MEGA LECTURE · A LEVEL CHEMISTRY

Chapter 25: Transition Elements

OCR A Level Chemistry A (H432) — Structured Practice Worksheet

SPECIFICATION	TOTAL MARKS	SUGGESTED TIME
3.3.6 Transition elements: electron configuration, properties, complex ions, ligand substitution, colour, redox titrations	118	2 hours 20 minutes

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Instructions to candidates

- Answer **all** questions in the spaces provided. Show all working in calculations.
- Marks are shown in brackets [ ] at the end of each part.

Question 1 — Definition of a transition element

3.3.6

a. State what is meant by the term *transition element*. **[2]**

b. Give the full electron configuration of a scandium atom and of the Sc^{3+} ion. Hence explain why scandium is not classified as a transition element. **[3]**

c. Give the full electron configuration of a zinc atom and of the Zn^{2+} ion. Hence explain why zinc is not classified as a transition element. **[3]**

d. State the block of the periodic table in which scandium, zinc and all the transition elements are found. **[1]**

Question 1 total: 9 marks

Question 2 — Electron configurations of d-block atoms and ions

3.3.6

a. Complete the table to give the full electron configuration of each atom. **[2]**

Species	Full electron configuration
Ti (atom)	
Fe (atom)	

b. Chromium has the electron configuration $[Ar]3d^5 4s^1$ rather than the "expected" $[Ar]3d^4 4s^2$. Explain why. **[2]**

c. Explain why copper has the electron configuration [Ar]$3d^{10}4s^1$ rather than [Ar]$3d^9 4s^2$. **[2]**

d. Give the electron configurations of the Fe^{2+} and Fe^{3+} ions, and state which sub-shell's electrons are removed first when a first-row transition metal atom is ionised. **[3]**

e. Give the electron configuration of the Cr^{3+} ion. **[1]**

Question 2 total: 10 marks

Question 3 — Characteristic properties of transition elements 3.3.6

a. State four characteristic properties shown by transition elements and their compounds. **[4]**

b. Explain, in terms of electron configuration, why transition elements are able to show variable oxidation states. **[2]**

c. Give the formula of a common compound in which iron shows the +2 oxidation state, and one in which it shows the +3 oxidation state. **[2]**

Question 3 total: 8 marks

Question 4 — Catalytic activity of transition elements 3.3.6

a. Distinguish between a heterogeneous catalyst and a homogeneous catalyst. **[2]**

b. Complete the table to name the catalyst used in each process and state its role. **[6]**

Process	Catalyst used	Role of the catalyst
Haber process: $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$		
Contact process: $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$		
Decomposition of hydrogen peroxide: $2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g)$		

c. Explain what is meant by *autocatalysis*, referring to the reaction between MnO_4^- and ethanedioate ($C_2O_4^{2-}$) ions. **[2]**

Question 4 total: 10 marks

Question 5 — Complex ions, ligands and coordination number 3.3.6

a. Define the term *complex ion*. **[2]**

b. Define the term *ligand*, referring to the type of bond formed with the central metal ion. **[2]**

c. Define *coordination number*. **[1]**

d. Complete the table to give the coordination number and shape of each complex ion/molecule. **[6]**

Complex	Coordination number	Shape
$[Cu(H_2O)_6]^{2+}$		
$[CuCl_4]^{2-}$		
$[Pt(NH_3)_2Cl_2]$ (cisplatin)		

Question 5 total: 11 marks

Question 6 — Denticity of ligands and the chelate effect 3.3.6

a. Define, giving an example of each, the terms *monodentate ligand*, *bidentate ligand* and *multidentate (polydentate) ligand*. State how many dative bonds your multidentate example forms to a metal ion. **[4]**

b. Draw a diagram to show how a molecule of 1,2-diaminoethane ("en") binds to a metal ion, M^{2+}, via two dative bonds. **[3]**

Draw the en ligand bonded to M^{2+}, showing both dative (coordinate) bonds and the ring formed

c. Explain, in terms of entropy, why a complex formed with a bidentate or multidentate ligand (the chelate effect) is thermodynamically more stable than the equivalent complex formed with monodentate ligands. **[2]**

Question 6 total: 9 marks

Question 7 — Ligand substitution reactions of copper 3.3.6

a. State the colour and shape of the $[Cu(H_2O)_6]^{2+}$ ion in aqueous solution. **[2]**

b. Write an equation for the reaction of $[Cu(H_2O)_6]^{2+}$ with excess aqueous ammonia, and state the colour change observed. **[3]**

c. Write an equation for the reaction of $[Cu(H_2O)_6]^{2+}$ with excess concentrated hydrochloric acid, and state the colour change and change in shape observed. **[4]**

d. Explain why the coordination number changes from 6 to 4 when Cl^- ligands replace H_2O ligands. **[2]**

e.

