1 Born–Haber cycles provide a model that chemists use to determine unknown enthalpy changes from known enthalpy changes. In this question, you will use a Born–Haber cycle to determine an enthalpy change of hydration.

(a) Magnesium chloride has a lattice enthalpy of –2493 kJ mol^{-1}.

Define in words the term *lattice enthalpy*.

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.... **[2]**

(b) The table below shows the enthalpy changes that are needed to determine the enthalpy change of hydration of magnesium ions.

enthalpy change	**energy/kJ mol^{-1}**
lattice enthalpy of magnesium chloride	–2493
enthalpy change of solution of magnesium chloride	–154
enthalpy change of hydration of chloride ions	–363

(i) Why is the enthalpy change of hydration of chloride ions exothermic?

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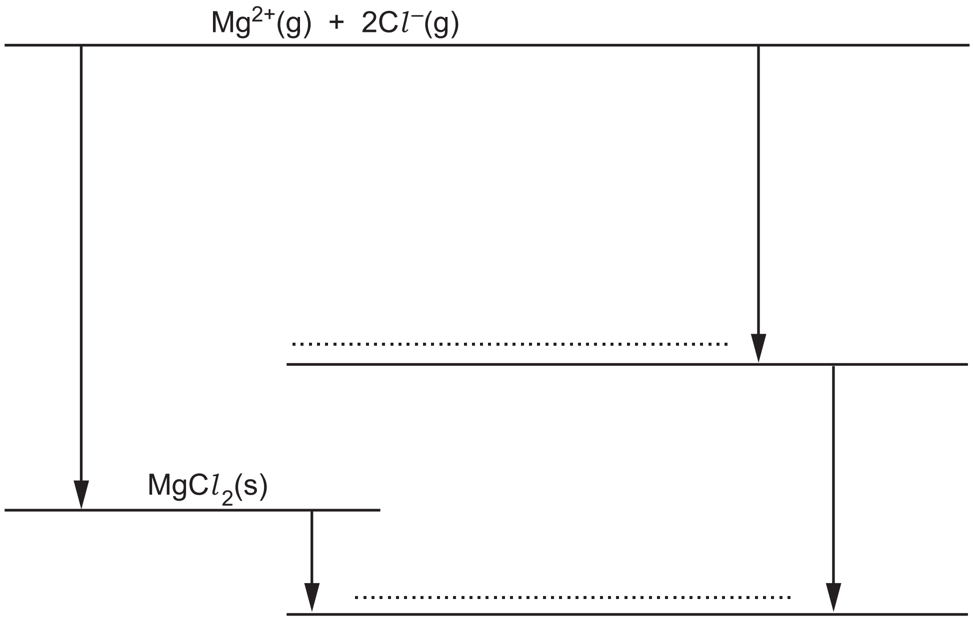
.... **[1]**

(ii) In this part, you will use the Born–Haber cycle to determine the enthalpy change of hydration of magnesium ions.

On the two dotted lines, add the species present, including state symbols.



[2]

(iii) Calculate the enthalpy change of hydration of magnesium ions.

answer = ... kJ mol^{-1} **[2]**

(c) The enthalpy change of hydration of magnesium ions is more exothermic than the enthalpy change of hydration of calcium ions.

Explain why.

