3rd

ICHO

International Chemistry Olympiad

6 theoretical problems
2 practical problems

THE THIRD
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THEORETICAL PROBLEMS

PROBLEM 1

An amount of 23 g of gas (density ρ = 2.05 g dm^{-3} at STP) when burned, gives 44 g of carbon dioxide and 27 g of water.

Problem:

What is the structural formula of the gas (compound)?

SOLUTION

The unknown gas : X

From the ideal gas law : $M(\text{X}) = \dfrac{\rho(\text{X})\, R\, T}{p} = 46 \text{ g mol}^{-1}$

$$n(\text{X}) = \frac{23 \text{ g}}{46 \text{ g mol}^{-1}} = 0.5 \text{ mol}$$

$$n(\text{CO}_2) = \frac{44 \text{ g}}{44 \text{ g mol}^{-1}} = 1 \text{ mol}$$

n(C) = 1 mol

m(C) = 12 g

$$n(\text{H}_2\text{O}) = \frac{27 \text{ g}}{18 \text{ g mol}^{-1}} = 1.5 \text{ mol}$$

n(H) = 3 mol

m(H) = 3 g

The compound contains also oxygen, since

$m(C) + m(H) = 12\text{ g} + 3\text{ g} = 15\text{ g} < 23\text{ g}$

$m(O) = 23\text{ g} - 15\text{ g} = 8\text{ g}$

$n(O) = 0,5\text{ mol}$

$n(C) : n(H) : n(O) = 1 : 3 : 0,5 = 2 : 6 : 1$

The empirical formula of the compound is C_2H_6O.

C_2H_6O	C_2H_5OH	ethanol
	CH_3-O-CH_3	dimethyl ether

Ethanol is liquid in the given conditions and therefore, the unknown gas is dimethyl ether.

PROBLEM 2

A sample of crystalline soda (**A**) with a mass of 1.287 g was allowed to react with an excess of hydrochloric acid and 100.8 cm^3 of a gas was liberated (measured at STP).

Another sample of different crystalline soda (**B**) with a mass of 0.715 g was decomposed by 50 cm^3 of 0.2 N sulphuric acid.

After total decomposition of soda, the excess of the sulphuric acid was neutralized which required 50 cm^3 of 0.1 N sodium hydroxide solution (by titration on methyl orange indicator).

Problems:

2.1 How many molecules of water in relation to one molecule of Na_2CO_3 are contained in the first sample of soda?

2.2 Have both samples of soda the same composition?

Relative atomic masses: $A_r(Na) = 23$; $A_r(H) = 1$; $A_r(C) = 12$; $A_r(O) = 16$.

SOLUTION

2.1 Sample **A**: $Na_2CO_3 . x H_2O$

$m(A) = 1.287$ g

$$n(CO_2) = \frac{p V}{R T} = 0.0045 \text{ mol} = n(A)$$

$$M(A) = \frac{1.287 \text{ g}}{0.0045 \text{ mol}} = 286 \text{ g mol}^{-1}$$

$M(A) = M(Na_2CO_3) + x\ M(H_2O)$

$$x = \frac{M(A) - M(Na_2CO_3)}{M(H_2O)} = \frac{(286 - 106) \text{ g mol}^{-1}}{18 \text{ g mol}^{-1}} = 10$$

Sample **A**: $Na_2CO_3 .10 H_2O$

2.2 Sample **B**: $Na_2CO_3 . x H_2O$

m(B) = 0.715 g

$H_2SO_4 + 2 NaOH = Na_2SO_4 + 2 H_2O$

$n(NaOH) = c\, V = 0.1 \text{ mol dm}^{-3} \times 0.05 \text{ dm}^3 = 0.005 \text{ mol}$

Excess of H_2SO_4: $n(H_2SO_4) = 0.0025$ mol

Amount of substance combined with sample **B**:

$n(H_2SO_4) = 0.0025 \text{ mol} = n(B)$

$$M(B) = \frac{0.715 \text{ g}}{0.0025 \text{ g mol}^{-1}} = 286 \text{ g mol}^{-1}$$

Sample **B**: $Na_2CO_3 .10 H_2O$

PROBLEM 3

Carbon monoxide was mixed with 1.5 times greater volume of water vapours. What will be the composition (in mass as well as in volume %) of the gaseous mixture in the equilibrium state if 80 % of carbon monoxide is converted to carbon dioxide?

