DIAS Delhi Institute for Administrative Services
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ALL INDIA TEST SERIES CSE-2024

PHTS-2401050

Candidate 's Information

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2. UPSC ROLL NO:-
3. MOBILE NO:- [redacted]
4. SUBJECT:- Solid State
5. DATE:- 2 Aug 2024

FOR OFFICE USE ONLY:-

Q.NO	MARKS
1.	26
2.	31 1/2
3.	22
4.	25 1/2
5.	25
6.	
7.	
8.	

Presentation is Excellent!

TOTAL MARKS	130/250

EXAMINER SIGNATURE

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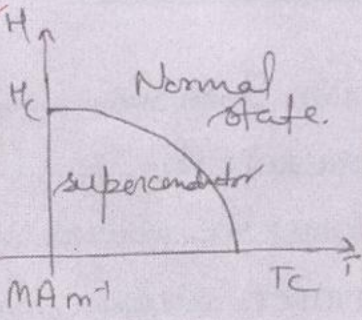
प्रश्न संख्या (Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें (Don't write anything in this part)

1(a) Critical field of a superconductor refers to max. magnetic field below which it remains superconductor.

$$\boxed{H_c(T) = H_c(0)\left[1 - \frac{T^2}{T_c^2}\right]}$$



Given H_c at $T = 6K$ is $7.616\ MAm^{-1}$

& H_c at $T = 8K$ is $4.284\ MAm^{-1}$

$$\Rightarrow 7.616 = H_c(0)\left[1 - \frac{36}{T_c^2}\right] \quad \text{——} ①$$

$$\& \ 4.284 = H_c(0)\left[1 - \frac{64}{T_c^2}\right] \quad \text{——} ②$$

Solving above equations.

$\boxed{T_c = 10K}$ & $\boxed{H_c(0) = 11.9\,MAm^{-1}}$

So below $T_c = 10K$ & $H_c(0) = 11.9\ MAm^{-1}$, NbTi alloy will act as superconductor. & above them, it will act as normal alloy.

$6\frac{1}{2}$ / 10

1(b) $\boxed{\text{Op-amp}}$ is an operational amplifier, used for operations like addition, subtraction, division etc.

ii) $A_{cl} = -\frac{R_f}{R_i} = \underline{\underline{99}}$
(closed loop gain)

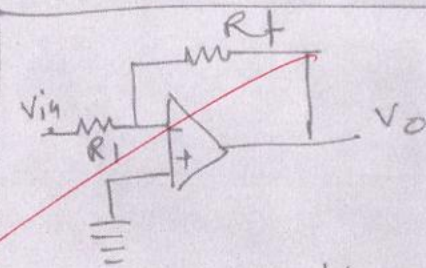
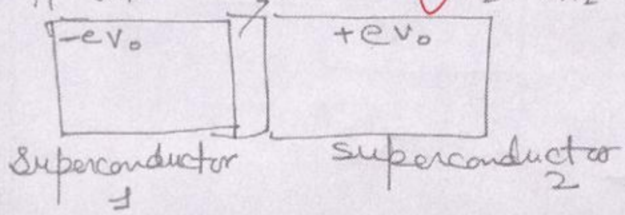


Fig: Non-inverting OP-Amp.

1(c) AC Josephson effect is flow of current between two superconductors with a layer of insulator sandwitched between them when there is an applied dc voltage across it.

$\psi_1 = \sqrt{n_1} e^{i\theta_1}$ insulator $\psi_2 = \sqrt{n_2} e^{i\theta_2}$



as $\boxed{|\psi|^2 \propto n}$

n is no. of superelectrons per unit volume.

Using ~~Heisenberg~~ Schrondinger equations,

$$\boxed{\begin{aligned} i\hbar \frac{d\psi_1}{dt} &= -eV_0 \psi_1 + \hbar T \psi_2 \quad —(1) \\ \& \quad i\hbar \frac{d\psi_2}{dt} &= eV_0 \psi_2 + \hbar T \psi_1 \quad —(2) \end{aligned}}$$

Here T is Transfer interaction & $2eV_0$ is spread as $-eV_0$ & eV_0 on two superconductors

Here $\psi_1 = \sqrt{n_1} e^{i\theta_1}$ & $\psi_2 = \sqrt{n_2} e^{i\theta_2}$

$$\frac{\partial \psi_1}{dt} = \frac{1}{2\sqrt{n_1}} e^{i\theta_1} \frac{dn_1}{dt} + \sqrt{n_1} e^{i\theta_1} i \frac{d\theta_1}{dt}$$

putting in (1) & (2) values of $\frac{d\psi_1}{dt}$ & $\frac{d\psi_2}{dt}$ & ψ_1 & ψ_2 & separating their real & imaginary parts, we get

$$\boxed{\begin{aligned} \frac{dn_1}{dt} &= 2T\sqrt{n_1 n_2} \sin \delta \quad —(3) \\ \frac{d\theta_1}{dt} &= \frac{eV_0}{\hbar} - T\sqrt{\frac{n_2}{n_1}} \cos \delta \quad —(4) \end{aligned}}$$

प्रश्न संख्या
(Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें
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also

$$\frac{dn_1}{dt} = -2T\sqrt{n_1 n_2}\sin\delta$$

$$\frac{d\theta_2}{dt} = -\frac{eV_2}{\hbar} - T\sqrt{\frac{n_2}{n_1}}\cos\delta$$

$$\Rightarrow \frac{dn_1}{dt} = -\frac{dn_2}{dt} = \frac{dn}{dt} \quad \&$$

$$\frac{d\theta_2}{dt} - \frac{d\theta_1}{dt} = \boxed{\frac{d\delta}{dt} = -\frac{2eV_0}{\hbar}} \quad \text{—— (5)}$$

So Integrating equation (5)

$$\int_{\delta(0)}^{\delta(t)} d\delta = \int_0^t -\frac{2eV_0}{\hbar}\,dt$$

$$\Rightarrow \boxed{\delta(t) = \delta(0) - \frac{2eV_0}{\hbar}t} \quad \text{—— (6)}$$

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Current density $J = J_0 \sin\delta(t)$

$$\Rightarrow \boxed{J = J_0 \sin\left(\delta(0) - \frac{2eV_0}{\hbar}t\right)}$$

where $\omega_0 = \frac{2eV_0}{\hbar} \Rightarrow \boxed{\nu = \frac{2eV_0}{h}}$ frequency.

