KSQUARE CAREER INSTITUTE

MAGNETISM AND MATTER

Class 12 Physics • NEET / JEE Notes

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Chapter at a Glance

1. Bar magnet as a magnetic dipole — pole strength, magnetic moment
2. Magnetic field lines & their properties
3. Field of a bar magnet on axis & equatorial line (analogy with electric dipole)
4. Torque, potential energy, work done & time period of a dipole in uniform B
5. Gauss's law for magnetism
6. Magnetisation, magnetic intensity, susceptibility, permeability
7. Dia-, para- & ferromagnetism, Curie temperature, Curie–Weiss law
8. Added: comparison tables, hysteresis, formula sheet

BAR MAGNET AS A MAGNETIC DIPOLE

- **m** → **pole strength**, measured in **ampere-metre (A m)**.
- **2l** → **magnetic length** (distance between the poles).
- **Magnetic (dipole) moment:** M = m × 2l; unit **A m²** (same as iA).
- M is a **vector** directed from **S → N** inside the magnet (like electric dipole p = q × 2l, directed – → +).

Magnetic moment

$$M = m\,(2l) \qquad \text{unit: A m}^2 \;\; (= \text{J T}^{-1})$$

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Bent magnet: pole strength stays the same, only the **distance between the poles** changes. Bent into an arc of angle θ (radius r = l/θ): new distance = chord.

For an arc of 60° (θ = π/3): chord = r = 3l/π ⇒ **M′ = 3M/π**.

Bent into a semicircle: M′ = 2M/π. Bent into an L (90°, equal arms): M′ = M/√2.

Q1. Four arrangements of identical bar magnets (moment M each): (a) two at 90° (L-shape), (b) antiparallel side by side, (c) two at 30°, (d) two at 60°. Which has the highest net magnetic moment?

Configuration	Net M = √(M² + M² + 2M² cos θ)
(a) θ = 90°	√2 M
(b) antiparallel (θ = 180°)	0
(c) θ = 30°	**M√(2 + √3) ≈ 1.93 M (highest)**

Configuration	Net M = √(M² + M² + 2M² cos θ)
(d) θ = 60°	√3 M

Answer: (c)

Q2. A bar magnet of length l and magnetic moment M is bent in the form of an arc subtending 60° at the centre. The new magnetic dipole moment will be

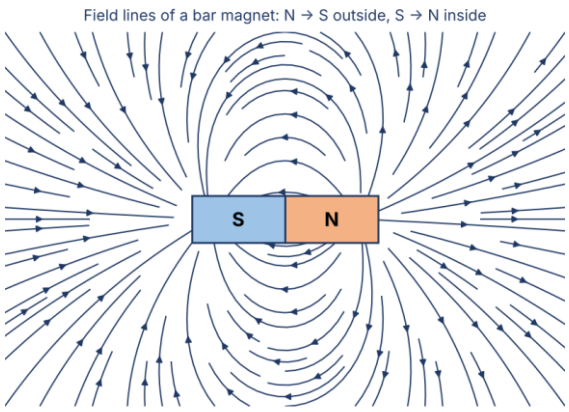
(a) M
(b) 3M/π
(c) 2M/π
(d) M/2

Answer: (b) — l = r(π/3) ⇒ r = 3l/π; new separation = r (equilateral triangle) ⇒ M′ = m·r = M·3/π.

MAGNETIC FIELD LINES

Definition

Imaginary lines/curves drawn in space along which a **'free north pole' would move**, if allowed to do so.



Properties

1. Magnetic field lines form **closed loops** — **outside the magnet: N → S**; **inside the magnet: S → N**.
2. The **tangent** at any point on a field line gives the **direction of B** at that point.
3. In a region of **strong** field the lines are **closer**; in a region of **weak** field they are **far apart** ($B_A > B_B$ where lines are denser).
4. Two magnetic field lines **never intersect** each other (B would have two directions at one point).

