

**OCR A Chemistry A-Level**  
Module 5 - Physical Chemistry &  
Transition Elements

**Equilibria**  
Notes and Example Calculations

Answers given at the end of the booklet



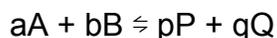


## The Equilibrium Constant, K<sub>c</sub>

### Le Chatelier Principle

If a closed system under equilibrium is subjected to a change, the system will move to minimise the effect of the change. These changes can be either temperature, pressure or concentration.

The equilibrium constant shows where the equilibrium lies for a general reaction:

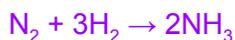


The equilibrium constant expression is:

$$K_c = \frac{[P]^p [Q]^q}{[A]^a [B]^b}$$

### Example 1:

Write the equilibrium constant expression for this reaction and include the units:



**Step 1:** Write an expression for K<sub>c</sub>.

[Remember it is always products over reactants.]

$$\Rightarrow K_c = \frac{[NH_3]^2}{[N_2] [H_2]^3}$$

**Step 2:** Find the units for K<sub>c</sub>.

$$\frac{\cancel{\text{Mol dm}^{-3}} \times \cancel{\text{Mol dm}^{-3}}}{\cancel{\text{Mol dm}^{-3}} \times \cancel{\text{Mol dm}^{-3}} \times \cancel{\text{Mol dm}^{-3}} \times \cancel{\text{Mol dm}^{-3}}}$$

⇒ Units: **mol<sup>-2</sup>dm<sup>6</sup>**

### Example 2:





For the equilibrium:



the equilibrium concentrations of  $\text{PCl}_5$ ,  $\text{PCl}_3$  and  $\text{Cl}_2$  are 1.0, 0.205 and 0.205 mol dm<sup>-3</sup> respectively. Calculate the value of  $K_c$ .

**Step 1:** Write an equilibrium constant expression for this reaction.

$$\Rightarrow K_c = \frac{[\text{Cl}_2] [\text{PCl}_3]}{[\text{PCl}_5]}$$

**Step 2:** Input the values with the corresponding molecules into the expression.

$$\begin{aligned} \Rightarrow K_c &= \frac{(0.205) \times (0.205)}{1} \\ &= \underline{\underline{0.042}} \text{ mol dm}^{-3} \end{aligned}$$

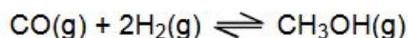
## Worked Exam Style Questions

### Question 1

*Syngas* is a mixture of carbon monoxide and hydrogen gases, used as a feedstock for the manufacture of methanol.

A dynamic equilibrium was set up between carbon monoxide,  $\text{CO}$ , hydrogen,  $\text{H}_2$ , and methanol,  $\text{CH}_3\text{OH}$ , in a 2.0 dm<sup>3</sup> sealed vessel.

The equilibrium is shown below.



The number of moles of each component at equilibrium is shown below

component	$\text{CO}(\text{g})$	$\text{H}_2(\text{g})$	$\text{CH}_3\text{OH}(\text{g})$
number of moles at equilibrium	$6.20 \times 10^{-3}$	$4.80 \times 10^{-2}$	$5.20 \times 10^{-5}$

(i) Write an expression for  $K_c$  for this equilibrium system.





(ii) Calculate  $K_c$  for this equilibrium. State the units.

$$K_c = \dots\dots\dots \text{units:}\dots\dots\dots$$

[4]

**Step 1:** Write the  $K_c$  expression.

$$\Rightarrow K_c = \frac{[\text{CH}_3\text{OH}]}{[\text{CO}] [\text{H}_2]^2}$$

**Step 2:** Convert moles to concentration. Use the formula: Concentration = Moles / Volume.

$$6.2 \times 10^{-3} / 2 = 3.1 \times 10^{-3}$$

$$4.8 \times 10^{-2} / 2 = 2.4 \times 10^{-2}$$

$$5.2 \times 10^{-5} / 2 = 2.6 \times 10^{-5}$$

**Step 3:** Input the values into the expression.

$$K_c = \frac{2.6 \times 10^{-5}}{(2.4 \times 10^{-2})^2 \times 3.1 \times 10^{-3}} = \underline{\underline{14.56}}$$

