# Transition metal chemistry

## Transition metals recap

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Find in the word search above, the answers to each of the questions below to gain the mark(s);

**1.** The catalyst in the Haber process used to make ammonia

(1 mark)

**2.** 3 Common catalysts found in the catalytic converter

(3 marks)

**3.** The aqueous solution of this metal sulphate is blue

(1 mark)

**4.** This metal has a melting point of −38.3 ºC

(1 mark)

**5.** These two transition metals are found in the smart alloy, nitinol.

(2 marks)

**6.** These two metals when in oxidation states +6 and +7 respectively and combined with oxygen are common oxidising agents used in organic chemistry.

(2 marks)

# Transition metal complexes

A transition metal complex consists of a central metal ion surrounded by ligands. A **ligand** is an ion or molecule with a lone pair of electrons that forms a coordinate bond with a transition metal ion.

**1.** For each of the ligands below, **mark** on any lone pairs which are able to form coordinate bonds, and **identify** the ligand as *unidentate* (can form one coordinate bond), *bidentate* (can form two coordinate bonds) or *multidentate* (can form three or more coordinate bonds).

(4 marks)

A group of chemical formulas

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**2.** For each of the complexes listed (a)-(c) below, draw a 3-dimensional representation of its structure, and identify the name given to its shape.

A group of squares with lines and dots

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# Colours of complex ions

**1.** Despite being a d-block element, zinc is not considered a transition element. Explain why.

(2 marks)

**2.** Anhydrous solid copper (II) sulfate is white but once hydrated, copper(II) sulfate solution is blue.

Use the diagrams below to help you explain why.

Decide on the best order for the diagrams and then add a few words of explanation to each.

(8 marks)

A page of a math exercise

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# Colorimetry

**1.** Nick is trying to determine the formula of the complex formed between Cu2+ ions and NH3. He mixes different volumes of solutions containing the two ions and measures the absorbance of the resulting solution. His results are shown in the table opposite.

A table of chemical formulas

Description automatically generated with medium confidence

(a) Plot Nick’s results on the graph paper below.

(1 mark)

(b) Use the graph to;

(i) Determine the stoichiometry of the Cu2+ : NH3 complex,

(ii) Suggest a formula for the complex ion formed.

(4 marks)

A graph paper with a graph on it

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**2.** In a different experiment, Nick wishes to determine the concentration of the blue dye, E133 (Blue no. 1) in a new sports drink, “*Go Go Go*.”

Outline the experiment Nick could perform in order to determine the concentration of the blue dye in “*Go Go Go*.” You can assume he has access to a solution of E133 of known concentration (0.20 mol dm−3) and a sample of the sports drink as well as access to common laboratory equipment.

(5 marks)

# Redox titrations

The pharmacists have had an accident and managed to mix up all their iron tablets. They have three foils of tablets (labelled A-C) which they know must have come from one of the bottles below;

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Help the pharmacists work out which tablets are which by interpreting the results of their analyses below.

One of **Tablet A** (1.05 g) was dissolved in excess sulfuric acid and made up to 250 cm3 in a volumetric flask. A 25.00 cm3 aliquot of this solution required 21.65 cm3 of a 0.005 mol dm−3 solution of KMnO4 for complete oxidation.

**Tablet A is from**

(3 marks)

2.10 g of **Tablet B** (2 tablets) were dissolved in excess sulfuric acid and made up to 500 cm3 in a volumetric flask. A 25.00 cm3 aliquot of this solution required 19.45 cm3 of a 0.010 mol dm−3 solution of KMnO4 for complete oxidation.

**Tablet B is from**

(3 marks)

One of **Tablet C** (1.21 g) was dissolved in excess sulfuric acid and made up to 500 cm3 in a volumetric flask. A 20.00 cm3 aliquot of this solution required 10.5 cm3 of a 0.0022 mol dm−3 solution of K2Cr2O7 for complete oxidation.

**Tablet C is from**

(3 marks)

**BONUS MARK** How could you check that all of the iron in the ***FeRICH*** tablets is in the form of iron(II) and not iron(III)?

(1 mark)

# Redox chemistry of transition metals

One of the important properties of transition metals is that they can exist in a range of oxidation states in their compounds. The different oxidation states can be readily inter-converted.