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1(d) For a semiconductor, conductivity is given by $\boxed{\sigma = CT^{3/2}\exp\left(\frac{-E_g}{2kT}\right)}$ & resistivity is inverse of it.

$$\frac{\rho_1}{\rho_2} = \frac{\sigma_2}{\sigma_1} = \frac{T_2^{3/2}\exp\left(\frac{-E_g}{2kT_2}\right)}{T_1^{3/2}\exp\left(\frac{-E_g}{2kT_1}\right)}$$

$$\Rightarrow \frac{4.5}{2} = \left(\frac{305}{295}\right)^{3/2}\exp\left[\frac{-E_g}{2k}\left(\frac{1}{305}-\frac{1}{293}\right)\right]$$

$$\Rightarrow 2.118527 = \exp\left[\frac{E_g}{2k}\left(\frac{1}{293}-\frac{1}{305}\right)\right]$$

$$\Rightarrow \frac{E_g}{2k}\left[\frac{1}{293}-\frac{1}{305}\right] = 0.750721$$

$$\Rightarrow \boxed{E_g = 1.543\times 10^{-19}\ J}$$

$$\Rightarrow \boxed{E_g = 0.964\ eV}$$

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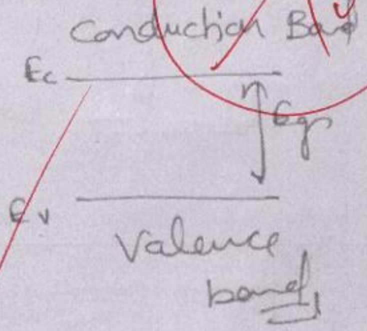

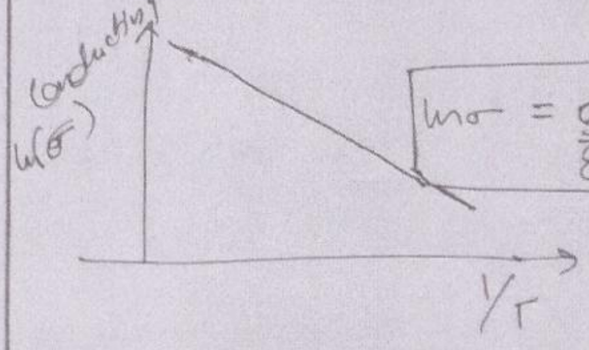

$$\boxed{\ln\sigma = \frac{g}{g}T^{3/2} - \frac{E_g}{2kT}}$$

conductivity vs $1/T$ curve for semiconductors.

प्रश्न संख्या
(Question No.)

U.P.S.C.

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1(c) Boolean expression can be realised using NAND gates as they are universal gates.

Given $\boxed{Y = \overline{A\overline{B} + A + AB}}$

Using D' Morgan's theorem's

$\overline{A+B} = \overline{A}\,\overline{B}$ & $\overline{AB} = \overline{A} + \overline{B}$

$\Rightarrow Y = (\overline{A\overline{B}}).\overline{A}.\overline{AB}$

$= (\overline{A}+B).\overline{A}.(\overline{A}+\overline{B})$

$= (\overline{A} + \overline{A}B)(\overline{A}+\overline{B})$ Using $\underline{\underline{A^2 = A}}$

$= \overline{A} + \overline{A}\overline{B} + \overline{A}B + \overline{A}B\overline{B}$ since $\underline{\underline{A\overline{A} = 0}}$

$= \overline{A} + \overline{A}B + \overline{A}\overline{B}$

$= \overline{A}(1+B) + \overline{A}\overline{B}$ $\because 1 + B = 1$

$= \overline{A}(1+\overline{B}) = \underline{\underline{\overline{A}}}$ $\because 1 + \overline{B} = \underline{\underline{1}}$

So $= \boxed{Y = \overline{A}}$ NOT gate.

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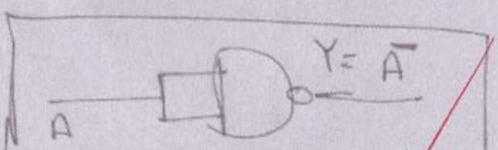
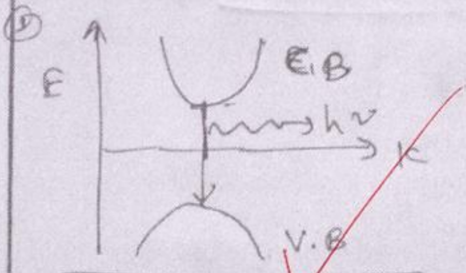
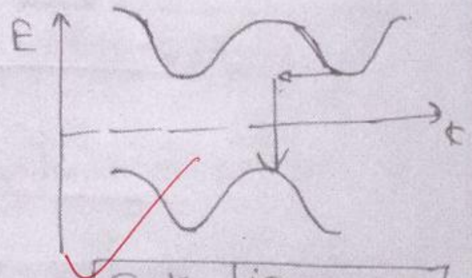
Realisation using NAND gate -



This is NOT gate or $Y = \overline{A}$ realisation using NAND gate..

Q.2(a) Direct & Indirect band semiconductors differ in their conduction & valence band k-vector positions.

Direct Band	Indirect Band
(1)  E-k diagram	 E-k diagram
(2) Min. of C.B. lies above max. of V.B.	(2) Min. of C.B. & max. of V.B. doesn't coincide.
(3) e^--hole recombination faster as same $\vec{k}$-vector (momentum conservation)	(3) Recombination is slow as radiative deactivation preceeds to allow same $\vec{k}$.
(4) Emits photons & used in devices eg. Photodiodes, LEDs.	(4) Emission of photon is not efficient here & used in devices like Solar cells.