SOLUTION

$CO + H_2O \rightleftharpoons CO_2 + H_2$

Assumption:

$n(CO) = 1$ mol

$n(H_2O) = 1.5$ mol

After reaction:

$n(CO) = 0.2$ mol

$n(H_2O) = 0.7$ mol

$n(CO_2) = 0.8$ mol

$n(H_2) = 0.8$ mol

$$\varphi(CO) = \frac{V(CO)}{V} = \frac{0.2\ \text{mol}}{2.5\ \text{mol}} = 0.08 \quad \text{i.e. 8 vol. \% of CO}$$

$$\varphi(H_2O) = \frac{V(H_2O)}{V} = \frac{0.7\ \text{mol}}{2.5\ \text{mol}} = 0.28 \quad \text{i.e. 28 vol. \% of } H_2O$$

$$\varphi(CO_2) = \frac{V(CO_2)}{V} = \frac{0.8\ \text{mol}}{2.5\ \text{mol}} = 0.32 \quad \text{i.e. 32 vol. \% of } CO_2$$

$$\varphi(H_2) = \frac{V(H_2)}{V} = \frac{0.8\ \text{mol}}{2.5\ \text{mol}} = 0.32 \quad \text{i.e. 32 vol. \% of } H_2$$

Before reaction:

$m(CO) = n(CO) \times M(CO) = 1\ \text{mol} \times 28\ \text{g mol}^{-1} = 28\ \text{g}$

$m(H_2O) = 1.5\ \text{mol} \times 18\ \text{g mol}^{-1} = 27\ \text{g}$

After reaction:

$m(\text{CO}) = 0{,}2 \text{ mol} \times 28 \text{ g mol}^{-1} = 5.6 \text{ g}$

$m(\text{H}_2\text{O}) = 0.7 \text{ mol} \times 18 \text{ g mol}^{-1} = 12.6 \text{ g}$

$m(\text{CO}_2) = 0.8 \text{ mol} \times 44 \text{ g mol}^{-1} = 35.2 \text{ g}$

$m(\text{H}_2) = 0.8 \times 2 \text{ g mol}^{-1} = 1.6 \text{ g}$

$$w(\text{CO}) = \frac{m(\text{CO})}{m} = \frac{5.6 \text{ g}}{55.0 \text{ g}} = 0.102 \text{ i.e. } 10.2 \text{ mass \% of CO}$$

$$w(\text{H}_2\text{O}) = \frac{m(\text{H}_2\text{O})}{m} = \frac{12.6 \text{ g}}{55.0 \text{ g}} = 0.229 \text{ i.e. } 22.9 \text{ mass \% of H}_2\text{O}$$

$$w(\text{CO}_2) = \frac{m(\text{CO}_2)}{m} = \frac{35.2 \text{ g}}{55.0 \text{ g}} = 0.640 \text{ i.e. } 64.0 \text{ mass \% of CO}_2$$

$$w(H_2) = \frac{m(\text{H}_2)}{m} = \frac{1.6 \text{ g}}{55.0 \text{ g}} = 0.029 \text{ i.e. } 2.9 \text{ mass \% of H}_2$$

PROBLEM 4

An alloy consists of rubidium and one of the other alkali metals. A sample of 4.6 g of the alloy when allowed to react with water, liberates 2.241 dm^3 of hydrogen at STP.

Problems:

4.1 Which alkali metal is the component of the alloy?

4.2 What composition in % by mass has the alloy?

Relative atomic masses:

A_r(Li) = 7; A_r(Na) = 23; A_r(K) = 39; A_r(Rb) = 85.5; A_r(Cs) = 133

SOLUTION

4.1 M - alkali metal

Reaction: $2\,M + 2\,H_2O \rightarrow 2\,MOH + H_2$

$n(H_2) = 0.1$ mol

$n(M) = 0.2$ mol

Mean molar mass:

$$M = \frac{4.6\ \text{g}}{0.2\ \text{mol}} = 23\ \text{g mol}^{-1}$$

4.2 Concerning the molar masses of alkali metals, only lithium can come into consideration, i.e. the alloy consists of rubidium and lithium.

$n(\text{Rb}) + n(\text{Li}) = 0.2$ mol

$m(\text{Rb}) + m(\text{Li}) = 4.6$ g

$n(\text{Rb})\, M(\text{Rb}) + n(\text{Li})\, M(\text{Li}) = 4.6$ g

$n(\text{Rb})\, M(\text{Rb}) + (0.2 - n(\text{Rb}))\, M(\text{Li}) = 4.6$

$n(\text{Rb})\ .\ 85.5 + (0.2 - n(\text{Rb})) \times 7 = 4.6$

$n(\text{Rb}) = 0.0408$ mol

$n(\text{Li}) = 0.1592$ mol

$$\%\ \text{Rb} = \frac{0.0408\ \text{mol} \times 85.5\ \text{g mol}^{-1}}{4.6\ \text{g}} \times 100 = 76$$

$$\%\ \text{Li} = \frac{0.1592\ \text{mol} \times 7\ \text{g mol}^{-1}}{4.6\ \text{g}} \times 100 = 24$$

PROBLEM 5

An amount of 20 g of cooper (II) oxide was treated with a stoichiometric amount of a warm 20% sulphuric acid solution to produce a solution of copper (II) sulphate.