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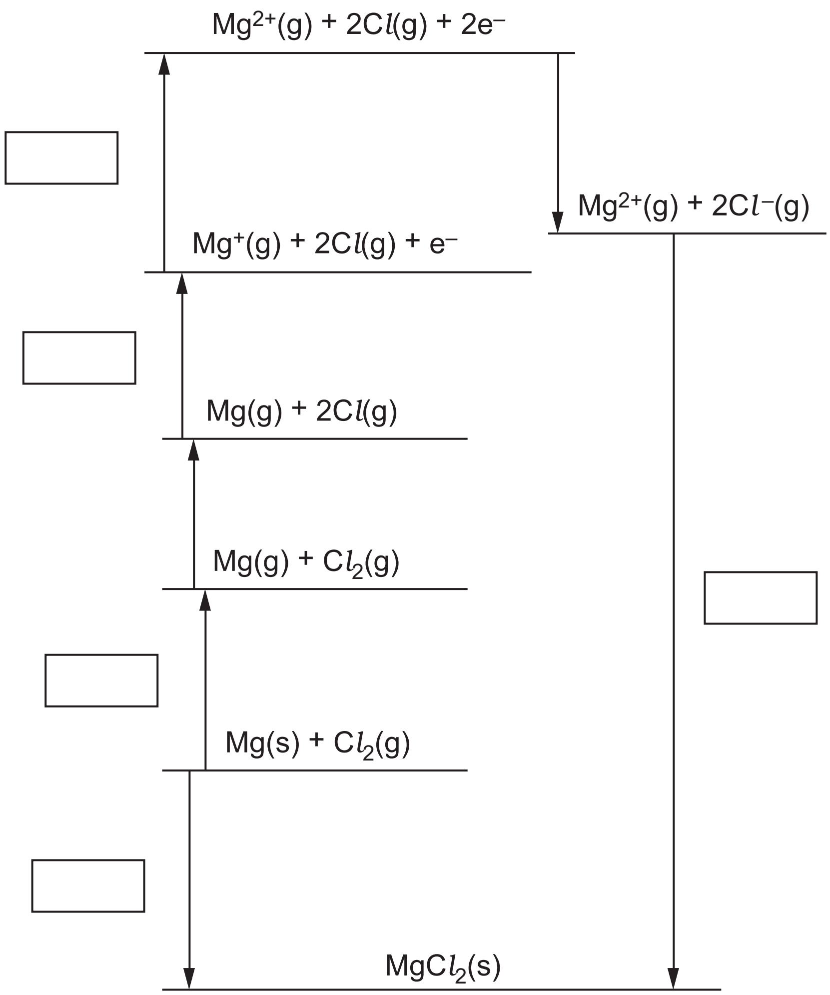
[Total: 9]

2 Lattice enthalpy can be used as a measure of ionic bond strength. Lattice enthalpies are determined indirectly using an enthalpy cycle called a Born–Haber cycle.

The table below shows the enthalpy changes that are needed to determine the lattice enthalpy of magnesium chloride, $MgCl_2$.

letter	enthalpy change	energy/ $kJ\,mol^{-1}$
A	1st electron aff nity of chlorine	–349
B	1st ionisation energy of magnesium	+736
C	atomisation of chlorine	+150
D	formation of magnesium chloride	–642
E	atomisation of magnesium	+76
F	2nd ionisation energy of magnesium	+1450
G	lattice enthalpy of magnesium chloride	

(a) On the cycle below, write the correct letter in each empty box.



[3]

(b) Use the Born–Haber cycle to calculate the lattice enthalpy of magnesium chloride.

answer = ... kJ mol^{-1} **[2]**

(c) Magnesium chloride has stronger ionic bonds than sodium chloride.

Explain why.

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[Total: 8]

3 Ammonia is one of our most important chemicals, produced in enormous quantities because of its role in the production of fertilisers.

Much of this ammonia is manufactured from nitrogen and hydrogen gases using the Haber process. The equilibrium is shown below.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H = -92\,kJ\,mol^{-1}$$

(a) (i) Write an expression for K_c for this equilibrium.

[1]

(ii) Deduce the units of K_c for this equilibrium.

.... **[1]**

(b) A research chemist was investigating methods to improve the synthesis of ammonia from nitrogen and hydrogen at 500 °C.

- The chemist mixed together nitrogen and hydrogen and pressurised the gases so that their total gas volume was 6.0 dm^3.
- The mixture was allowed to reach equilibrium at constant temperature and without changing the total gas volume.
- The equilibrium mixture contained 7.2 mol N_2 and 12.0 mol H_2.
- At 500 °C, the numerical value of K_c for this equilibrium is 8.00×10^{-2}.

Calculate the amount, in mol, of ammonia present in the equilibrium mixture at 500 °C.

equilibrium amount of NH_3 = ……………………... mol **[4]**

(c) The research chemist doubled the pressure of the equilibrium mixture whilst keeping all other conditions the same. As expected the equilibrium yield of ammonia increased.

(i) Explain in terms of le Chatelier's principle why the equilibrium yield of ammonia increased.

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(ii) Explain in terms of K_c why the equilibrium yield of ammonia increased.

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.... **[3]**

(d) For the industrial manufacture of ammonia, nitrogen and hydrogen gases are required in large quantities from readily available resources.

Various methods have been developed to obtain hydrogen gas for this process.

(i) Much of the hydrogen is obtained by reacting together natural gas (methane) and steam.

Construct an equation for this reaction.

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(ii) Natural gas is a fossil fuel and the annual production of ammonia accounts for about 2% of all methane consumption. In the future, as fossil fuels become more depleted, the use of methane for ammonia production may become too expensive.

Suggest another process that might be used in the future to obtain hydrogen gas for the Haber process.

