▶ Video explanation (YouTube Short)

Magnetic Properties: Paramagnetism and the Spin-only Magnetic Moment

Hang a little blue copper sulphate between the poles of an electromagnet on a sensitive balance and switch the magnet on: the balance reads a little *more*, because the sample is pulled into the field. White zinc sulphate shows no such pull. These notes explain why, and how to calculate the **magnetic moment** of a transition-metal ion (NCERT 4.3.9).

1. Types of magnetic behaviour

Type	In a magnetic field	Cause	Examples
Diamagnetic	weakly **repelled**	all electrons paired	Zn^{2+} ($3d^{10}$), Sc^{3+} ($3d^{0}$), Cu^{+} ($3d^{10}$), Ti^{4+}
Paramagnetic	**attracted**	one or more **unpaired electrons**	Cu^{2+}, Mn^{2+}, Fe^{3+}, Ti^{3+}
Ferromagnetic	attracted **very strongly**	an extreme form of paramagnetism	Fe, Co, Ni metals

Many transition-metal ions are paramagnetic because their partly filled d orbitals hold unpaired electrons.

2. Why unpaired electrons make a substance magnetic

- Every electron behaves like a **tiny magnet**: it has a magnetic moment from its **spin** (and its orbital motion).
- In a **pair** the two spins are opposite (↑↓), so their magnetic effects **cancel**.
- An **unpaired** electron is not cancelled, so its magnet remains. The more unpaired electrons, the stronger the pull.
- For ions of the **first (3d) series**, the orbital contribution is effectively **quenched** (suppressed by the surrounding ligands), so the magnetic moment depends only on the number of unpaired electrons, *n*.

3. Counting unpaired electrons (n)

Step 1: write the ion's configuration

Remove electrons from **4s first**, then from 3d. Fe = [Ar] $3d^6 4s^2$ → Fe^{2+} = [Ar] $3d^6$ (not $3d^4$). Cu = [Ar] $3d^{10} 4s^1$ → Cu^{2+} = [Ar] $3d^9$.

Step 2: fill the five 3d orbitals singly first (Hund's rule), then pair

d count	d^1	d^2	d^3	d^4	d^5	d^6	d^7	d^8	d^9	d^{10}
orbital picture	↑	↑ ↑	↑ ↑ ↑	↑↓ ↑ ↑	↑↓ ↑ ↑ ↑	↑↓ ↑↓ ↑	↑↓ ↑↓ ↑ ↑ ↑	↑↓ ↑↓ ↑↓ ↑	↑↓ ↑↓ ↑↓ ↑↓ ↑	all paired

n	1	2	3	4	**5**	4	3	2	1	0

Shortcut: d^1 to d^5 → n = number of d electrons; d^6 to d^{10} → n = 10 − (number of d electrons). The maximum, n = 5, is at **d^5** (Mn^{2+}, Fe^{3+}).

These are high-spin (free / hydrated) ions, as in NCERT. In some complexes electrons pair up earlier (low spin): that is studied in Coordination Compounds.

4. The spin-only formula

$\mu = \sqrt{n(n+2)}$ BM where n = number of unpaired electrons and BM = Bohr magneton, the unit of magnetic moment.

n	**0**	**1**	**2**	**3**	**4**	**5**
n(n+2)	0	3	8	15	24	35
μ (BM)	0	1.73	2.84	3.87	4.90	5.92

- One unpaired electron has a moment of **1.73 BM**.
- μ **increases** with n, but **not in proportion**: two unpaired electrons give 2.84 BM, not 2 × 1.73 = 3.46 BM. Always use the formula.
- (Where it comes from: $\mu = 2\sqrt{S(S+1)}$ with total spin S = n/2, which simplifies to $\sqrt{n(n+2)}$.)

5. Calculated and observed values (NCERT Table 4.7)

Ion	Configuration	n	μ calculated (BM)	μ observed (BM)
Sc^{3+}	$3d^0$	0	0	0
Ti^{3+}	$3d^1$	1	1.73	1.75
Ti^{2+}	$3d^2$	2	2.84	2.76
V^{2+}	$3d^3$	3	3.87	3.86
Cr^{2+}	$3d^4$	4	4.90	4.80
Mn^{2+}	$3d^5$	5	5.92	5.96
Fe^{2+}	$3d^6$	4	4.90	5.3 – 5.5
Co^{2+}	$3d^7$	3	3.87	4.4 – 5.2
Ni^{2+}	$3d^8$	2	2.84	2.9 – 3.4
Cu^{2+}	$3d^9$	1	1.73	1.8 – 2.2
Zn^{2+}	$3d^{10}$	0	0	0

- The observed values are close to the spin-only values, so a **measured μ tells you n**: Mn^{2+} measures 5.96 BM, so it has 5 unpaired electrons.
- Fe^{2+} and Co^{2+} read higher than spin-only because their orbital contribution is not completely quenched.
- μ rises from d^0 to a peak at d^5 and falls back to 0 at d^{10}.