Problem:

How many grams of crystalline copper(II) sulphate ($CuSO_4 \cdot 5\ H_2O$) have crystallised when the solution is cooled to 20 °C?

Relative atomic masses: $A_r(Cu) = 63.5$; $A_r(S) = 32$; $A_r(O) = 16$; $A_r(H) = 1$

Solubility of $CuSO_4$ at 20 °C: s = 20.9 g of $CuSO_4$ in 100 g of H_2O.

SOLUTION

$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$

$$n(\text{CuO}) = \frac{m(\text{CuO})}{M(\text{CuO})} = \frac{20\ \text{g}}{79.5\ \text{g mol}^{-1}} = 0.2516\ \text{g}$$

$n(H_2SO_4) = n(CuSO_4) = 0.2516$ mol

Mass of the $CuSO_4$ solution obtained by the reaction:

m(solution $CuSO_4$) = m(CuO) + m(solution H_2SO_4) =

$$= m(\text{CuO}) + \frac{n(\text{H}_2\text{SO}_4) \times M(\text{H}_2\text{SO}_4)}{w(\text{H}_2\text{SO}_4)} = 20\ \text{g} + \frac{0.2516\ \text{mol} \times 98\ \text{g mol}^{-1}}{0.20}$$

m(solution $CuSO_4$) = 143.28 g

Mass fraction of $CuSO_4$:

a) in the solution obtained:

$$w(\text{CuSO}_4) = \frac{m(\text{CuSO}_4)}{m(\text{solution CuSO}_4)} = \frac{n(\text{CuSO}_4) \times M(\text{CuSO}_4)}{m(\text{solution CuSO}_4)} = 0.28$$

b) in saturated solution of $CuSO_4$ at 20°C:

$$w(\text{CuSO}_4) = \frac{20.9\ \text{g}}{120.9\ \text{g}} = 0.173$$

c) in crystalline $CuSO_4 . 5 H_2O$:

$$w(CuSO_4) = \frac{M(CuSO_4)}{M(CuSO_4 . 5H_2O)} = 0.639$$

Mass balance equation for $CuSO_4$:

$0.28\ m = 0.639\ m_1 + 0.173\ m_2$

m - mass of the $CuSO_4$ solution obtained by the reaction at a higher temperature.

m_1 - mass of the crystalline $CuSO_4 . 5H_2O$.

m_2 - mass of the saturated solution of $CuSO_4$ at 20 °C.

$0.28 \times 143.28 = 0.639\ m_1 + 0.173 \times (143.28 - m_1)$

$m_1 = 32.9$ g

The yield of the crystallisation is 32.9 g of $CuSO_4 . 5H_2O$.

PROBLEM 6

Oxide of a certain metal contains 22.55 % of oxygen by mass. Another oxide of the same metal contains 50.48 mass % of oxygen.

Problem:

1. What is the relative atomic mass of the metal?

SOLUTION

Oxide 1: M_2O_x

$$2 : x = \frac{w(M)}{A_r(M)} : \frac{w(O)}{A_r(O)}$$

$$2 : x = \frac{0.7745}{A_r(M)} : \frac{0.2255}{16} = \frac{54.95}{A_r(M)} \qquad (1)$$

Oxide 2: M_2O_y

$$2 : y = \frac{w(M)}{A_r(M)} : \frac{w(O)}{A_r(O)}$$

$$2 : y = \frac{0.4952}{A_r(M)} : \frac{0.5048}{16} = \frac{15.695}{A_r(M)} \qquad (2)$$

When (1) is divided by (2):

$$\frac{y}{x} = \frac{54.95}{15.695} = 3.5$$

$$\frac{y}{x} = \frac{7}{2}$$

By substituting x = 2 into equation (1):

$A_r(M) = 54.95$

M = Mn

Oxide 1 = MnO

Oxide 2 = Mn_2O_7

PRACTICAL PROBLEMS

PROBLEM 1 (Practical)

An unknown sample is a mixture of 1.2-molar H_2SO_4 and 1.47-molar HCl. By means of available solutions and facilities determine:

1. the total amount of substance (in val) of the acid being present in 1 dm^3 of the solution,
2. the mass of sulphuric acid as well as hydrochloric acid present in 1 dm^3 of the sample.

PROBLEM 2 (Practical)

By means of available reagents and facilities perform a qualitative analysis of the substances given in numbered test tubes and write down their chemical formulas.

Give 10 equations of the chemical reactions by which the substances were proved:

5 equations for reactions of precipitation,

2 equations for reactions connected with release of a gas,

3 equations for redox reactions.