units of \( \frac{\alpha T^3}{k^3} \) must also be J kg\(^{-1}\) K\(^{-1}\). This means that the units of \( \alpha \) must be:

\[ \frac{J}{kg^{-1}K^{-1}} = J kg^{-1} K^{-4} \]

\[ \boxed{[2]} \]

c) The lattice vibrations and conduction electrons make an equal contribution to the specific heat capacity when:

\[ \alpha T^3 = \gamma T \]

Dividing both sides by \( T \) gives:

\[ \alpha T^2 = \gamma \Rightarrow T = \sqrt{\frac{\gamma}{\alpha}} = \sqrt{\frac{5.8 \times 10^{-3} J kg^{-1} K^{-2}}{1.7 \times 10^{-4} J kg^{-1} K^{-4}}} \]

\[ = 5.8 K \approx 6 K \]

\[ \boxed{[1]} \]

d) At 5.8 K, as \( \alpha T^3 = \gamma T \), we can express \( c = \alpha T^3 + \gamma T \) as:

\[ c = \gamma T + \gamma T = 2\gamma T \]

\[ = 2 \times 5.8 \times 10^{-3} J kg^{-1} K^{-2} \times 5.8 K \]

\[ = 0.067 J kg^{-1} K^{-1} \]

\[ \boxed{[1]} \]

\[ \boxed{[2]} \]

\[ \boxed{[3]} \]

12 a) You should find values the \( c \) at temperatures \( T \) of 1 K, 2 K, 3, ..., 10 K.

Then plot a graph of \( c \) against \( T \). Your graph should look like the figure below.

![Graph of c vs T](image)

The energy needed to increase the temperature of 5 g of silver from 0 K to 10 K can then be found determined by finding the area under the graph from 0 K to 10 K (in J kg\(^{-1}\)) and multiplying this by \( 5.0 \times 10^{-3} \) kg. You should get a value of about \( 4 \times 10^{-3} \).
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b) \[ \delta E = mc\delta T = m(\alpha T^3 + \gamma T)\delta T \]
\[ E = m\int_0^{10K} (\alpha T^3 + \gamma T) dT = m\left[ \frac{\alpha T^4}{4} + \frac{\gamma T^2}{2} \right]_0^{10K} \]
\[ = 5.0 \times 10^{-3} \text{ kg} \times \left[ \frac{1.7 \times 10^{-4}\text{ J kg}^{-1}\text{K}^{-4} \times (10\text{ K})^4}{4} + \frac{5.8 \times 10^{-3}\text{ J kg}^{-1}\text{K}^{-2} \times (10\text{ K})^2}{2} \right] \]
\[ = 5.0 \times 10^{-3} \text{ kg} \times (0.425 + 0.290) \text{ J kg}^{-1} \]
\[ = 3.6 \times 10^{-3} \text{ J} \]

[Total 12 marks]

13 a) As temperature is related to the kinetic energy \( \frac{1}{2}mv^2 \) of the atoms, slowing down the atoms will reduce their kinetic energy and therefore the temperature.

b) \[ E = hf = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34}\text{ J s} \times 3.00 \times 10^8 \text{ m s}^{-1}}{589.6 \times 10^{-9} \text{ m}} \]
\[ = 3.37 \times 10^{-19} \text{ J} \]
\[ E = \frac{3.37 \times 10^{-19}\text{ J}}{1.6 \times 10^{-19} \text{ J eV}^{-1}} = 2.109 \text{ eV} = 2.1 \text{ eV} \]

c) From de Broglie:
\[ \lambda = \frac{\hbar}{p} \Rightarrow p = \frac{\hbar}{\lambda} = \frac{6.63 \times 10^{-34}\text{ J s}}{589.6 \times 10^{-9} \text{ m}} \]
\[ \nu = 1.12 \times 10^{-27} \text{ kg m s}^{-1} \]

[1 mark]

d) The law of conservation of momentum states the total momentum of a system remains the same provided that no resultant external force acts on the system.

Consider the momentum of the system shown in the figure below.

Before the sodium atom absorbs the photon of momentum \( p \) (Figure a above), the momentum of the system is \( (Mv - p) \) to the right.

After absorption (Figure b above), the momentum is \( M(v - \Delta v) \) to the left.

By conservation of momentum \( M(v - \Delta v) = (Mv - p) \) \( \Rightarrow M\Delta v = p \)

This means that \( \Delta v \) is in the same direction as \( p \) (to the left) so the atom will slow down.

[1 mark]

e) From (d) we have \( M\Delta v = p \) \( \Rightarrow \Delta v = \frac{p}{M} \)

[1 mark]

f) \[ \Delta v = \frac{p}{M} = \frac{1.12 \times 10^{-27}\text{ kg m s}^{-1}}{(23 \times 1.66 \times 10^{-27}\text{ kg})} \]
\[ = 0.029 \text{ m s}^{-1} = 3 \text{ cm s}^{-1} \]

[1 mark]
g) The sodium atom has an original speed of \(570\, \text{m s}^{-1}\). Each collision slows it down by \(0.029\, \text{m s}^{-1}\), so to bring it to rest the number of collisions needed will be:

\[
\text{number of collisions} = \frac{570\, \text{m s}^{-1}}{0.029\, \text{m s}^{-1}}
\]

\[= 19\,655\, \text{collisions} \approx 20\,000\, \text{collisions}.\]  

h) As there are \(10^7\) absorptions per second, the time required will be:

\[t = \frac{20\,000\, \text{collisions}}{1 \times 10^7\, \text{collisions s}^{-1}} = 2\, \text{ms}\]

This would suggest that an atom would be stopped in a matter of milliseconds.

i) A sodium atom will selectively absorb photons that have exactly the right amount of energy, \(hf\), to excite an electron to a higher energy level \((hf = E_2 - E_1)\). The frequency \(f\) of photons for which this occurs is called the resonant frequency.

j) The laser is tuned to a frequency slightly below that of the resonant frequency so that the Doppler shift, due the speed of approach of the atom relative to the photon, brings the frequency to exactly the resonant frequency. This means that an atom will absorb photons coming head-on towards it, but not photons coming from behind, which will have a Doppler shift away from the resonant frequency.

k) Doppler shift:

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta f}{f} = \frac{v}{c} \Rightarrow \Delta f = \frac{fv}{c}
\]

As \(c = \frac{\lambda}{f}\) \(\Rightarrow f = \frac{c}{\lambda}\)

\[
\Rightarrow \Delta f = \frac{cv}{\lambda c} = \frac{v}{\lambda} = \frac{570\, \text{m s}^{-1}}{589.6 \times 10^{-9}\, \text{m}}
\]

\[= 9.67 \times 10^8\, \text{Hz} = 0.97\, \text{GHz}\]

[Total 24 marks]