Describe what is observed when a small volume of dilute aqueous ammonia is added to a solution of $[Cu(H_2O)_6]^{2+}$, and write an equation for this reaction. **[2]**

Question 7 total: 13 marks

Question 8 — Ligand substitution of cobalt; colour in complexes 3.3.6

a. State the colour and shape of the $[Co(H_2O)_6]^{2+}$ ion in aqueous solution. **[2]**

b. Write an equation for the reaction of $[Co(H_2O)_6]^{2+}$ with excess concentrated hydrochloric acid, and state the colour change observed. **[3]**

c. Explain, in terms of the d-orbitals, why transition metal complex ions are typically coloured. **[3]**

d. Explain why $[Sc(H_2O)_6]^{3+}$ and $[Zn(H_2O)_6]^{2+}$ are both colourless. **[3]**

e. State two factors, other than coordination number, that affect the colour of a transition metal complex ion. **[2]**

Question 8 total: 13 marks

Question 9 — Variable oxidation states: the chemistry of vanadium 3.3.6

Vanadium is unusual among the first-row transition elements in that four different oxidation states can readily be observed in aqueous solution, and interconverted by reduction with zinc in the presence of dilute acid.

a. Complete the table to give the oxidation number of vanadium and the colour of each species. **[8]**

Vanadium species	Oxidation number of V	Colour
VO_2^+		
VO^{2+}		
V^{3+}		
V^{2+}		

b. Describe how a solution containing VO_2^+ ions can be converted into a solution of V^{2+} ions, and describe what would be observed. **[2]**

Question 9 total: 10 marks

Question 10 — Redox titrations 3.3.6

a. Explain why no indicator is required in a titration using aqueous potassium manganate(VII), and describe how the end point is recognised. **[2]**

b. Write a half-equation for the reduction of MnO_4^- ions to Mn^{2+} ions in acidic solution. **[2]**

c. A 25.0 cm^3 sample of iron(II) sulfate solution, acidified with excess dilute sulfuric acid, required 22.60 cm^3 of 0.0200 mol dm^{-3} potassium manganate(VII) solution for complete reaction, according to the ionic equation $MnO_4^- + 5Fe^{2+} + 8H^+ \rightarrow Mn^{2+} + 5Fe^{3+} + 4H_2O$. Calculate the concentration of Fe^{2+} in the original solution, in mol dm^{-3}. **[4]**

d. Hence calculate the concentration of Fe^{2+} in the original solution in g dm^{-3}. [A_r: Fe = 55.8] **[3]**

e. When excess potassium iodide solution is added to a solution containing Cu^{2+} ions, a precipitate of copper(I) iodide forms and iodine is liberated; the iodine can then be titrated against standard sodium thiosulfate solution using starch indicator. Write equations for both reactions, and state the colour change observed at the end point of the titration. **[4]**

f. A 25.0 cm^3 sample of copper(II) sulfate solution was treated with excess potassium iodide solution. The iodine liberated required 18.40 cm^3 of 0.100 mol dm^{-3} sodium thiosulfate solution for complete reaction. Calculate the concentration of Cu^{2+} in the original solution, in mol dm^{-3}. **[4]**

Question 10 total: 19 marks

Question 11 — Extended response

Synoptic

Transition elements characteristically form coloured compounds, show catalytic activity, and exhibit variable oxidation states. Using ideas about electron configuration and the d-orbitals, explain how these three characteristic properties arise, illustrating your answer with named examples. **[6]**

This question is marked using a level of response.

Question 11 total: 6 marks

PAPER TOTAL: 118 MARKS

MARK SCHEME — Chapter 25: Transition Elements

Award marks independently unless stated. ECF applies to calculations.

Q1 (a) [2]

- A d-block element (1) that forms at least one stable ion with a partially filled (incomplete) d-subshell (1).

