▶ Video explanation (YouTube Short)

Formation of Coloured Ions: Why Transition-Metal Ions Are Coloured

A ruby is red and an emerald is green, yet both owe their colour to the same ion, **Cr^{3+}**. Copper sulphate solution is blue, nickel salts are green, but zinc and scandium salts are colourless. These notes explain where the colour of transition-metal ions comes from (NCERT 4.3.10, Table 4.8).

1. Light and colour: what we see

- **White light** contains all the colours of the visible spectrum (violet, blue, green, yellow, orange, red; about 400–700 nm).
- When white light passes through a solution, the solution may **absorb** some wavelengths. The light that is **not absorbed** (transmitted) reaches our eye.
- Remove one band of colours from white light and the rest mix to give the **complementary colour** of the band that was removed.

Key rule: the colour we see is the **complementary** colour of the light absorbed, not the colour that is absorbed.

Colour absorbed	Colour seen (complementary)
red	green
orange	blue
yellow	violet
green-yellow	purple (red + blue left)
blue	orange
violet	yellow

On a colour wheel, complementary colours sit opposite each other.

2. Splitting of the d orbitals

- In a **free** (isolated) transition-metal ion, the five d orbitals have the **same energy** (they are degenerate).
- When **ligands** (molecules or ions such as H_2O, NH_3, Cl^-) surround the ion, the d orbitals are no longer equal: they **split** into a lower-energy set and a higher-energy set. With six ligands (octahedral), three orbitals go lower and two go higher.
- The difference in energy between the two sets is a small **energy gap**. (Its name and details come in Unit 5, Coordination Compounds: crystal field splitting, Δo.)

3. The d–d transition

1. A d electron in the lower set absorbs a photon whose energy is **exactly equal** to the gap: E = hν = gap.
2. The electron is excited (jumps) from the lower-energy d orbital to a higher-energy d orbital. This is a **d–d transition**.
3. For most transition-metal ions the energy of excitation corresponds to a frequency in the **visible region**, so a band of visible light is absorbed.
4. The remaining light reaches the eye: the ion shows the complementary colour.

NCERT (4.3.10): the energy of excitation corresponds to the frequency of light absorbed; this frequency generally lies in the visible region; the colour observed is the complementary colour of the light absorbed; the frequency absorbed is determined by the nature of the ligand.

4. Worked examples

Example 1: Ti^{3+}(aq) is purple

Ti (Z = 22): [Ar] $3d^2 4s^2$ → Ti^{3+} = **$3d^1$**, one d electron. In $[Ti(H_2O)_6]^{3+}$ the electron absorbs light of about **500 nm** (green-yellow; band ≈ 450–600 nm) and jumps to the upper level. Red and blue light are transmitted → the solution looks **purple**.

Example 2: Cu^{2+}(aq) is blue

Cu^{2+} = **$3d^9$**: one vacancy in the upper level. $[Cu(H_2O)_6]^{2+}$ absorbs in the red-orange region (broad band near 800 nm), so the transmitted light is **blue**.

Example 3: Sc^{3+} and Zn^{2+} are colourless

Sc^{3+} = **$3d^0$**: no d electron to jump. Zn^{2+} = **$3d^{10}$**: every d orbital is full, so there is no empty place above. No d–d transition is possible → no visible light is absorbed → **colourless**. The same holds for Ti^{4+} ($3d^0$) and Cu^+ ($3d^{10}$).

Example 4: ruby and emerald (the ligand sets the gap)

Both contain Cr^{3+} ($3d^3$) surrounded by oxide ions. In **ruby** (Al_2O_3 with Cr^{3+}) the gap is larger (≈ 2.2 eV): it absorbs yellow-green (and violet) light, leaving **red**. In **emerald** (beryl with Cr^{3+}) the gap is a little smaller (≈ 2.05 eV): the absorption shifts toward red-orange, leaving **green**. Same ion, different surroundings, different colour.