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Electric field lines start on + and end on – charge (not closed); magnetic field lines are **always closed loops** — magnetic monopoles do not exist.

MAGNETIC FIELD DUE TO A BAR MAGNET

Results are exactly analogous to an electric dipole: replace **p → M** and **k = 1/4πε₀ → μ₀/4π** (= 10^{-7} T m A^{-1}).

Position	Electric dipole	Bar magnet (magnetic dipole)	Direction
Axial line (distance $r \gg l$)	$E = 2kp / r^3$	$B = (\mu_0/4\pi) \cdot 2M / r^3$	Along M (S → N)
Equatorial line	$E = -kp / r^3$	$B = -(\mu_0/4\pi) \cdot M / r^3$	Opposite to M

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$B_{axial} : B_{equatorial} = 2 : 1$ at the same distance.

For short magnet, $B \propto 1/r^3$.

DIPOLE IN A UNIFORM MAGNETIC FIELD

Torque

Torque on a bar magnet

$$\tau = M \times B ; \quad \tau = MB \sin\theta$$

(electric analogue: $\tau = p \times E = pE \sin\theta$)

This torque always tries to **align the magnetic dipole in the direction of the magnetic field**.

Potential Energy & Work Done

Potential energy

$$U = -M \cdot B = -MB \cos\theta$$

$$W_{ext} = \Delta U ; \quad W(\theta_1 \to \theta_2) = U_f - U_i = MB(\cos\theta_1 - \cos\theta_2)$$

$$\text{From } \theta = 0 \text{ to } \theta: \quad W = MB(1 - \cos\theta)$$

Position	Torque	Potential energy	Equilibrium
$\theta = 0°$ (M parallel to B)	0	– MB (**minimum**)	**Stable**
$\theta = 90°$	MB (maximum)	0	—
$\theta = 180°$ (M antiparallel to B)	0	+ MB (**maximum**)	**Unstable**

Q3. A bar magnet having a magnetic moment of 2×10^4 J T^{-1} is free to rotate in a horizontal plane. A horizontal field $B = 6 \times 10^{-4}$ T exists. The work done in taking the magnet slowly from a direction parallel to the field to 60° from the field is

(a) 12 J
(b) 6 J
(c) 2 J
(d) 0.6 J

Answer: (b) — $W = MB(1 - \cos 60°) = 2\times10^4 \times 6\times10^{-4} \times ½ = 6$ J.

Q4. A bar magnet hung in a uniform horizontal field is in equilibrium. The energy required to rotate it by 60° is W. The torque required to keep it in the new position is

(a) 2W/√3
(b) W/√3
(c) √3 W
(d) √3W/2

Answer: (c) — W = MB(1 – cos 60°) = MB/2; τ = MB sin 60° = (√3/2)MB = √3 W.

▸ Time Period of Oscillation

Oscillating magnet (like a pendulum)

$$T = 2\pi \sqrt{(I / MB)}$$

I = moment of inertia; for a bar of mass m and length l: $I = ml^2/12$

(electric analogue: $T = 2\pi \sqrt{(I / pE)}$)

Q5. A bar magnet is oscillating in the Earth's magnetic field with a period T. What happens to its period and motion if its mass is quadrupled?

(a) SHM with period T/2
(b) SHM with period 2T
(c) SHM with period 4T
(d) SHM and period nearly constant

Answer: (b) — I ∝ mass ⇒ T ∝ √I ⇒ T′ = √4 T = 2T.

GAUSS'S LAW FOR MAGNETISM

Gauss's law

$$\text{Electric: } \oint E \cdot dS = q_{in} / \varepsilon_0$$

$$\text{Magnetic: } \oint B \cdot dS = 0$$

- The **net magnetic flux** through any **closed surface is zero**.
- Reason: **isolated magnetic poles (monopoles) do not exist** — field lines entering a closed surface also leave it.