Q1 (b) [3]

- Sc: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^1 4s^2$ (1)
- Sc^{3+}: $1s^2 2s^2 2p^6 3s^2 3p^6$ (i.e. [Ar], empty 3d) (1)
- Scandium only ever forms the Sc^{3+} ion, which has an empty (not partially filled) 3d subshell, so it does not meet the definition of a transition element. (1)

Q1 (c) [3]

- Zn: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2$ (1)
- Zn^{2+}: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$ (i.e. [Ar]$3d^{10}$, full 3d) (1)
- Zinc only ever forms the Zn^{2+} ion, which has a full (completely filled) 3d subshell, so it does not meet the definition of a transition element. (1)

Q1 (d) [1]

- d-block. (1)

Q2 (a) [2]

- Ti: [Ar]$3d^2 4s^2$ (or full $1s^2 2s^2 2p^6 3s^2 3p^6 3d^2 4s^2$). (1)
- Fe: [Ar]$3d^6 4s^2$ (or full $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$). (1)

Q2 (b) [2]

- A half-filled 3d subshell (one electron in each of the five 3d orbitals) is an especially stable/lower-energy arrangement. (1)
- One electron moves from the 4s orbital into the 3d subshell to achieve this extra stability, giving [Ar]$3d^5 4s^1$. (1)

Q2 (c) [2]

- A fully-filled 3d subshell (each of the five 3d orbitals doubly occupied) is an especially stable/lower-energy arrangement. (1)
- One electron moves from the 4s orbital into the 3d subshell to achieve this extra stability, giving [Ar]$3d^{10} 4s^1$. (1)

Q2 (d) [3]

- Fe^{2+}: [Ar]$3d^6$. (1)
- Fe^{3+}: [Ar]$3d^5$. (1)
- The 4s electrons are always removed before any 3d electrons, because in the ion the 3d subshell is at a lower energy than the 4s subshell. (1)

Q2 (e) [1]

- Cr^{3+}: [Ar]$3d^3$. (1)

Q3 (a) [4]

- Any four of: variable/multiple oxidation states; formation of coloured ions/compounds; catalytic activity (as elements or compounds); formation of complex ions with ligands. (1 mark each, max 4)

Q3 (b) [2]

- The 3d and 4s sub-shells are close together in energy. (1)
- So varying numbers of both 4s and 3d electrons can be lost/involved in bonding, giving several oxidation states of similar stability. (1)

Q3 (c) [2]

- Any correct Fe^{2+} compound, e.g. $FeSO_4$, $FeCl_2$, $FeCO_3$. (1)
- Any correct Fe^{3+} compound, e.g. Fe_2O_3, $FeCl_3$, $Fe_2(SO_4)_3$. (1)

Q4 (a) [2]

- A heterogeneous catalyst is in a different physical state/phase from the reactants. (1)
- A homogeneous catalyst is in the same physical state/phase as the reactants. (1)

Q4 (b) [6]

- Haber process: catalyst = iron (1); role = increases the rate at which equilibrium/ammonia is reached, without affecting the position of equilibrium or the yield (1).
- Contact process: catalyst = vanadium(V) oxide, V_2O_5 (1); role = increases the rate of oxidation of SO_2 to SO_3 (1).
- Decomposition of H_2O_2: catalyst = manganese(IV) oxide, MnO_2 (1); role = increases the rate of decomposition of hydrogen peroxide into water and oxygen (1).

Q4 (c) [2]

- The reaction between MnO_4^- and $C_2O_4^{2-}$ is catalysed by Mn^{2+} ions, which are themselves a product of the reaction. (1)
- The reaction starts slowly, but speeds up as Mn^{2+} builds up and catalyses the reaction (self-catalysis), before slowing again as the reactants are used up. (1)

Q5 (a) [2]

- A central metal ion/atom (1) surrounded by/bonded to a number of ligands by dative (coordinate) bonds (1).

Q5 (b) [2]

- A molecule or ion that donates a lone pair of electrons (1) to the central metal ion, forming a dative (coordinate) bond (1).