**Step 4:** Work out the units

$\frac{\text{Mol dm}^{-3}}{\text{Mol dm}^{-3} \times \text{Mol dm}^{-3} \times \text{Mol dm}^{-3}}$
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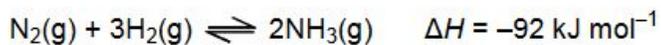
$$\Rightarrow \underline{\underline{\text{mol}^{-2}\text{dm}^6}}$$





### Question 2

Nitrogen gas and hydrogen gas produce ammonia gas as shown below.



(i) Write the expression for  $K_c$  for this equilibrium.

At 500 °C,  $K_c = 8.00 \times 10^{-2} \text{ dm}^6 \text{ mol}^{-2}$ .

At equilibrium, the concentration of  $\text{N}_2$  is  $1.20 \text{ mol dm}^{-3}$  and the concentration of  $\text{H}_2$  is  $2.00 \text{ mol dm}^{-3}$ .

Calculate the equilibrium concentration of ammonia under these conditions.

equilibrium concentration of  $\text{NH}_3 = \dots\dots\dots \text{ mol dm}^{-3}$

[3]

**Step 1:** Write the  $K_c$  expression.

$$\Rightarrow K_c = \frac{[\text{NH}_3]^2}{[\text{N}_2] [\text{H}_2]^3}$$

**Step 2:** Rearrange the expression so that ammonia is the subject.

$$\Rightarrow [\text{NH}_3]^2 = K_c \times [\text{N}_2] \times [\text{H}_2]^3$$

**Step 3:** Input values into the expression.

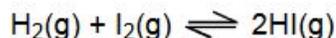
$$\begin{aligned} \Rightarrow [\text{NH}_3]^2 &= 8 \times 10^{-2} \times 1.2 \times 2^3 \\ &= 0.768 \\ [\text{NH}_3] &= \sqrt{0.768} \\ &= \underline{\underline{0.88 \text{ mol dm}^{-3}}} \end{aligned}$$





### Question 3

The preparation of hydrogen iodide, HI(g), from hydrogen and iodine gases is a reversible reaction which reaches equilibrium at constant temperature.



- (a) Write the expression for  $K_c$  for this equilibrium.
- (b) A student mixed together 0.30 mol  $\text{H}_2(\text{g})$  with 0.20 mol  $\text{I}_2(\text{g})$  and the mixture was allowed to reach equilibrium. At equilibrium, 0.14 mol  $\text{H}_2(\text{g})$  was present.
- (i) Complete the table below to show the amount of each component in the equilibrium mixture.

component	$\text{H}_2(\text{g})$	$\text{I}_2(\text{g})$	$\text{HI}(\text{g})$
initial amount / mol	0.30	0.20	0
equilibrium amount / mol			

[2]

**Step 1:** Write the  $K_c$  expression.

$$\Rightarrow K_c = \frac{[\text{HI}]^2}{[\text{H}_2][\text{I}_2]}$$

**Step 2:** Work out the change between initial and equilibrium moles present of  $\text{H}_2$ .

$$\Rightarrow 0.3 - 0.14 = 0.16 \text{ mol}$$

**Step 3:** Calculate the equilibrium moles for the other reactants by subtracting the difference in moles that was calculated in step 1 from the initial moles of each reactant.

$$\Rightarrow \text{I}_2: 0.2 - 0.16 = 0.04 \text{ mol}$$

**Step 4:** Calculate the equilibrium moles of the product by adding the difference in moles that was calculated in step 1 to the initial amount.

$$\Rightarrow 0 + 0.16 + 0.16 = 0.32 \text{ mol}$$

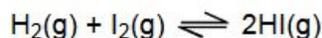
[Two lots of 0.16 is added because from the balanced equation the ratio between the reactants and products is 1:2.]





