🔷 Background: Magnetic Moment and Its Components

The **magnetic moment** (μ) of a transition metal ion has two main contributions:

1. **Spin magnetic moment** — due to the spin of unpaired electrons.
2. **Orbital magnetic moment** — due to the motion (orbital angular momentum) of electrons around the nucleus.

In an isolated (free) ion, **both** contributions are present, and the total magnetic moment is given by quantum mechanics using the **Russell–Saunders (LS) coupling scheme**:

$$\mu = \sqrt{4S(S+1) + L(L+1)\mu_B}$$

Where S= total spin quantum number

- L= total orbital angular momentum quantum number
- μ_B= Bohr magneton

However, in **coordination compounds**, the **orbital contribution is often "quenched"**, leaving mainly the **spin-only** component.

🔷 What is "Quenching"?

Orbital quenching means that the orbital contribution to the magnetic moment is *suppressed* or *lost* because the degeneracy of the d orbitals is removed by the surrounding ligand field.

In simpler terms:

The orbital motion of electrons (which contributes to magnetism) gets "frozen" or "restricted" by the geometry and electric field created by ligands.

🔷 Why Does Quenching Happen?

In a **free ion**, the five d orbitals are degenerate — electrons can move easily between them, generating a net orbital angular momentum.

In a **ligand field** (like octahedral or tetrahedral coordination), these d orbitals split in energy:

- **Octahedral field:** $t_{2g}$and e_g
- **Tetrahedral field:** opposite ordering

Because the orbitals are **no longer degenerate**, electrons can't easily change between them — the orbital motion that contributes to the magnetic moment is effectively "quenched."

This is why **coordination compounds** often obey the **spin-only formula**:

$$\mu_{\text{spin only}} = \sqrt{n(n+2)}\ \mu_B$$

where n= number of unpaired electrons.

◆ When Is Orbital Quenching Incomplete?

Orbital quenching is **not always complete**. It depends on:

- **Symmetry of the complex:** Lower symmetry (e.g., distorted octahedral, square planar) can allow partial orbital contribution.
- **Presence of spin–orbit coupling:** In heavier transition metals (4d, 5d series), spin–orbit coupling is stronger, so the orbital contribution may reappear.
- **Electronic configuration:** For example, d^1, d^9configurations can have residual orbital angular momentum.

◆ Examples

Ion / Complex	Expected μ (spin-only)	Experimental μ	Comment
$[Ti(H_2O)_6]^{3+}$ (d^1)	1.73 μB	1.8 μB	Slight orbital contribution
$[Mn(H_2O)_6]^{2+}$ (d^5, high spin)	5.92 μB	≈5.9 μB	Orbital motion fully quenched
$[Co(H_2O)_6]^{2+}$ (d^7, high spin)	3.87 μB	4.8 μB	Partial quenching (orbital contribution present)

◆ Summary

Concept	Description
Orbital quenching	Suppression of orbital magnetic moment due to ligand field splitting
Cause	Removal of degeneracy of d orbitals by ligand field
Result	Magnetic moment approximates spin-only value
Exceptions	Low symmetry fields, strong spin–orbit coupling, or certain configurations

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Example for **calculate the magnetic moment** for a given complex (both spin-only and including orbital effects)?

Perfect 👍 — let's go step by step through how to **calculate the magnetic moment** of a coordination complex, both for:

1. **Spin-only case** (when orbital contribution is quenched), and
2. **When orbital contribution is significant** (unquenched or partially quenched cases).

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1. Spin-Only Magnetic Moment

When the **orbital contribution is quenched**, the formula simplifies to:

$$\mu_{\text{spin-only}} = \sqrt{n(n+2)} \quad \mu_B$$

where:

- n= number of unpaired electrons
- μ_B= Bohr magneton

This works well for most **3d transition metal** complexes.

Example 1: $[Fe(H_2O)_6]^{2+}$

- $Fe^{2+} \rightarrow 3d^6$ configuration
- In a **weak field ligand** environment (H_2O), it's **high spin**, so:
  $n = 4$unpaired electrons

$$\mu_{\text{spin-only}} = \sqrt{4(4+2)} = \sqrt{24} = 4.90 \quad \mu_B$$

Experimental value ≈ 5.0 μB → matches well (orbital moment is quenched).

Example 2: $[Mn(H_2O)_6]^{2+}$

- $Mn^{2+} \rightarrow 3d^5$ (high-spin always)
- $n = 5$

$$\mu_{\text{spin-only}} = \sqrt{5(5+2)} = \sqrt{35} = 5.92 \quad \mu_B$$

Experimental ≈ 5.9 μB → almost perfect spin-only behavior (no orbital contribution).

2. Including Orbital Contribution (Unquenched or Partial Quenching)

When the orbital motion is **not fully quenched**, the observed magnetic moment is **larger** than the spin-only value.

In such cases, we can approximate the total moment as:

$$\mu_{\text{eff}} = g\sqrt{S(S+1)}\mu_B$$

where $g$is the **Landé g-factor**, which includes spin–orbit coupling.

For a free ion:

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

and

$$\mu_{\text{eff}} = g_J\sqrt{J(J+1)}\ \mu_B$$

where:

- L= total orbital angular momentum quantum number
- S= total spin quantum number
- $J = \mid L - S \mid$or $L + S$(depending on whether the shell is less than or more than half-filled)

Example 3: Co^{2+} Ion ($3d^7$)

For **high-spin octahedral $[Co(H_2O)_6]^{2+}$**, orbital contribution is *partially quenched.*

Spin-only value:

$$n = 3 \Rightarrow \mu_{\text{spin-only}} = \sqrt{3(3+2)} = \sqrt{15} = 3.87\mu_B$$

Experimental value ≈ **4.8 μB**

🔶 The difference (~1 μB) arises because **orbital angular momentum is only partially quenched** due to residual degeneracy in the t_2g orbitals and spin–orbit coupling.

3. Rules of Thumb (Observational Trends)

Ion	Config.	Typical μ (μB)	Quenching
Ti^{3+} (d^1)	~1.8	Partial	
V^{2+} (d^3)	~2.8	Quenched	
Mn^{2+} (d^5)	~5.9	Quenched	
Fe^{2+} (d^6, HS)	~5.0	Quenched	
Co^{2+} (d^7, HS)	~4.8	Partial	
Ni^{2+} (d^8)	~3.2	Partial	
Cu^{2+} (d^9)	~1.9	Partial	

Quick Procedure for Any Complex:

1. **Determine oxidation state** of the metal.
2. **Write its d-electron configuration.**
3. **Determine high-spin or low-spin** (based on ligand field strength).
4. **Count unpaired electrons (n).**
5. Compute:
    - **Spin-only μ** = $\sqrt{n(n + 2)}$ μB
    - Compare with **experimental value** → if higher → **orbital contribution present**.