Q5 (c) [1]

- The number of dative (coordinate) bonds formed between the ligands and the central metal ion. (1)

Q5 (d) [6]

- $[Cu(H_2O)_6]^{2+}$: coordination number 6 (1); octahedral (1).
- $[CuCl_4]^{2-}$: coordination number 4 (1); tetrahedral (1).
- $[Pt(NH_3)_2Cl_2]$: coordination number 4 (1); square planar (1).

Q6 (a) [4]

- Monodentate ligand: forms one dative bond to the central metal ion, e.g. H_2O, NH_3 or Cl^-. (1)
- Bidentate ligand: forms two dative bonds to the central metal ion, e.g. 1,2-diaminoethane ("en"). (1)
- Multidentate (polydentate) ligand: forms more than two dative bonds to the central metal ion, e.g. $EDTA^{4-}$. (1)
- $EDTA^{4-}$ is hexadentate — it forms six dative bonds to the metal ion. (1)

Q6 (b) [3]

- Correct structure of en, $H_2NCH_2CH_2NH_2$, shown with a lone pair on each N atom. (1)
- Both N atoms shown bonded to the same M^{2+} ion, forming a five-membered ring. (1)
- Two dative bonds correctly shown with arrows (→) pointing from each N atom to M^{2+}. (1)

Q6 (c) [2]

- When a bidentate/multidentate ligand displaces several monodentate ligands, more moles of free ligand particles are released than are used up, increasing the total number of particles/species in solution. (1)
- This increases the entropy of the system, making ΔG more negative (more favourable), so the chelate complex is thermodynamically more stable. (1)

Q7 (a) [2]

- Pale blue. (1)
- Octahedral. (1)

Q7 (b) [3]

- $[Cu(H_2O)_6]^{2+} + 4NH_3 \rightarrow [Cu(NH_3)_4(H_2O)_2]^{2+} + 4H_2O$ (2 — 1 for correct formulae, 1 for balancing)
- Colour changes from pale blue to deep (royal) blue. (1)

Q7 (c) [4]

- $[Cu(H_2O)_6]^{2+} + 4Cl^- \rightarrow [CuCl_4]^{2-} + 6H_2O$ (2 — 1 for correct formulae, 1 for balancing)
- Colour changes from pale blue to yellow. (1)
- Shape changes from octahedral to tetrahedral. (1)

Q7 (d) [2]

- Cl^- ions are larger (have a greater ionic radius) than H_2O molecules. (1)
- So fewer Cl^- ligands can fit around/bond to the central Cu^{2+} ion, reducing the coordination number from 6 to 4. (1)

Q7 (e) [2]

- A pale blue precipitate (of $Cu(OH)_2$) forms. (1)
- $[Cu(H_2O)_6]^{2+} + 2NH_3 \rightarrow Cu(OH)_2(H_2O)_4 + 2NH_4^+$ (1)

Q8 (a) [2]

- Pink. (1)
- Octahedral. (1)

Q8 (b) [3]

- $[Co(H_2O)_6]^{2+} + 4Cl^- \rightarrow [CoCl_4]^{2-} + 6H_2O$ (2 — 1 for correct formulae, 1 for balancing)
- Colour changes from pink to blue. (1)

Q8 (c) [3]

- In a complex ion, the ligands cause the five d-orbitals of the metal ion to split into two groups of different (slightly different) energy. (1)
- An electron can absorb energy and be excited from a lower-energy d-orbital to a higher-energy d-orbital (a d–d transition). (1)
- The energy absorbed corresponds to a particular frequency of visible light; the complementary colour (the light transmitted/not absorbed) is what is observed. (1)

Q8 (d) [3]

- Sc^{3+} has an empty 3d subshell, so there are no d-electrons available to be excited/undergo a d–d transition. (1)
- Zn^{2+} has a full $3d^{10}$ subshell, so there is no vacant higher-energy d-orbital for an electron to move into (no d–d transition is possible). (1)
- Since no visible light is absorbed by either ion, both are colourless. (1)

Q8 (e) [2]

- Any two of: the identity of the metal; the oxidation state of the metal; the identity of the ligand(s). (1 mark each, max 2)

Q9 (a) [8]

- VO_2^+: oxidation number +5 (1); colour yellow (1).
- VO^{2+}: oxidation number +4 (1); colour blue (1).
- V^{3+}: oxidation number +3 (1); colour green (1).
- V^{2+}: oxidation number +2 (1); colour violet (1).