MAGNETIC BEHAVIOUR OF MATTER

1. Matter is made up of **atoms**.
2. An **electron revolving around the nucleus** constitutes a **current loop**.
3. This current loop behaves as a **magnetic dipole (atomic dipole)** with magnetic moment **M = iA**.

▸ Cause of Dia-, Para- and Ferromagnetism

- In certain materials **all electrons are paired** — their magnetic moments cancel ⇒ **net atomic moment = 0** (diamagnetic).
- In others, electrons are **unpaired** ⇒ **net atomic moment ≠ 0** (para / ferro).

- In a sample with thousands of atoms, with **no external field** the atomic dipoles are **randomly oriented** ⇒ net magnetic moment of the sample is still **zero**.
- When the sample is placed in an **external field**, a **torque** acts on the atomic dipoles and tries to align them along the field ⇒ **net moment ≠ 0**.

MAGNETIC QUANTITIES

Magnetisation (I or M)

- **Magnetic moment per unit volume** of the material: **I = M / V**; unit **A m² / m³ = A m⁻¹**.

Q14. For a bar magnet of length 2l, cross-section A and pole strength m: I = M/V = m(2l)/(A·2l) = **m/A** (A m^{-1}).

Magnetic Intensity / Magnetising Field (H)

- Consider a solenoid carrying current i with a **soft-iron core**. The field inside depends on two factors:
  - **External factor** — the current i ⇒ **magnetising field H** (H = ni for a solenoid).
  - **Internal factor** — alignment of atomic dipoles ⇒ **magnetisation I**.

Net field inside the core

$$B = \mu_0 (H + I)$$

$$\text{Unit of } H = \text{unit of } I = A\ m^{-1}$$

Magnetic Susceptibility (χ)

- Magnetisation is influenced by external factors — **stronger H ⇒ more I**.

Susceptibility

$$I \propto H \Rightarrow I = \chi H \qquad (\chi \text{ is dimensionless})$$

Permeability

- In **vacuum** (no medium, I = 0): $\mathbf{B_0 = \mu_0 H}$ — μ_0 = **absolute permeability** ($4\pi \times 10^{-7}$ T m A^{-1}).
- In any material: $B_m = \mu_0(H + \chi H) = \mu_0(1 + \chi)H = \mathbf{\mu_m H}$ — μ_m = **magnetic permeability**.

Recap — all formulas

1. $I = M / V$ $\quad (A\ m^{-1})$
2. $B_m = \mu_0 (H + I)$
3. $I = \chi H$ $\quad (\chi \text{ dimensionless})$
4. $B_0 = \mu_0 H$ $\quad$ (absolute permeability)
5. $B_m = \mu_m H$ $\quad$ (magnetic permeability)
6. $\mu_m = \mu_0 (1 + \chi)$
7. $\mu_r = \mu_m / \mu_0 = 1 + \chi = B_m / B_0$ $\quad$ (relative permeability)

DIAMAGNETISM, PARAMAGNETISM & FERROMAGNETISM

When an external field is applied across any material, **two effects** occur:

1. If there are **atomic dipoles**, they **align with the external field** ⇒ **magnetisation** (para & ferro).
2. An **induced magnetic dipole moment** appears in every atom; its field **always opposes the applied field** (**Lenz's law**) — present in dia, para and ferro.

1. Diamagnetism

- Electrons are **paired** — **no atomic dipoles**, so no alignment occurs.
- Only the **induced dipole moment** exists, which **weakly opposes** the applied field ⇒ **weakly repelled** by a magnet.
- **Examples:** copper, water, air, hydrogen, bismuth, gold, mercury, NaCl.

2. Paramagnetism

- Electrons are **unpaired** — atomic dipoles exist, but are **randomly aligned** without a field ⇒ net moment zero.
- On applying a field the dipoles **align** due to torque ⇒ **weakly attracted**.
- **Examples:** chromium, manganese, aluminium, copper sulphate, O_2 (at STP), sodium, platinum.