A black rectangle with a black line and a black text

Description automatically generated**1.** Vanadium has an extensive redox chemistry.

(a) Complete the diagram by;

(i) Identifying the oxidation state of vanadium in each of the vanadium containing species

(ii) Adding labels to indicate if the change shown by the arrows is oxidation or reduction.

(2 marks)

(b) Use the electrode potentials in the table to explain the following;

(i) Nitric acid will oxidise V2+ to VO2+ but no further.

(2 marks)

(ii) Zinc will reduce VO2+ to V2+.

(2 marks)

**2.** Write two half equations and combine to give a full redox equation for the following oxidations;

(a) The oxidation of [Cr(OH)6]3− to CrO42- using hydrogen peroxide under alkaline conditions.

(2 marks)

(b) The oxidation of [Co(NH3)6]2+ to [Co(NH3)6]3+ by oxygen in the air under alkaline conditions.

(HINT: O2 is reduced to OH− ions under these conditions)

(2 marks)

# Transition metals as catalysts

A phase is defined as a distinct form of matter with uniform properties throughout, that is separated by its surface from other forms. Catalysts can be referred to as either;

***Heterogeneous*** if the catalyst is present in the reaction in a different phase to the reactants, or

***Homogeneous*** if the catalyst is present in the reaction in the same phase as the reactants.

**1.** For each of the reactions (a)-(g) below, identify the transition metal catalyst and state whether it is an example of a heterogeneous catalyst or a homogeneous catalyst. (7 marks)

(a) Hydrogenation of ethene to make ethane; *Catalyst* =

CH2=CH2 + H2 → CH3CH3 homogeneous/ heterogenous

(b) The Haber process to make ammonia; *Catalyst* =

N2 + 3 H2 ⇌ 2 NH3 homogeneous/ heterogenous

(c) The Contact process *Catalyst =*

2 SO2 + O2 ⇌ 2 SO3 homogeneous/ heterogenous

(d) A catalytic converter  *Catalyst =*

2 NO + 2 CO → N2 + 2 CO2 homogeneous/ heterogenous

(e) The oxidation of iodide by peroxodisulfate ions *Catalyst* =

S2O82- + 2 I- → 2 SO42- + I2 homogeneous/ heterogenous

(f) The decomposition of hydrogen peroxide *Catalyst* =

2 H2O2 → 2 H2 + O2 homogeneous/ heterogenous

(g) The oxidation of ethanedioic acid by MnO4- ions *Catalyst* =

2 MnO4- + 16 H+ + 5 C2O42- → 2 Mn2+ + 8 H2O + 10 CO2 homogeneous/ heterogenous

**2.** The reaction in **1.** (g) is an example of *autocatalysis*.

(a) Explain what is meant by *autocatalysis*

(1 mark)

(b) By writing balanced symbol equations for the stages involved in the reaction, explain how *autocatalysis* in this case works.

(2 marks)

# Transition metal chemistry – Answers

## Transition metals recap

A crossword puzzle with letters

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Coordinates are for the first letter of each answer.

**1.** iron (14 across, 6 down) *(1 mark)*

**2.** platinum (10 across, 6 down), rhodium (9 across, 15 down) or palladium (2 across, 1 down) *(3 marks)*

**3.** copper (4 across, 7 down) *(1 mark)*

**4.** mercury (2 across, 13 down) *(1 mark)*

**5.** nickel (12 across, 1 down) and titanium (13 across, 8 down) *(2 marks)*

**6.** chromium (10 across, 15 down) and manganese (9 across, 7 down) *(2 marks)*

# A group of chemical formulas Description automatically generatedTransition metal complexes

## Colours of complex ions

**1.** The formal definition of a transition metal is ‘*an element that forms at least one stable ion with a partially full d-shell*.’ Zinc forms only one stable ion, Zn2+ which has an electronic configuration of [Ar] 4so 3d10 i.e. has a full d shell.

*(1 mark for definition, 1 mark for full explanation of why zinc does not meet the criteria)*

**NOTE** IUPAC gives the definition of a transition element as *‘An element whose atom has an incomplete d sub-shell, or which can give rise to cations with an incomplete d sub-shell.*’ Elemental zinc does not contain an incomplete d sub-shell either ([Ar] 4s2 3d10) so can also be ruled out on the basis of this criteria.