Q9 (b) [2]

- Warm the acidified VO_2^+ solution with (excess) zinc metal/granules. (1)
- The vanadium is successively reduced through each oxidation state (+5 → +4 → +3 → +2), with the colour changing yellow → blue → green → violet. (1)

Q10 (a) [2]

- $KMnO_4$ is self-indicating: the MnO_4^- ion is intensely purple/coloured while its reduction product Mn^{2+} is almost colourless. (1)
- The end point is shown by the first permanent faint (pale) pink colouration in the flask. (1)

Q10 (b) [2]

- $MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O$ (1 for species/electrons, 1 for correct H/O balancing and charge)

Q10 (c) [4]

- Moles MnO_4^- = 0.0200 × (22.60/1000) = 4.52×10^{-4} mol. (1)
- Moles Fe^{2+} = 5 × 4.52×10^{-4} = 2.26×10^{-3} mol (using the 1 : 5 mole ratio MnO_4^- : Fe^{2+}). (1)
- Concentration of Fe^{2+} = 2.26×10^{-3} ÷ (25.0/1000). (1)
- = 0.0904 mol dm^{-3}. (1)

Q10 (d) [3]

- Mass concentration = 0.0904 × 55.8 (1)
- = 5.04 g dm^{-3} (to 3 s.f.). (1)
- Correct units (g dm^{-3}) stated. (1)

Q10 (e) [4]

- $2Cu^{2+} + 4I^- \rightarrow 2CuI + I_2$. (1)
- $I_2 + 2S_2O_3^{2-} \rightarrow 2I^- + S_4O_6^{2-}$. (1)
- Starch indicator is added (close to the expected end point). (1)
- Colour changes from blue-black to colourless at the end point. (1)

Q10 (f) [4]

- Moles $S_2O_3^{2-}$ = 0.100 × (18.40/1000) = 1.840×10^{-3} mol. (1)
- Moles I_2 = 1.840×10^{-3} ÷ 2 = 9.20×10^{-4} mol. (1)
- Moles Cu^{2+} = 2 × moles I_2 = 2 × 9.20×10^{-4} = 1.840×10^{-3} mol. (1)
- Concentration of Cu^{2+} = 1.840×10^{-3} ÷ (25.0/1000) = 0.0736 mol dm^{-3}. (1)

Note: because 2 mol Cu^{2+} ≡ 1 mol I_2 ≡ 2 mol $S_2O_3^{2-}$, moles Cu^{2+} = moles $S_2O_3^{2-}$ directly; full working via I_2 as shown, or this direct route, both gain full credit.

Q11 [6] — Level of response

- **Level 3 (5–6):** Explains all three properties (colour, catalytic activity, variable oxidation states) fully and correctly in terms of electron configuration/d-orbitals, with correctly named supporting examples for each.
- **Level 2 (3–4):** Explains two of the three properties fully, with a partial or less complete explanation (or missing/incorrect example) for the third.
- **Level 1 (1–2):** Identifies the properties with limited or generic reasoning; little reference to electron configuration/d-orbitals or to specific examples.

Indicative content: *Colour arises because ligands split the five 3d orbitals of the metal ion into two groups of different energy; an electron can be excited between these split d-orbitals (a d–d transition) by absorbing a specific frequency of visible light, and the complementary colour is observed (e.g. $[Cu(H_2O)_6]^{2+}$ is pale blue). Ions such as Sc^{3+} (empty 3d) and Zn^{2+} (full $3d^{10}$) are colourless because no d–d transition is possible. Catalytic activity arises because the 3d and 4s energy levels are close together, allowing transition metals/ions to change oxidation state readily and to use partially filled d-orbitals to form weak/temporary bonds with reactant molecules (adsorption), providing an alternative reaction pathway of lower activation energy — e.g. iron in the Haber process (heterogeneous), or Mn^{2+} autocatalysing the $MnO_4^-/C_2O_4^{2-}$ reaction (homogeneous). Variable oxidation states occur because the 3d and 4s electrons are similar in energy, so different numbers of electrons can be lost or gained with only a small energy penalty, giving several oxidation states of comparable stability — e.g. vanadium exists as VO_2^+ (+5), VO^{2+} (+4), V^{3+} (+3) and V^{2+} (+2), interconverted by reduction with zinc.*

END OF MARK SCHEME · 118 marks