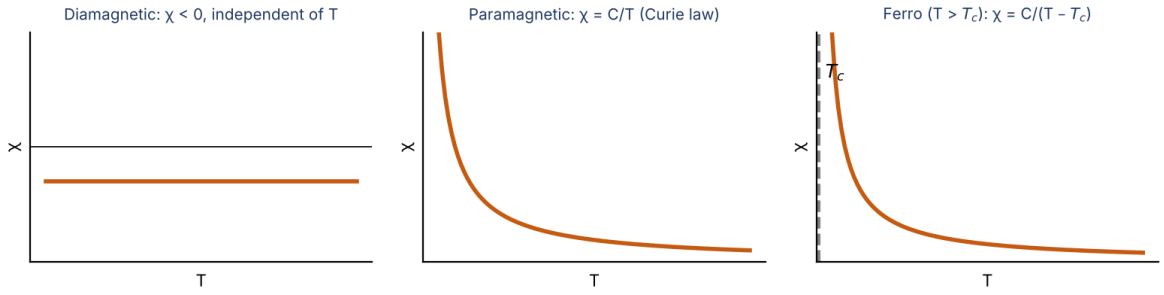
3. Ferromagnetism

- Atomic dipoles present (like paramagnetics).
- **Domain theory:** atomic dipoles interact and **spontaneously align** in small volumes called **domains** (size ~10^{-12} m^3 … ~10^{10} atoms each).
- In an external field: (i) **Domain growth** — domains aligned with the field grow, others shrink; (ii) **Domain orientation** — domains rotate to align with the field.
- ⇒ **Strongly attracted**. **Examples:** iron, nickel, cobalt, gadolinium, alloys like **Alnico**.

Comparison of Properties

Property	Diamagnetic	Paramagnetic	Ferromagnetic
Atomic dipole moment	**Zero**	Non-zero	Non-zero (domains)
Magnetisation I	Slightly **negative**	Small **positive**	Large **positive**
Susceptibility χ	Small –ve (≈ -10^{-5}, Cu)	Small +ve (≈ $+2.3 \times 10^{-5}$, Al)	Very large +ve (≈ 10^3)
Relative permeability μ_r	Slightly **< 1**	Slightly **> 1**	**≫ 1**
Field inside material	Slightly less than outside	Slightly greater	Greatly enhanced
Field lines	Slightly **less dense** (expelled)	Slightly **more dense**	**Highly dense**
In non-uniform field	Moves **strong → weak**	Moves **weak → strong**	Moves quickly **weak → strong**

Property	Diamagnetic	Paramagnetic	Ferromagnetic
Behaviour with magnet	Weakly **repelled**	Weakly **attracted**	Strongly **attracted**
Temperature dependence	**Independent** of T	$\chi = C/T$ (**Curie law**)	$\chi = C/(T - T_c)$ above T_c (**Curie–Weiss**)



▸ Effect of Temperature on Ferromagnetism

- Temperature ↑ ⇒ kinetic energy ↑ ⇒ random motion ↑ ⇒ alignment ↓ ⇒ **magnetisation ↓**.
- With rise of temperature, **susceptibility of ferromagnetic materials decreases**.
- At a certain temperature, ferromagnetics pass over to **paramagnetics** — this transition temperature is the **Curie temperature / Curie point (T_c)**.
- Curie temperature of **iron ≈ 770 °C** (1043 K); nickel ≈ 358 °C; cobalt ≈ 1120 °C.
- Above T_c, susceptibility obeys the **Curie–Weiss law**: $\chi \propto 1/(T - T_c)$.

> **NEET Point / PYQ Alert**
>
> A **superconductor** is a perfect diamagnet: $\chi = -1$, $\mu_r = 0$ (**Meissner effect**).
>
> Diamagnetism is present in **all** substances but is masked in para/ferro materials.