A screenshot of a computer

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## Colorimetry

A graph of a number of substances

Description automatically generated with medium confidence(1 mark for correctly plotting points)

(b) (i) Maximum absorbance at 33 cm3 0.05 mol dm−3 CuSO4 : 67 cm3 of 0.10 mol dm−3 NH3 solution

In moles this is, 1.65 × 10−3 mol : 6.70 × 10−3 mol

Stoichiometric ratio 1 : 4

*(1 mark for reading correct volume of graph, 1 mark for mol calculations, 1 mark for stoichiometry)*

(ii) Since copper is normally hexacoordinate, the formula of the complex formed must be;

[Cu(NH3)4(H2O)2]2+ *(1 mark)*

**2.** Key features of the experiment described include;

1. Initially the sample of E133 of known concentration must be diluted with water to produce dilute samples of known concentration. Five or more solutions must be produced. Possible dilutions would be;

A table with numbers and symbols

Description automatically generated

2. Measure the absorbance of each new known concentration of E133 and record these results in a suitable table.

3. Plot a calibration graph of concentration of E133 (x-axis) against absorbance (y-axis).

4. Measure the absorbance of the sports drink ‘*Go, go, go*.’

5. Use the calibration graph plotted in 3. to determine the concentration of E133 in ‘*Go, go, go.*’

*(5 marks)*

## Redox titrations

*Tablet A*

5 Fe2+ + MnO4- + 8 H+ → 5 Fe3+ + Mn2+ + 4 H2O

No. of moles in 21.65 cm3 of 0.005 mol dm−3 KMnO4

= 1.08 × 10−4 mol

Therefore, no. of moles of Fe2+ in 25.00 cm3 aliquot

= (1.08 × 10−4 mol) × 5 = 5.41 × 10−4 mol

Therefore, no. of moles of Fe2+ in 250 cm3 and hence in one of Tablet A

= (5.41 × 10−4 mol) × 10

= 5.41 × 10−3 mol

*(1 mark)*

Molar mass of FeSO4 = 151.9 g mol−1

Therefore mass of FeSO4 per tablet = 5.41 × 10−3 mol × 151.9 g mol−1 = 0.82 g *(1 mark)*

Therefore Tablet A comes from the ***IRON TO GO*** pack.

*(1 mark)*

*Tablet B*

5 Fe2+ + MnO4- + 8 H+ → 5 Fe3+ + Mn2+ + 4 H2O

No. of moles in 19.45 cm3 of 0.010 mol dm−3 KMnO4

= 1.945 × 10−4 mol

Therefore, no. of moles of Fe2+ in 25.00 cm3 aliquot

= (1.08 × 10−4 mol) × 5 = 9.725 × 10−4mol

Therefore, no. of moles of Fe2+ in 500 cm3 and hence in two of Tablet B

= (9.725 × 10−4 mol) × 20

= 0.01945 mol

*(1 mark)*

Mass of iron in two tablets of B = 0.01945 mol × 55.8 g mol−1 = 1.085 g *(1 mark)*