### Try these questions ...

1. The preparation of hydrogen iodide, HI(g), from hydrogen and iodine gases is a reversible reaction which reaches equilibrium at constant temperature.



[1 mark]

- (a) Write the expression for  $K_c$  for this equilibrium.
- (b) A student mixed together 0.30 mol  $\text{H}_2(\text{g})$  with 0.20 mol  $\text{I}_2(\text{g})$  and the mixture was allowed to reach equilibrium. At equilibrium, 0.14 mol  $\text{H}_2(\text{g})$  was present.
- (i) Complete the table below to show the amount of each component in the equilibrium mixture.

component	$\text{H}_2(\text{g})$	$\text{I}_2(\text{g})$	HI(g)
initial amount / mol	0.30	0.20	0
equilibrium amount / mol			

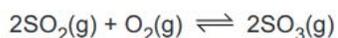
[2]

- (ii) Calculate  $K_c$  to an appropriate number of significant figures. State the units, if any.

[3 marks]

2.

A chemist investigates the equilibrium reaction between sulfur dioxide, oxygen, and sulfur trioxide, shown below.



- The chemist mixes together  $\text{SO}_2$  and  $\text{O}_2$  with a catalyst.
- The chemist compresses the gas mixture to a volume of  $400\text{ cm}^3$ .
- The mixture is heated to a constant temperature and is allowed to reach equilibrium without changing the total gas volume.

The equilibrium mixture contains 0.0540 mol  $\text{SO}_2$  and 0.0270 mol  $\text{O}_2$ .

At the temperature used, the numerical value for  $K_c$  is  $3.045 \times 10^4 \text{ dm}^3 \text{ mol}^{-1}$ .

- (i) Write the expression for  $K_c$  and the units of  $K_c$  for this equilibrium.
- (ii) Determine the amount, in mol, of  $\text{SO}_3$  in the equilibrium mixture at this temperature.

[2 marks]

Give your final answer to an **appropriate** number of significant figures.

Show all your working.

[4 marks]





## Partial Pressure and K<sub>p</sub>

The partial pressure of a gas is the contribution that each gas in a mixture makes towards the total pressure  $P_{\text{tot}}$ .

Consider mixtures of gas made up of gas A, gas B, gas C.

$$\text{Mole fraction of A} = \frac{\text{number of moles of sample A}}{\text{total number of moles in gas mixture}}$$

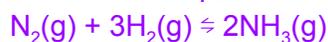
$$P_{\text{tot}} = p_A + p_B + p_C$$

To work out the partial pressure of a gas in a gas mixture you multiply the mole fraction of the gas by the total pressure.

K<sub>p</sub> can only be used for mixtures of gases.

### Example 1:

Write an expression for the equilibrium constant, K<sub>p</sub>, for this reaction:



**Step 1:** Form the expression with partial pressures of the products over the reactants.

$$\Rightarrow K_p = \frac{p(\text{NH}_3)^2}{p(\text{N}_2)p(\text{H}_2)^3}$$

### Example 2:



A mixture at equilibrium contains 0.320 mol N<sub>2</sub>, 0.960 mol H<sub>2</sub> and 0.120 mol NH<sub>3</sub>. What is the mole fraction of H<sub>2</sub> in the equilibrium mixture?

**Step 1:** Sub in the values to find the molar fraction of A.

$$\Rightarrow \text{mole fraction of A} = \frac{\text{number of moles of sample A}}{\text{total number of moles in mixture}}$$



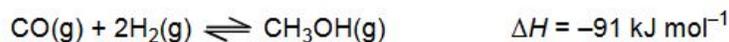


$$\Rightarrow \frac{0.96}{0.96 + 0.120 + 0.32}$$
$$= \underline{\underline{0.686}}$$

## Worked Exam Style Questions

### Question 1

Methanol,  $\text{CH}_3\text{OH}(\text{g})$ , is manufactured from carbon monoxide and hydrogen in an equilibrium reaction.