5. Colours of some aquated 3d ions (NCERT Table 4.8)

Configuration	Ion	Colour
$3d^0$	Sc^{3+}, Ti^{4+}	colourless
$3d^1$	Ti^{3+} / V^{4+}	purple / blue
$3d^2$	V^{3+}	green
$3d^3$	V^{2+}, Cr^{3+}	violet
$3d^4$	Mn^{3+} / Cr^{2+}	violet / blue

$3d^5$	Mn^{2+} / Fe^{3+}	pink / yellow
$3d^6$	Fe^{2+} / Co^{3+}	green / blue
$3d^7$	Co^{2+}	pink
$3d^8$	Ni^{2+}	green
$3d^9$	Cu^{2+}	blue
$3d^{10}$	Zn^{2+}	colourless

6. Common mistakes

- ✗ "Cu^{2+} is blue because it absorbs blue light." ✓ It absorbs red-orange; blue is what is **left**.
- ✗ "Every transition-metal ion is coloured." ✓ d^0 (Sc^{3+}, Ti^{4+}) and d^{10} (Zn^{2+}, Cu^{+}) ions are colourless.
- ✗ "The colour depends only on the metal." ✓ The same ion changes colour with its ligands (Cr^{3+} in ruby vs emerald; Cu^{2+} is pale blue in water and deep blue with ammonia).
- ✗ "$KMnO_4$ is purple because of d–d transitions." ✓ Mn(VII) is d^0; its colour comes from **charge transfer** (a different process, studied separately).

7. Key takeaways

- Ligands split the d orbitals; a d electron absorbs light whose energy equals the gap and jumps (d–d transition).
- The absorbed light is usually visible; we see the complementary colour.
- The ligand decides the size of the gap, so the colour.
- d^0 and d^{10} ions are colourless.

Practice questions

1. (MCQ) Which aquated ion is colourless? (a) Ti^{3+} (b) Cu^{2+} (c) Sc^{3+} (d) Ni^{2+}
2. (MCQ) The colour of transition-metal ions is mainly due to: (a) s–p transitions (b) d–d transitions (c) nuclear spin (d) paired electrons
3. (MCQ) A solution absorbs orange light. It appears: (a) orange (b) blue (c) red (d) yellow
4. (MCQ) Which pair contains only colourless ions? (a) Sc^{3+}, Zn^{2+} (b) Ti^{3+}, Cu^{2+} (c) V^{3+}, Zn^{2+} (d) Mn^{2+}, Fe^{3+}
5. (Very short) What decides the frequency of light absorbed by a transition-metal ion?
6. (Very short) Write the colour of Ni^{2+}(aq) and its configuration.
7. (Short) Why is Ti^{3+}(aq) purple?
8. (Short) Why are Zn^{2+} salts white/colourless?
9. (Short) Ruby and emerald both contain Cr^{3+}. Why are their colours different?
10. (NCERT exercise type) Which of these aqueous ions are coloured: Ti^{3+}, V^{3+}, Sc^{3+}, Mn^{2+}, Fe^{3+}, Co^{2+}, Ti^{4+}? Give reasons.

Answer key

1. (c) Sc^{3+} ($3d^0$).
2. (b) d–d transitions.
3. (b) blue (complementary of orange).
4. (a) Sc^{3+} ($3d^0$), Zn^{2+} ($3d^{10}$).
5. The nature of the ligand (it sets the size of the d-orbital splitting).
6. Green; $3d^8$.

7. Ti^{3+} is $3d^1$; water splits the d orbitals; the electron absorbs green-yellow light (~500 nm) in a d–d transition; red + blue are transmitted, so it looks purple.
8. Zn^{2+} is $3d^{10}$: all d orbitals are full, so no d–d transition can occur and no visible light is absorbed.
9. The surroundings (ligand field) differ: ruby's gap is larger (absorbs yellow-green → red), emerald's smaller (absorbs red-orange → green).
10. Coloured: Ti^{3+} ($3d^1$), V^{3+} ($3d^2$), Mn^{2+} ($3d^5$), Fe^{3+} ($3d^5$), Co^{2+} ($3d^7$): partly filled d orbitals allow d–d transitions. Colourless: Sc^{3+} and Ti^{4+} ($3d^0$).

▶ Watch the video explanation