Indirect Band gap semiconductors

प्रश्न संख्या
(Question No.)

U.P.S.C.

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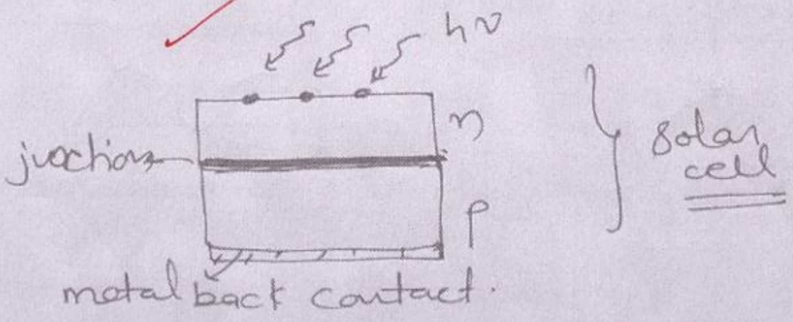
are used for devices like Solar cells.

$\boxed{\text{Reasons}}$

↳ ① Solar cell are used for generation of photocurrent due to photovoltaic effect.



↳ ② For more photocurrent, e⁻ & holes need to be separated & the less they recombine, the better it is.

direct band gap → recombination faster ⇒ not good for solar cell

Indirect band gap ⇒ recombination slower ⇒ good for solar cells.

Semiconductors like Si, GaAs used for solar cells.

$9\frac{1}{2}$ / 15

2(b) Superconductor materials shows perfect diamagnetism and hence expell magnetic field lines below critical temperature.

London equation for superconductors

1st London equation: London assumed two kinds of charge carriers

normal e^- (n_e) — superelectrons (n_s)

Below T_c & H_c, ns dominates.

$$m\frac{dV_s}{dt} = -eE$$

$$\Rightarrow \frac{dV_s}{dt} = -\frac{eE}{m} \quad \& \quad \boxed{J_s = -neV_s}$$

$$\Rightarrow \boxed{\frac{dJ_s}{dt} = \frac{ne^2}{m}E} \quad \text{—— (1)}$$

2nd London equation: Using 3rd Maxwell equation, $\boxed{\vec{\nabla}\times\vec{E} = -\frac{d\vec{B}}{dt}}$

putting value of E from (1) equation,

$$\vec{\nabla}\times\frac{dJ_s}{dt} = -\frac{ne^2}{m}\frac{d\vec{B}}{dt}$$

integrating both sides, we get

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U.P.S.C.

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$\boxed{\vec{J_s} = -\frac{ne^2}{m}\vec{A}}$

→ $\boxed{\vec{\nabla} \times \vec{J_s} = -\frac{ne^2}{m}\vec{B}}$ 2nd London equation.

Explaination of Meissner's effect

Meissner's effect is expulsion of magnetific field lines below critical temperation & magnetic field.

Penetration depth of magnetic field was calculated using London eqn as — $\boxed{\vec{\nabla} \times \vec{B} = \mu_0 \vec{J_s}}$ 4th Maxwell's equation

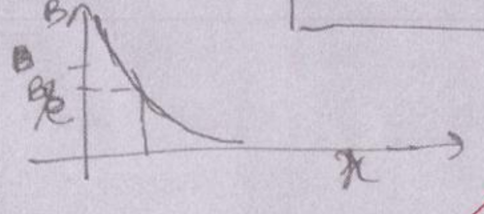
Using 2nd London equation & taking curl,

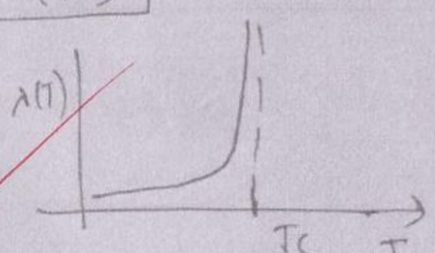
$$\vec{\nabla} \times \vec{\nabla} \times \vec{B} = \mu_0 \vec{\nabla} \times \vec{J_s}$$

$$\Rightarrow -\nabla^2 \vec{B} = \mu_0 \left(-\frac{ne^2}{m}\vec{B}\right)$$

$$\Rightarrow \boxed{\nabla^2 \vec{B} = \frac{1}{\lambda^2}\vec{B}} \quad \text{where } \lambda = \left(\frac{m}{\mu_0 n e^2}\right)^{1/2}$$

$$\boxed{B = B_0 \exp\left(\frac{-x}{\lambda}\right)}$$





So at $x = \lambda$, value of B is $\frac{1}{e}$ times its maximum value.

9/15

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U.P.S.C.

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2(c) Debye's theory of lattice heat capacity rightly explained T^3 law by

assuming —

1. Vibrations of lattice as a whole i.e. Phonon vibrations.

2. A definit upper limit on vibrational frequency

$$\boxed{\int_0^{\nu_D} g(\nu)d\nu = 3N}$$

3. Assumed quantum vibrations of lattice following planck's law.

i.e. average energy

$$\bar{E} = \frac{\sum_{n=0}^{\infty} nh\nu \exp\left(\frac{-nh\nu}{k_BT}\right)}{\sum_{n=0}^{\infty} \exp\left(\frac{-nh\nu}{k_BT}\right)} = \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1} \rightarrow (1)$$

Density of states of a 3D solid is given by —

$$\boxed{g(\nu)d\nu = \frac{4\pi V}{v^3}\nu^2 d\nu} \rightarrow (2)$$

Solids have two velocity direction

longitudinal velocity (v_l)

transverse velocity (v_t)

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So $\int_0^{\nu_D} g(\nu)d\nu = 3N$ given

$$\int_0^{\nu_D} 4\pi V\left[\frac{1}{v_l^3} + \frac{2}{v_t^3}\right] \cdot \nu^2 d\nu = 3N$$

$$\Rightarrow \boxed{4\pi V\left[\frac{1}{v_l^3} + \frac{2}{v_t^3}\right] = \frac{9N}{\nu_D^3}} \quad \text{--- (3)}$$