This equilibrium reaction is normally carried out at 10MPa pressure and 550 K, and starting with a 1 : 2 CO :  $\text{H}_2$  mixture. At equilibrium, only 10% of the CO has reacted.

- (i) Deduce the equilibrium amounts, mole fractions and partial pressures of CO,  $\text{H}_2$  and  $\text{CH}_3\text{OH}$  present at equilibrium. Write your answers in the table below.

Assume that you have started with a mixture of 1.0 mol CO and 2.0 mol  $\text{H}_2$ .

	CO	$\text{H}_2$	$\text{CH}_3\text{OH}$
initial amount /mol	1.0	2.0	0.0
equilibrium amount /mol	0.9		
mole fraction at equilibrium			
partial pressure at equilibrium /MPa			

[4]

**Step 1:** Work out the change between initial and equilibrium moles present of CO.

[this is because you have both data for this substance.]

$$\Rightarrow 1 - 0.9 = 0.1$$





**Step 2:** Work out the equilibrium amount of  $\text{H}_2$  and  $\text{CH}_3\text{OH}$ .

[To work out the equilibrium amount for a reactant subtract the change in moles from the initial amount.]

$$\Rightarrow 2.0 - 0.1 - 0.1 = \underline{\mathbf{1.8}} \text{ mol of H}_2$$

[To work out the equilibrium amount of a product add the change in moles to the initial amount of that substance.]

$$0 + 0.1 = \underline{\mathbf{0.1}} \text{ mol of CH}_3\text{OH}$$

**Step 3:** Work out mole fraction of each gas

$\Rightarrow$  Total number of moles in gas mixture = 2.8 moles

$$\text{CO} = 0.9 / 2.8 = \underline{\mathbf{0.321}}$$

$$\text{H}_2 = 1.8 / 2.8 = \underline{\mathbf{0.643}}$$

$$\text{CH}_3\text{OH} = 0.1 / 2.8 = \underline{\mathbf{0.036}}$$

**Step 4:** To work out partial pressure of each gas multiply mole fraction by the total pressure given in the question

$$\text{CO} - 0.321 \times 10 = \underline{\mathbf{3.21 \text{ MPa}}}$$

$$\text{H}_2 - 0.643 \times 10 = \underline{\mathbf{6.43 \text{ MPa}}}$$

$$\text{CH}_3\text{OH} - 0.036 \times 10 = \underline{\mathbf{0.36 \text{ MPa}}}$$

(ii) Write the expression for  $K_p$  for this equilibrium.

$$\Rightarrow K_p = \frac{p(\text{CH}_3\text{OH})}{p(\text{H}_2)^2 p(\text{CO})}$$

(iv) In another experiment, the equilibrium partial pressures were:

CO, 3.70 MPa;  $\text{H}_2$ , 5.10 MPa;  $\text{CH}_3\text{OH}$ , 0.261 MPa.

Calculate the value of  $K_p$  for this equilibrium. Express your answer to an appropriate number of significant figures. State the units of  $K_p$ .





**Step 1:** Input the values into the  $K_p$  expression.

$$K_p = \frac{0.261}{(5.10)^2 \times (3.70)}$$
$$= \underline{2.71 \times 10^{-3}}$$

### Question 2

I When heated, chlorine gas,  $\text{Cl}_2$  dissociates into gaseous chlorine atoms.



A chemist placed some chlorine gas in a container which was heated to 1400 K. The container was left until equilibrium had been reached.

Under these conditions, the equilibrium partial pressure of  $\text{Cl}_2(\text{g})$  is 85.0 kPa and that of  $\text{Cl}(\text{g})$  is 3.0 kPa.