HYSTERESIS (ADDITIONAL TOPIC)

- The lag of **B (or I)** behind **H** when a ferromagnet is taken through a cycle of magnetisation is called **hysteresis**; the B–H curve is the **hysteresis loop**.
- **Retentivity (remanence):** value of B left when H is reduced to zero.
- **Coercivity:** reverse H needed to make B zero.
- Area of loop = **energy lost per cycle per unit volume** (as heat).

Use	Requirement	Material
Permanent magnets	High retentivity, **high coercivity**	Steel, Alnico, Cobalt steel
Electromagnets / transformer cores	High permeability, **low coercivity**, low hysteresis loss	**Soft iron**

PRACTICE — MAGNETIC MATERIALS

Q15. The magnetic moment of a diamagnetic atom is

(a) much greater than one
(b) 1
(c) between zero and one
(d) equal to zero

Answer: (d)

Q16. If a diamagnetic substance is brought near the north or south pole of a bar magnet, it is
(a) attracted by the poles
(b) repelled by the poles
(c) repelled by N and attracted by S
(d) attracted by N and repelled by S

Answer: (b)

Q17. A diamagnetic material in a magnetic field moves
(a) from weaker to stronger parts
(b) perpendicular to the field
(c) from stronger to weaker parts
(d) in none of these directions

Answer: (c)

Q18. Four light rods A, B, C, D are suspended by threads; a bar magnet is brought near: A is feebly repelled, B feebly attracted, C strongly attracted, D unaffected. Which is true?
(a) A is non-magnetic
(b) B is paramagnetic
(c) C is diamagnetic
(d) D is ferromagnetic

Answer: (b) — A → dia, C → ferro.

Q19. The magnetic susceptibility is negative for
(a) Ferromagnetic only
(b) Paramagnetic and ferromagnetic
(c) Diamagnetic only
(d) Paramagnetic only

Answer: (c)

Q20. If the atomic dipole moments of dia-, para- and ferromagnetic materials are μ_d, μ_p, μ_f, then
(a) $\mu_d \neq 0$ and $\mu_f \neq 0$
(b) $\mu_p = 0$ and $\mu_f \neq 0$
(c) $\mu_d = 0$ and $\mu_p \neq 0$
(d) $\mu_d \neq 0$ and $\mu_p = 0$

Answer: (c)

Q21. In which of the following does susceptibility NOT depend on temperature?
(a) Diamagnetism
(b) Paramagnetism
(c) Ferromagnetism
(d) Ferrite

Answer: (a)

Q22. Above the Curie temperature
(a) paramagnetic becomes ferromagnetic
(b) ferromagnetic becomes diamagnetic

(c) ferromagnetic becomes paramagnetic
(d) paramagnetic becomes diamagnetic

Answer: (c)

Q23. Nickel is ferromagnetic at room temperature. Beyond its Curie temperature it shows
(a) antiferromagnetism
(b) no magnetic property
(c) diamagnetism
(d) paramagnetism

Answer: (d)

Q24. According to Curie's law, the susceptibility of a substance at absolute temperature T is proportional to
(a) 1/T
(b) T
(c) $1/T^2$
(d) T^2

Answer: (a)

FORMULA SHEET

Quantity	Formula
Magnetic moment	$M = m(2l)$ [A m²]
Field on axis	$B = (\mu_o/4\pi)\, 2M/r^3$
Field on equatorial line	$B = -(\mu_o/4\pi)\, M/r^3$
Torque	$\tau = MB \sin\theta$
Potential energy	$U = -MB\cos\theta$
Work ($0 \rightarrow \theta$)	$W = MB(1 - \cos\theta)$
Time period	$T = 2\pi\sqrt{(I/MB)}$
Gauss's law	$\oint B \cdot dS = 0$
Magnetisation	$I = M/V$ [A m^{-1}]
Net field	$B = \mu_o(H + I) = \mu_o(1 + \chi)H$
Relative permeability	$\mu_r = 1 + \chi = \mu/\mu_o$
Curie law (para)	$\chi = C/T$
Curie–Weiss (ferro, $T > T_c$)	$\chi = C/(T - T_c)$