Now Energy of lattice vibrations —

$$E = 4\pi V\left(\frac{1}{v_l^3} + \frac{2}{v_t^3}\right)\int_0^{\nu_D} \frac{h\nu^3 d\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

$$E = \frac{9N}{\nu_D^3}\int_0^{\nu_D} \frac{h\nu^3 d\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

debye temperature

Let $x_D = \frac{h\nu_D}{kT}$ & $x = \frac{h\nu}{kT}$ & $\theta_D = \frac{h\nu_D}{k}$

$$\Rightarrow \boxed{E = 9NkT\left(\frac{T}{\theta_D}\right)^3 \int_0^{x_D} \frac{x^3 dx}{\exp(x) - 1}}$$

High temp limit $\Rightarrow \frac{h\nu}{kT} << 1$

$\Rightarrow \exp(x) = 1 + x$

$$\Rightarrow E = 9NkT\left(\frac{T}{\theta_D}\right)^3 \cdot \left(\frac{\theta_D}{T}\right)^3 \times \frac{1}{3}$$

$$E = 3NkT$$

$$\Rightarrow C_V = \left.\frac{dE}{dT}\right)_V = 3Nk = 3R$$

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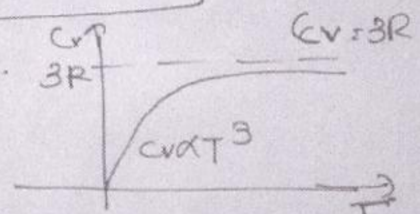
Low temperature limit — $\exp\left(\frac{h\nu}{kT}\right) >> 1$

$$\Rightarrow E = 9NkT\left(\frac{T}{\theta_D}\right)^3 \cdot \underbrace{\int_0^\infty \frac{x^3\,dx}{\exp(x)-1}}_{\pi^4/15}$$

$$\Rightarrow E = \frac{9}{15}\pi^4 NkT\left(\frac{T}{\theta_D}\right)^3$$

$$\boxed{C_v = \frac{dE}{dT} = \frac{12}{5}\pi^4 Nk\left(\frac{T}{\theta_D}\right)^3}$$

$\Rightarrow \boxed{C_v \propto T^3}$ T^3 law.



Cv vs T graph

Difference from Einstein theory —

Einstein theory	Debye theory
① N oscilliators vibrate independently in 3 directions	① Collective vibration of all oscillators in a solid.
② No upper limit on frequency. Oscillators can vibrate with any frequency of multiple of $h\nu$.	② There is definite upper limit (ν_D) on frequencies.
③ Not able to explain T3 law.	③ Explained T3 law. i.e. $C_v \propto T^3$ at low temp.

13/20

प्रश्न संख्या
(Question No.)

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Q.3 (a)

प्रश्न संख्या (Question No.)

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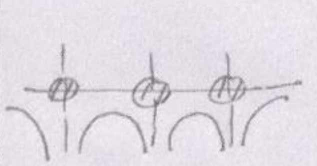
3(b) Nearly free e⁻ model or Kronig - Penny model describes the band formation in 1D periodic potential.

Electrons in solid with periodic potential -



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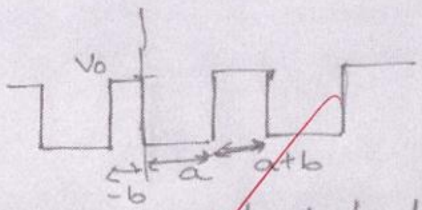


approximate potential.

Schrodinger equation in solid -

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} = E\psi \quad \text{for } 0 < x < a$$

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + V_0\psi = E\psi \quad -b < x < 0$$

$$\Rightarrow \frac{d^2\psi}{dx^2} + \alpha^2\psi = 0 \quad \text{where } \alpha = \sqrt{\frac{2mE}{\hbar^2}}$$

$$\& \quad \frac{d^2\psi}{dx^2} - \beta^2\psi = 0 \quad \beta = \sqrt{\frac{2m(V_0-E)}{\hbar^2}}$$

Using Bloch's theorem, solutions of periodic potential are plane wave, modulated by periodic function $u(x)$.

i.e. $\boxed{\psi(x) = u(x)e^{ikx}}$

So above equations becomes -

$$\frac{d^2u_1}{dx^2} + 2ik\frac{du_1}{dx} + (\alpha^2 - k^2)u_1 = 0 \quad 0<x<a$$

$$\frac{d^2u_2}{dx^2} + 2ik\frac{du_2}{dx} - (\beta^2 + k^2)u_2 = 0 \quad -b<x<0$$

So applying $\left.\begin{array}{l} u_1(0) = u_2(0) \\ \frac{du_1}{dx}(0) = \frac{du_2(0)}{dx} \end{array}\right\}$ continuity

& periodicity $\left\{\begin{array}{l} u_2(-b) = u_1(a) \\ \left.\frac{du_2}{dx}\right)_{x=-b} = \left.\frac{du_1}{dx}\right)_{x=a} \end{array}\right\}$

Solutions are –

$$u_1 = Ae^{i(\alpha-k)x} + Be^{-i(\alpha+k)x} \quad 0<x<a$$

$$u_2 = Ce^{(\beta-ik)x} + De^{-i(\beta+ik)x} \quad -b<x<0$$

Applying boundary conditions & solving

$$\frac{\beta^2+\alpha^2}{2\alpha\beta}\sinh\beta b \sin\alpha a + \cosh\beta b\cos\alpha a = \cos k(a+b)$$