(b) Determine the mole fraction of  $\text{Cl}$  in the equilibrium mixture.

**Step 1:** Find the total pressure in this gas mixture.

$$\Rightarrow 85 + 3 = 88 \text{ kPa}$$

**Step 2:** Work out the mole fraction of  $\text{Cl}$ .

$$\Rightarrow 3 / 88 = \underline{0.034}$$

(c) (i) Write an expression for  $K_p$  for this equilibrium.

$$\Rightarrow K_p = \frac{p(\text{Cl})^2}{p(\text{Cl}_2)}$$

(ii) Calculate  $K_p$  for this equilibrium. State the units.

$$\Rightarrow K_p = \frac{3^2}{85} = \underline{0.106}$$





85

$$\frac{\cancel{\text{kPa}} \times \cancel{\text{kPa}}}{\cancel{\text{kPa}}}$$

⇒

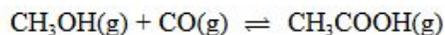
$$\frac{\text{kPa} \times \text{kPa}}{\text{kPa}}$$

⇒ Units = **kPa**

Try these questions...

3.

Ethanoic acid can be manufactured by the following reaction, which is carried out between 150 °C and 200 °C.



(a) A mixture of 50.0 mol of methanol and 50.0 mol of carbon monoxide reaches equilibrium at a pressure of 32.0 atm. At 175 °C, the equilibrium partial pressure of ethanoic acid is 22.2 atm.

(i) Write the expression for the equilibrium constant in terms of pressure,  $K_p$ , for this reaction.

(1)

(ii) Calculate the partial pressures of methanol and carbon monoxide at equilibrium.

(2)

(iii) Calculate the value of  $K_p$  for this reaction at 175 °C. Include a unit in your answer and give your answer to **three** significant figures.

(2)





(b) Another sample of 50.0 mol of methanol and 50.0 mol of carbon monoxide was allowed to reach equilibrium at the same pressure of 32.0 atm, but at a lower temperature. 93.6 % of the methanol was converted at equilibrium.

- (i) Complete the table below to show the number of moles of each species in the equilibrium mixture.

(2)

	CH <sub>3</sub> OH	CO	CH <sub>3</sub> COOH
Number of moles at start	50.0	50.0	0
Number of moles at equilibrium			

- (ii) Calculate the partial pressure of ethanoic acid in the equilibrium mixture.

(1)





## Answers

Q1.

(a)  $K_c = \frac{[\text{HI}]^2}{[\text{H}_2][\text{I}_2]}$  (1) 1

(b) (i)

H <sub>2</sub>	I <sub>2</sub>	HI
0.30	0.20	0
0.14	0.04	0.32
(1)		(1)

2

(ii)  $K_c = \frac{0.32^2}{0.14 \times 0.04} = 18.28571429$  (1)  
= 18 (to 2 sig figs) (1)  
no units (1)  
(or ecf based on answers to (i) and/or (a)) 3

Q2

(i)