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(e) In the industrial production of ammonia, a temperature in the range 400–500 °C is used.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H = -92\,kJ\,mol^{-1}$$

Standard entropies of $N_2(g)$, $H_2(g)$ and $NH_3(g)$ are given in the table below.

substance	$N_2(g)$	$H_2(g)$	$NH_3(g)$
S / $J\,K^{-1}\,mol^{-1}$	191	131	192

(i) Show that the formation of ammonia from nitrogen and hydrogen gases should be feasible at room temperature (25 °C).

[6]

(ii) Explain, in terms of entropy, why this reaction is **not** feasible at very high temperatures.

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(iii) Suggest why a temperature of 400–500 °C is used for ammonia production, despite the reaction being feasible at room temperature.

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[Total: 22]

4 Lattice enthalpies can be calculated indirectly using Born–Haber cycles.

Table 2.1 shows enthalpy changes needed to calculate the lattice enthalpy of sodium oxide, Na_2O.

letter	**enthalpy change**	**energy /kJ mol^{-1}**
A	1st electron affinity of oxygen	–141
B	2nd electron affinity of oxygen	+790
C	1st ionisation energy of sodium	+496
D	atomisation of oxygen	+249
E	atomisation of sodium	+108
F	formation of sodium oxide	–414
G	lattice enthalpy of sodium oxide	

Table 2.1

(a) Define the term *lattice enthalpy*.

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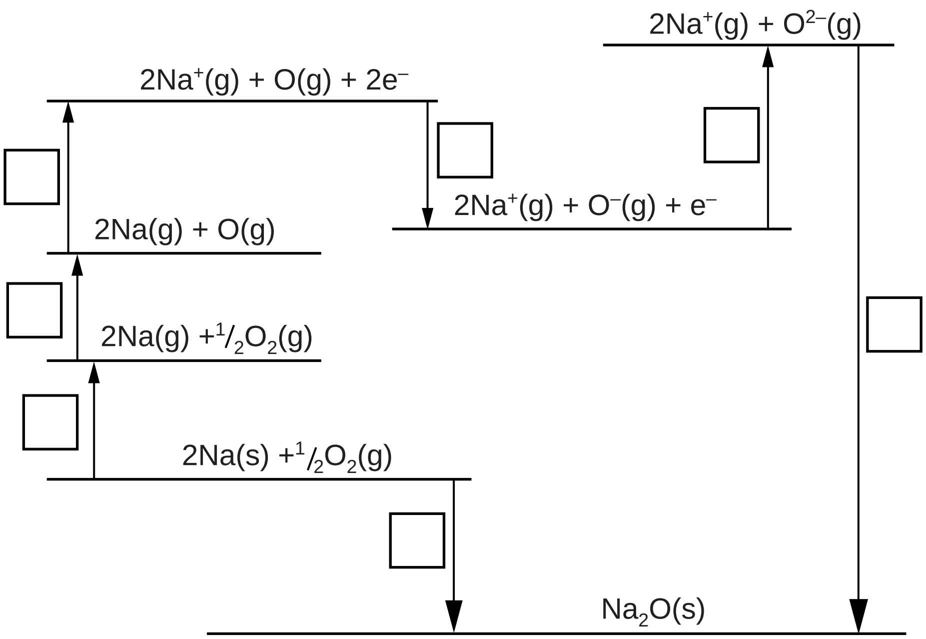
.... **[2]**

(b) The Born–Haber cycle below links the lattice enthalpy of sodium oxide with its enthalpy change of formation.

(i) On the Born–Haber cycle, write the correct letter from **Table 2.1** in each box.



[3]

(ii) Calculate the lattice enthalpy of sodium oxide, **G**.

answer = ... kJ mol^{-1} **[2]**

(c) Explain why it is difficult to predict whether the lattice enthalpy of magnesium sulfide would be more or less exothermic than the lattice enthalpy of sodium oxide.

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(d) A student wanted to determine the lattice enthalpy of sodium carbonate, Na_2CO_3. Unfortunately this is very difficult to do using a similar Born–Haber cycle to that used for sodium oxide in **(b)**.

(i) Suggest why this is very difficult.

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(ii) The student thought that he could determine the lattice enthalpy of Na_2CO_3 using a Born–Haber cycle that links lattice enthalpy with enthalpy change of solution.
The enthalpy change of solution of Na_2CO_3 is exothermic.

- Sketch this Born–Haber cycle,
- Explain how the lattice enthalpy of Na_2CO_3 could be calculated from the enthalpy changes in the cycle.

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[Total: 14]