Now $V_0 \to \infty$ & $b \to 0$ such that

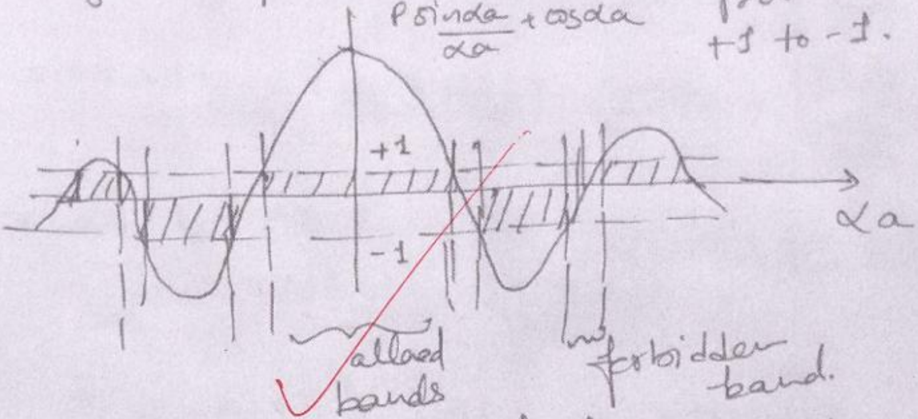
$V_0 b \to$ finite

$\Rightarrow \quad \sinh\beta b \to \beta b$ & $\cosh\beta b \to 1$

$$\Rightarrow \boxed{P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a = \cos k(a)}$$

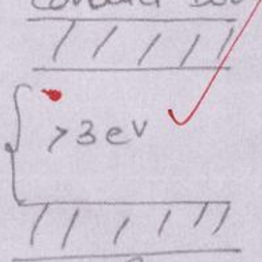
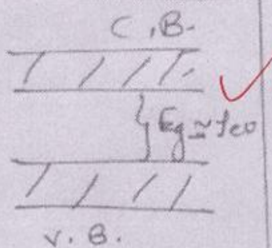
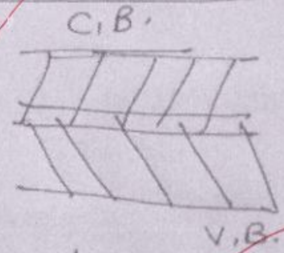
where $P = \frac{mV_0ba}{\hbar^2}$ = scattering power strength.

Plotting the equat^n – (As RHS varies from +1 to −1.



Thus explains the band formation in solids.

On basis of band structure,

Insulators	Semiconductors	Conductors
① Conduct^n Band  $E_g > 3eV$.	 $E_g \simeq 1eV$	 overlapping C.B. & V.B.
② eg. Boron Nitride $E_g = 5.4eV$ So huge E_g ⇒ Not conduct.	eg. Silicon $E_g = 1.1eV$ So conducts through e^- & holes.	eg. Copper, Aluminium → have either partially filled V.B. or overlapping C.B. & V.B.

9/15

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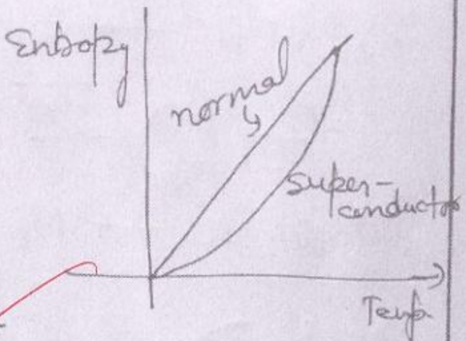
3(b) Superconducting state is highly ordered state so it has entropy lower than normal materials.

↳ ① presence of superelectrons – high coherence length.



② formation of cooper pairs (Bosons condensed to ground state)

③ presence of energy band gap (Δ)
↳ below which superelectrons are highly ordered.

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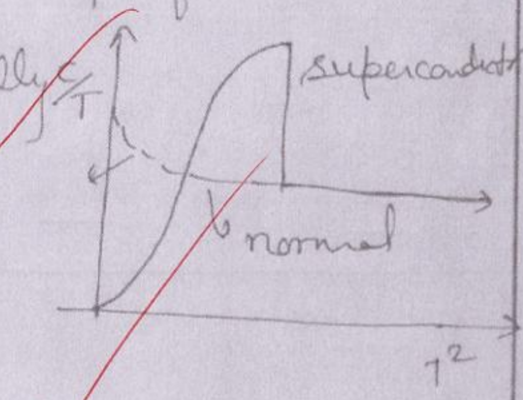
Specific heat – combination of both electronic & thermal specific heat.

$\boxed{C = \alpha T + \beta T^3}$ normally



for superconductors, $\frac{C}{T}$ vs T^2 curve is given in graph.

↳ Here electronic specific heat (c_e) depends on energy band gap –

$$\boxed{c_e \propto \exp\left(\frac{\Delta}{k_B T}\right)}$$

Δ = energy band gap.

प्रश्न संख्या
(Question No.)

U.P.S.C.

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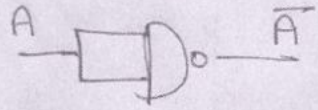
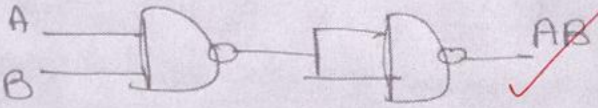
3(d) NAND & NOR gates are called universal gates bag using them all other basic gates can be constructed.

eg ① NAND → NOT gate

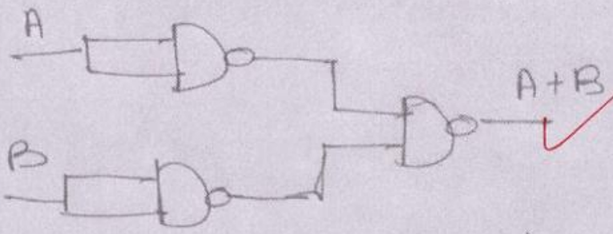


② NAND → AND gate



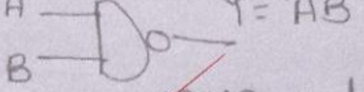
$6\frac{1}{2}/10$

③ NAND → OR gate



Similarly for NOR gates.