$$(K_c =) \frac{[\text{SO}_3]^2}{[\text{SO}_2]^2 [\text{O}_2]} \checkmark$$

Units:  $\text{dm}^3 \text{mol}^{-1}$  ✓





<p>(ii) <b>FIRST, CHECK THE ANSWER ON ANSWER LINE</b> <b>IF answer = 2.45, Award 4 marks.</b></p> <p>-----</p> <p><b>Equilibrium concentrations (moles × 2.5) 1 MARK</b></p> <p><math>SO_2 = 0.135 \text{ (mol dm}^{-3}\text{)}</math> <b>AND</b> <math>O_2 = 0.0675 \text{ (mol dm}^{-3}\text{)}</math> ✓</p> <p><b>Calculation of <math>[SO_3(g)]</math> 2 MARKS</b></p> <p><math>[SO_3] = \sqrt{(K_c \times [SO_2]^2 \times O_2)}</math> <b>OR</b> <math>\sqrt{(3.045 \times 10^4) \times 0.135^2 \times 0.0675}</math> ✓</p> <p><math>= 6.12039291 \text{ (mol dm}^{-3}\text{)}</math> ✓ <i>Answer scores both <math>[SO_3]</math> marks automatically</i></p> <p><b>Calculation of <math>n(SO_3)</math> in 400 cm<sup>3</sup> 1 MARK</b></p> <p><math>n(SO_3) = 6.12039291/2.5 = 2.45 \text{ (mol)}</math> ✓</p> <p><b>3SF required (Appropriate number)</b></p>	<p><b>4 FULL ANNOTATIONS NEEDED</b> <b>IF</b> there is an alternative answer, check to see if there is any <b>ECF</b> credit possible using working below</p> <p>-----</p> <p><b>ALLOW ECF</b> from incorrect concentrations of <math>SO_2</math> and/or <math>O_2</math></p> <p><b>ALLOW ECF</b> from incorrect <math>[SO_3]</math></p> <p><b>ALLOW 3 SF</b>, 6.12, up to calculator value of 6.12039291 correctly rounded.</p> <p><b>Common errors</b></p> <p><b>37.5 1 mark</b> <i>No <math>\sqrt{\text{for } [SO_3]^2}</math> and no scaling by 1/2.5</i></p> <p><b>15.0 2 marks</b> <i>No <math>\sqrt{\text{for } [SO_3]^2}</math></i></p> <p><b>0.619 3 marks</b> <i>Use of mol of <math>SO_2</math> and <math>O_2</math></i></p> <p><b>1.55 2 marks</b> <i>No conc used and Use of mol of <math>SO_2</math> and <math>O_2</math></i></p>
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Q3.

<p><b>(a)(i)</b></p>	<p><math>(K_p =) \frac{pCH_3CO_2H}{pCH_3OH (x) pCO}</math></p> <p>Partial pressure symbol can be shown in various ways, eg pp, <math>p_{CO}</math>, <math>(CO)p</math>, etc</p> <p><b>ALLOW</b> p in upper or lower case, round brackets <b>IGNORE</b> units</p>	<p>[ ] State symbols given as (l) + in bottom line</p>	<p><b>1</b></p>
<p><b>(a)(ii)</b></p>	<p>P <math>CH_3OH = 4.9 \text{ (atm)}</math> <b>(1)</b> P <math>CO = 4.9 \text{ (atm)}</math> <b>(1)</b></p> <p>1 mark for recognition that pressures are equal</p> <p><b>IGNORE</b> units</p>		<p><b>2</b></p>





(a)(iii)

$$K_p = ((22.2)/(4.9)^2) \\ = 0.925 \text{ (1)}$$

atm<sup>-1</sup> (1) stand alone mark but must match expression used in (a)(iii)

OR

$$9.25 \times 10^4 \text{ Pa}^{-1} / 92.5 \text{ kPa}^{-1} \text{ (2)}$$

ALLOW TE from (a)(i) if inverted and/or (a)(ii)

Answers to other than 3 significant figures

2

(b)(i)

CH<sub>3</sub>OH: 3.2  
CO : 3.2 (1) for both values

CH<sub>3</sub>CO<sub>2</sub>H: 46.8 (1)

ALLOW TE for moles of ethanoic acid based on numbers of methanol and carbon monoxide used, as long as moles of methanol and carbon monoxide are equal and moles ethanoic acid + moles methanol = 50

2

(b)(ii)

$$\left( \frac{46.8 \times 32}{53.2} \right) = 28.2 / 28.1504 \text{ (atm)}$$

IGNORE sf except 1

Value = 28.16 if mol fraction rounded

ALLOW TE from (b)(i)

28.1

$$\frac{46.8 \times 32}{50} = \\ 29.95 \text{ (atm)}$$

1