6. How it is measured: the Gouy balance

A sample tube hangs from a sensitive balance so that its lower end sits between the poles of an electromagnet. When the field is switched on, a paramagnetic sample is drawn into the stronger field and appears **heavier**; a diamagnetic sample appears very slightly lighter. The change in apparent mass gives the magnetic susceptibility, from which μ is calculated. (The real change is tiny; the video exaggerates the needle swing.)

Solved examples

1. (NCERT Example 4.8) Calculate the magnetic moment of a divalent ion in aqueous solution if its atomic number is 25.
A. Z = 25 is Mn: [Ar] $3d^5 4s^2$. $Mn^{2+} = 3d^5$ → 5 unpaired electrons. μ = √(5 × 7) = √35 = **5.92 BM**.

2. Calculate the spin-only magnetic moment of Fe^{3+} (Z of Fe = 26).
A. Fe = [Ar] $3d^6 4s^2$ → $Fe^{3+} = 3d^5$ → n = 5 → μ = √35 = **5.92 BM**.

3. An ion of the first transition series has μ = 3.87 BM. How many unpaired electrons does it have? Suggest one such ion.
A. √(n(n+2)) = 3.87 → n(n+2) = 15 → n = 3. Examples: V^{2+} ($3d^3$) or Cr^{3+} ($3d^3$).

4. Which of Ti^{4+}, Ni^{2+} and Cu^{+} are paramagnetic?
A. $Ti^{4+} = 3d^0$ (n = 0, diamagnetic); $Ni^{2+} = 3d^8$ (n = 2, paramagnetic, 2.84 BM); $Cu^{+} = 3d^{10}$ (n = 0, diamagnetic). Only Ni^{2+}.

Common mistakes

- Taking electrons from 3d before 4s when forming the ion (Fe^{2+} is $3d^6$, not $3d^4$).
- Counting all d electrons as unpaired beyond d^5 (d^8 has 2 unpaired, not 8).
- Multiplying 1.73 by n instead of using √(n(n+2)).
- Thinking "more d electrons = more magnetic": Zn^{2+} has ten d electrons and is diamagnetic.

Key takeaways

- Paramagnetism comes from **unpaired electrons**; paired spins cancel.
- Count n from the ion's d configuration (singly first, then pairing from d^6).
- μ = √(n(n+2)) BM: 1.73, 2.84, 3.87, 4.90, 5.92 for n = 1 to 5.
- μ peaks at d^5; a measured μ tells you the number of unpaired electrons.

Practice questions

1. (MCQ) Which ion is diamagnetic? (a) Cu^{2+} (b) Zn^{2+} (c) Mn^{2+} (d) Fe^{2+}
2. (MCQ) The spin-only magnetic moment of an ion with 2 unpaired electrons is: (a) 1.73 BM (b) 2.84 BM (c) 3.46 BM (d) 3.87 BM
3. (MCQ) The number of unpaired electrons in Ni^{2+} (Z of Ni = 28) is: (a) 0 (b) 2 (c) 4 (d) 8
4. (MCQ) Which of these has the highest magnetic moment? (a) V^{2+} (b) Cr^{3+} (c) Fe^{3+} (d) Cu^{2+}
5. (Very short) What is the unit of magnetic moment?
6. (Very short) Why is Sc^{3+} diamagnetic?
7. (Short) Explain why paired electrons do not contribute to paramagnetism.
8. (Short) Why does μ not double when the number of unpaired electrons doubles?

9. (Numerical) Calculate the spin-only magnetic moment of Cr^{3+} (Z of Cr = 24).
10. (Numerical, NCERT Intext 4.8) Calculate the spin-only magnetic moment of $M^{2+}(aq)$, Z = 27.

Answer key

1. (b) Zn^{2+} ($3d^{10}$).
2. (b) $\sqrt{8}$ = 2.84 BM.
3. (b) $Ni^{2+} = 3d^8 \rightarrow 2$.
4. (c) $Fe^{3+} = 3d^5$, n = 5 (5.92 BM).
5. Bohr magneton (BM).
6. Sc^{3+} is $3d^0$: it has no unpaired electrons.
7. The two electrons of a pair have opposite spins, so their magnetic moments cancel.
8. $\mu = \sqrt{n(n+2)}$, which is not proportional to n: n = 1 gives 1.73, n = 2 gives 2.84.
9. Cr = [Ar] $3d^5 4s^1 \rightarrow Cr^{3+} = 3d^3 \rightarrow n = 3 \rightarrow \mu = \sqrt{15} = 3.87$ BM.
10. Z = 27 is Co: [Ar] $3d^7 4s^2 \rightarrow Co^{2+} = 3d^7 \rightarrow n = 3 \rightarrow \mu = \sqrt{15} = 3.87$ BM.

▶ Watch the video explanation