NAND gate logic diagrame → Boolean equatn & truth table



NAND gate

A	B	$Y = \overline{AB}$
0	0	1
0	1	1
1	0	1
1	1	0

$\boxed{Y = \overline{AB}}$

Boolean equatn

प्रश्न संख्या
(Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें
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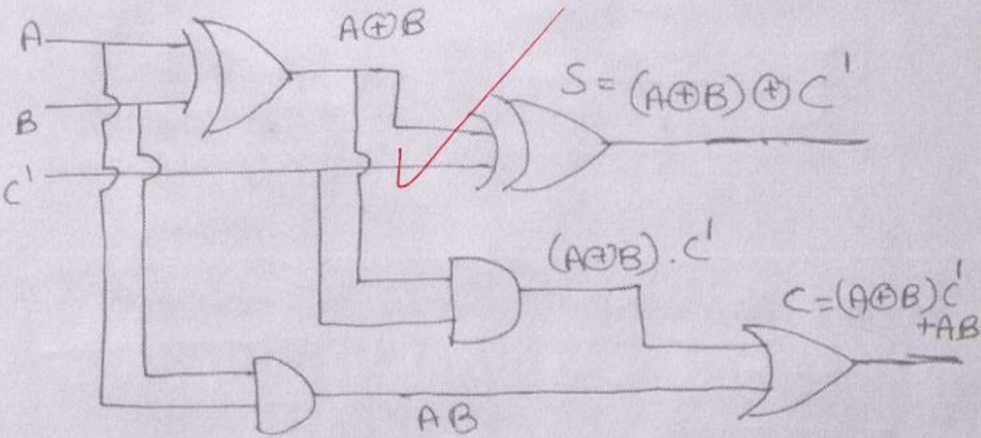
Q.5(a) Full adder circuit is used to add three bits as follows –

A	B	C'	C	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

$\boxed{\begin{aligned} \underset{(sum)}{S} &= A \oplus B \oplus C' \\ \underset{carry}{C} &= (A \oplus B).C' + AB \end{aligned}}$

Full adder circuit –



The above full adder circuit is formed using –

- 2 XOR gates
- 2 AND gates
- 1 OR gate.

9/15

प्रश्न संख्या (Question No.)

U.P.S.C.

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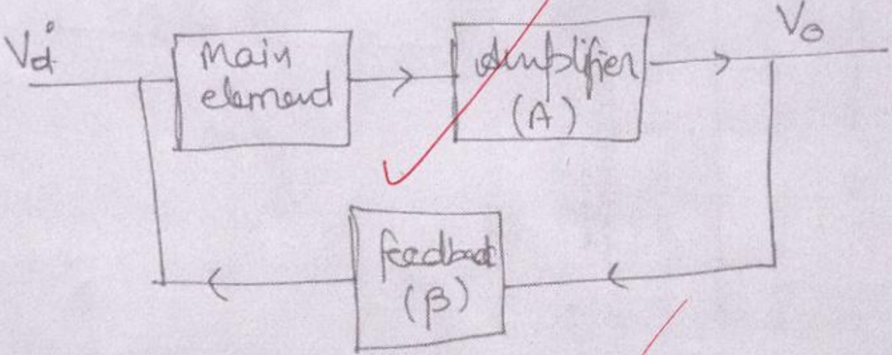
Q5(b) An oscillator circuit is self sustaining system with an amplifier, and feedback.

Block diagram of oscillator ckt —



$$V_o = A(V_i + \beta V_o)$$

$$\Rightarrow \boxed{\frac{V_o}{V_i} = \frac{A}{1 - A\beta}} \quad \text{for } \boxed{A\beta = 1}$$

$\Rightarrow$ Barkeinshen's criteria

~~Hartley~~ Essential parts of oscillators

① Amplifier - to amplify output from main element.

(eg) BJT, Op-Amp etc.

② Feedback circuit - with a gain of β. It feeds output voltage to input so that sustained oscillatⁿ occur.

प्रश्न संख्या
(Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें
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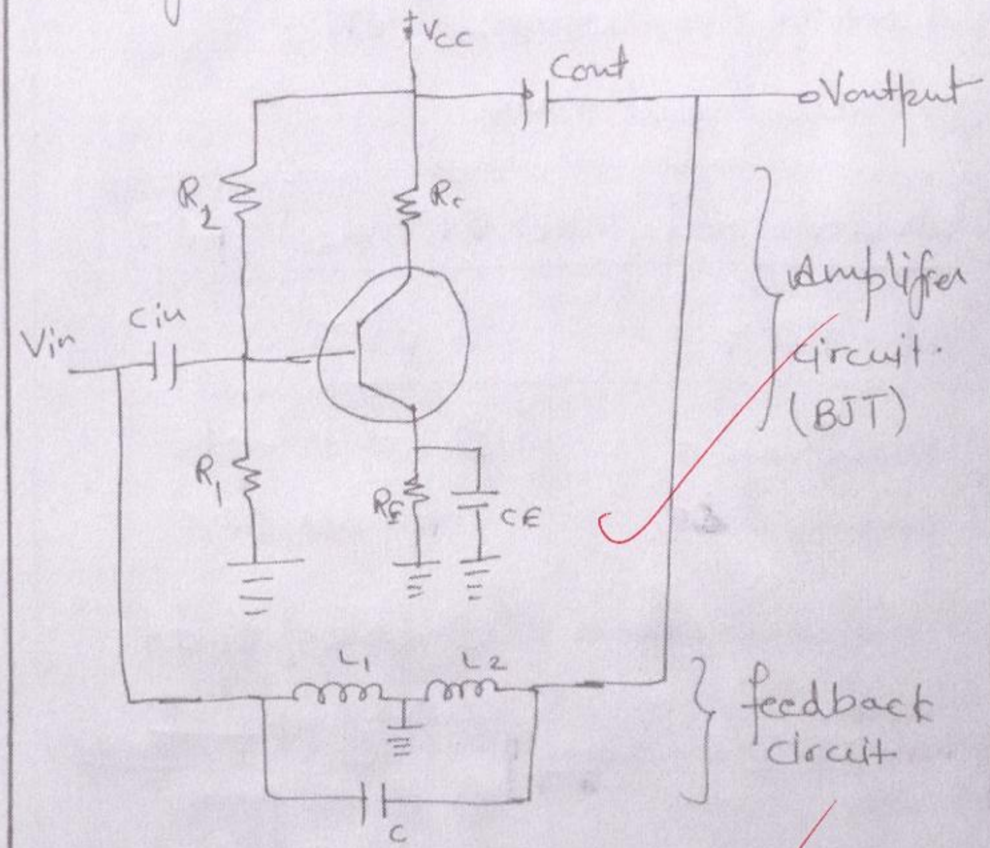
Hartley Oscillator circuit



$$f = \frac{1}{2\pi\sqrt{LC}}$$ where $L = L_1 + L_2 \pm 2M$

To achieve $f = 1600$ Hz, suitable values of L_1, L_2 & C can be chosen.