Therefore the % by mass of iron in Tablet B

= (1.085 g / 2.10 g) × 100% = 51.6 %

Therefore Tablet B comes from the ***FeRICH*** tablets. *(1 mark)*

*Tablet C*

6 Fe2+ + Cr2O72- + 14 H+ → 6 Fe3+ + 2 Cr3+ + 7 H2O

No. of moles in 10.5 cm3 of 0.0022 mol dm−3 K2Cr2O7

= 2.31 × 10−5 mol

Therefore, no. of moles of Fe2+ in 20.00 cm3 aliquot

= (2.31 × 10−5 mol) × 6 = 1.386 × 10−4 mol

Therefore, no. of moles of Fe2+ in 500 cm3 and hence in one of Tablet C

= (1.386 × 10−4 mol / 20) × 500

= 3.465 × 10−3 mol

*(1 mark)*

Molar mass of FeSO4.7H2O = 151.9 + (7 × 18.0) = 277.9 g mol−1

Therefore mass of FeSO4.7H2O per tablet

= 3.465 × 10−3 mol × 277.9 g mol−1 = 0.96 g *(1 mark)*

Therefore Tablet C comes from the ***Fe4U*** tablets. *(1 mark)*

**BONUS MARK**

*Either*

Add an excess of zinc to a 25.0 cm3 aliquot of the original solution. This will reduce any Fe3+ ions to Fe2+ ions. Filter off the unreacted zinc and titrate the mixture against KMnO4. If the titre is the same (i.e. the amount of KmnO4 needed for complete oxidation has not changed) then only Fe2+ ions were present in the original solution. If the titre has increased (i.e. more KmnO4 is needed for complete oxidation) then the original sample must have contained some Fe3+ ions.

Or

Dissolve the tablet in water and add sodium hydroxide solution until present in excess. If Fe2+ is present a green precipitate of [Fe(H2O)4(OH)2] would form. Any Fe3+ present would form an orange/brown precipitate of [Fe(H2O)3(OH)3].

*(1 mark for either method)*

## A black text with black text Description automatically generated with medium confidenceRedox chemistry of transition metals

(b) (i) The electrode potentials for the V3+/V2+ electrode and the VO2+/V3+ electrode are each more negative that the NO3-/NO electrode potential. Therefore, NO3- will initially oxidise V2+ to V3+ which will then be oxidised further to VO2+. Since the electrode potential for the VO2+/VO2+ electrode is more negative than that of the NO3- / NO electrode no further oxidation is possible.

*(2 marks; 1 mark for comment on electrode potentials and 1 mark for explaining comment)*

(ii) The electrode potential of the Zn2+/Zn electrode is more negative than each of the VO2+/VO2+, VO2+/V3+ and the V3+/V2+ electrodes. Therefore it will reduce each of the vanadium species in turn i.e. VO2+ will be reduced to VO2+ which in turn will be reduced to V3+ which in turn will be reduced to V2+.

*(2 marks; 1 mark for comment on electrode potentials and 1 mark for explaining comment)*

**2.** (a) In acid conditions the first half equation would be (this is purely a theoretical simplification, as [Cr(OH)6]3− would not exist under these conditions);

[Cr(OH)6]3− → CrO42- + 2 H2O + 2 H+ + 3 e−

But the oxidation is in alkali conditions so it becomes (just add enough OH− equally to both sides of the equation to remove any H+ ions);

2 OH− + [Cr(OH)6]3− → CrO42- + 4 H2O + 3 e− (× 2)

The hydrogen peroxide half equation is;

2 e− + H2O2 → 2 OH− (× 3)

Combining to give the full redox equation;

2 [Cr(OH)6]3− + 3 H2O2 → 2 CrO42- + 8 H2O + 2 OH−

*(2 marks; 1 for correct half equations, 1 for correct full redox equation)*

(b) [Co(NH3)6]2+ → [Co(NH3)6]3+ + 1 e− (× 4)

4 e− + 2 H2O + O2 → 4 OH−

4[Co(NH3)6]2+ + 2 H2O + O2 → 4[Co(NH3)6]3+ + 4 OH−

*(2 marks; 1 for correct half equations, 1 for correct full redox equation)*

## Transition metals as catalysts

**1.** (a) Nickel, heterogeneous

(b) Iron, heterogeneous

(c) Vanadium pentoxide (V2O5), heterogeneous

(d) Platinum, palladium or rhodium, heterogeneous

(e) Fe2+ ions, homogeneous

(f) Manganese dioxide, MnO2, heterogeneous

(g) Mn2+ ions, homogeneous *(7 marks)*

**2.** (a)Autocatalysis is when one of the products of the reaction acts as a catalyst for the reaction.

*(1 mark)*

(b) Initially a little of the Mn2+ catalyst is made by the reaction. Once a little is made, it reacts with MnO‹ ions to form Mn3+ as an intermediate species. The Mn3+ then reacts with the C2O42- ions to form CO2 and reform the Mn2+ catalyst;

4 Mn2+(aq) + MnO4-(aq) + 8 H+(aq) → 5 Mn3+(aq) + 4 H2O(l)

2 Mn3+(aq) + C2O42- (aq) → 2 CO2(g) + 2 Mn2+(aq)

*(2 marks)*