In Hartley oscillator
↳ 2 series inductor & 1 capacitor are used in feedback element.

Suitable?
7/15

प्रश्न संख्या (Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें (Don't write anything in this part)

Q.5 (c) MOSFET and JFET are both field effect Transistors, but differ in their functioning.

Advantages of MOSFET over JFET

MOSFET	JFET
① High input impedence	① Lower input impedence
② Higher speed than JFET	② Lower speed.
③ Both deplet^n & enhancement mode	③ only deplet^n mode.
④ Less power needed for operation.	④ More power compare to MOSFET
⑤ 4 terminal device	⑤ 3 terminal device.
⑥ Easy to construct	⑥ More complex

Disadvantages:-

MOSFET	JFET
① High cost of construction	① lower cost of construct^n
② Prone to damage	② lesser damage than MOSFET

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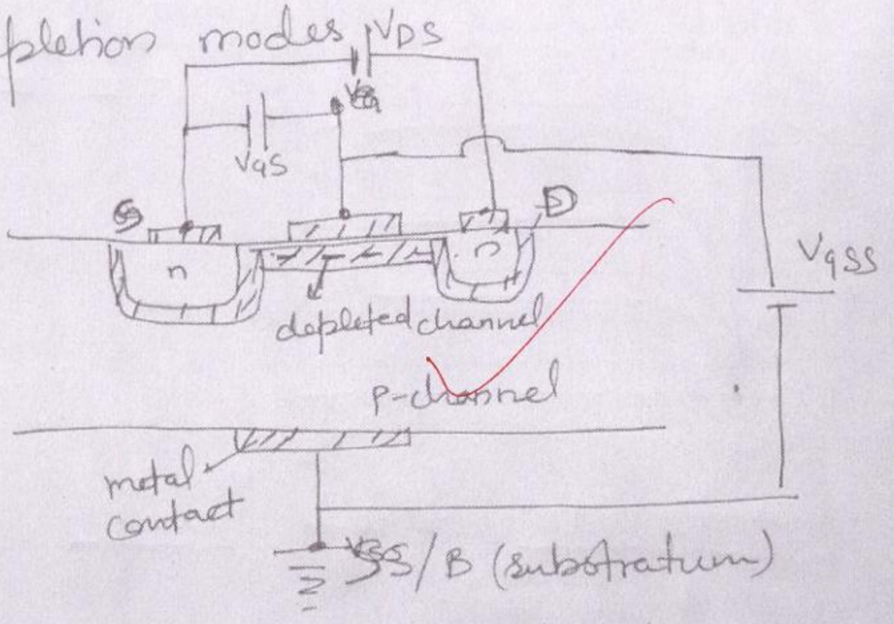
Depletion MOSFET (D-MOSFET) can work both in enhancement and depletion modes



Here the channel is already depleted.

Source & Gate are forward bias while Gate and substratum circuit are reversed biased.

Electrons move from source to drain resulting in drain current.

This works for both -

$V_{GS} = 0$ & $V_{GS} > 0$

9/25

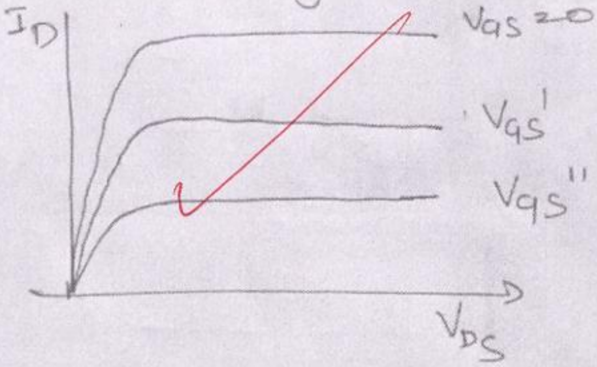
प्रश्न संख्या (Question No.)

U.P.S.C.

इस भाग में कुछ न लिखें (Don't write anything in this part)

$\boxed{\text{I-V characteristics}}$

↳ I_D vs V_{DS} (drain current vs drain voltage) with const. V_{GS}



Characteristics are for reverse biased circuit.

प्रश्न संख्या (Question No.)	U.P.S.C.	इस भाग में कुछ न लिखें (Don't write anything in this part)

Q.4 (a) i) Josephson junction across a d.c. voltage act as A.C. Josephson effect.

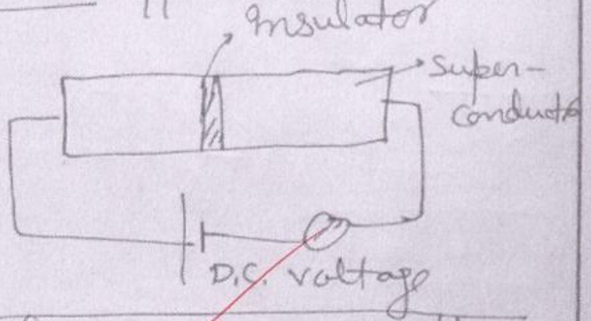


fig:- Josephson junction across D.C. voltage.

Josephson current across junction is calculated to be -

$J(t) = J(0) \sin\left(\delta(0) - \frac{2eV_0}{\hbar} t\right)$

$\Rightarrow \omega = \frac{2eV_0}{\hbar} \Rightarrow \boxed{\nu = \frac{2eV_0}{h}}$ frequency

Given - $V_0 = 0.5 mV$

$$\nu = \frac{2 \times 1.6 \times 10^{-19} \times 0.5 \times 10^{-3}}{6.626 \times 10^{-34}}$$

$\Rightarrow \boxed{\nu = 2.414 \times 10^{11} s^{-1}}$ is frequency of emitted EM wave by josephson junction.

Uses of Josephson junction

- ① formatn of sensitive magnetometer
- ② measurement of frequency
- ③ Accurate calculatn of Planck's constant.

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U.P.S.C.

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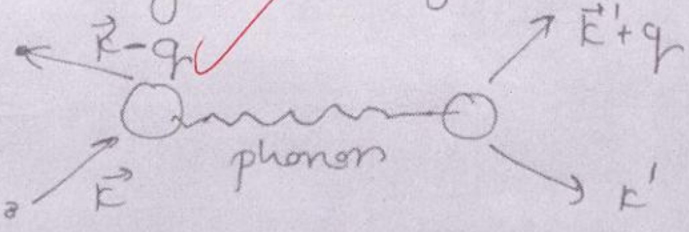
4 (a) ii) Cooper pairs are pair of superelectrons in a superconductor whose coherence length is larger enough to produce superconducting phenomenon.

Mechanism

① e^- – lattice – e^- interaction

↳ pair of e^- interacts with lattice ions by exchaning $\vec{k}$-vector –



these are phonon assisted interactⁿ.

② Energy band gap (Δ) is created

↳ below which Cooper pairs act as Bosons condensed to lower states and results in resistance less flow of current.

9½/15

BCS theory explains superconductivity via cooper pair interaction with lattice.

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प्रश्न संख्या
(Question No.)

U.P.S.C.

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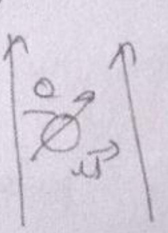
Q.4(b) Dy^{3+} has electronic configuration of $4f^9 6s^0$, so there is unpaired e^- in 4f orbital ⇒ paramagnetism due to unpaired e^-.

As per Langevin's classical theory,

$$M = \int_0^{\pi} \mu \cos\theta \, dN \quad \text{—— (1)}$$



As ∥al component of dN atoms contribute to magnetic moment.

Also from MB distribution —

$$dN \propto \exp\left(\frac{\mu B \cos\theta}{kT}\right) \quad \text{as } E = -\mu B \cos\theta$$

$$dN \propto \sin\theta \text{ (due to torque)}$$

$$\Rightarrow \int_0^N dN = \int_0^{\pi} C \sin\theta \exp\left(\frac{\mu B \cos\theta}{kT}\right) d\theta$$

$$\Rightarrow \boxed{C = \frac{N\alpha}{e^{\alpha} - e^{-\alpha}}} \quad \text{where } \alpha = \frac{\mu B}{kT}$$

putting in (1) & solving, we get

$$\boxed{M = N\mu \left[\coth\alpha - \frac{1}{\alpha}\right]}$$

for $\frac{\mu B}{kT} << 1$ (High T & low B)

$$M = \frac{N\mu^2\mu_0 H}{3k_B T} \Rightarrow \boxed{\chi = \frac{N\mu^2\mu_0}{3k_B T}} \quad \text{--- ②}$$

$\Rightarrow$ Given $N = 10^3$ moles

$\mu_0 = 4\pi \times 10^{-7}$ SI units

$k_B = 1.38 \times 10^{-23}$ SI unit

$T = 300K$

$\mu) \; s = \frac{1}{2} (e) = \sqrt{3}\,\mu_B$

Solve using Quantum Theory

putting in eq ②

4/15

$$\chi = \frac{10^3 \times 6.022 \times 10^{23} \times 3 \times (9.27 \times 10^{-24})^2 \times 4\pi \times 10^{-7}}{3 \times 1.38 \times 10^{-23} \times 300}$$

$$\boxed{\chi = 1.57 \times 10^{-5}}$$

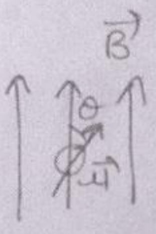
So $\chi << 1$ (slightly positive value)

Q.4 (c) Paramagnetic materials shows weak magnetism ($\chi << 1$) in presence of external magnetic field.

In case of Copper Sulphate with $S = 1/2 \Rightarrow$ unpaired e^- results in paramagnetism.

It can be explained by Langevin's classical theory.

In presence of ext. $\vec{B}$, rotation of magnetic dipole –



$E = -\vec{\mu} \cdot \vec{B}$ & $\vec{\tau} = \vec{\mu} \times \vec{B} = \mu B \sin\theta$

$\boxed{E = -\mu B \cos\theta}$ torque

No. of magnetic moments orient in θ to $\theta + d\theta$ direction –

$\boxed{dN \propto \exp\left(\frac{-E}{k_B T}\right)}$ using MB distribut^n

where $E = -\mu B \cos\theta$

also $dN \propto \sin\theta$ (due to torque)

$$\Rightarrow \int_0^N dN = \int_0^{\pi} C \exp\left(\frac{\mu B \cos\theta}{k_B T}\right) \sin\theta \, d\theta$$

$$\Rightarrow \boxed{C = \frac{N\alpha}{e^{\alpha} - e^{-\alpha}}}$$ where $\boxed{\alpha = \frac{\mu_B B}{k_B T}}$

प्रश्न संख्या
(Question No.)

U.P.S.C.

न लिखें
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Now calculating magnetisation along field direct^n = $\mu \cos\theta \, dN$

(as each dN contribute $\mu\cos\theta$ to magnetisat^n & ⊥al component cancels out)

$\Rightarrow M = \int_0^{\pi} \mu \cos\theta \, dN$

$$M = C\mu_B \int_0^{\pi} \exp\left(\frac{\mu B \cos\theta}{k_B T}\right) \sin\theta \cos\theta \, d\theta$$

Let $\cos\theta = x$

$\Rightarrow M = C\mu_B \int_{-1}^{1} e^{\alpha x} x \, dx$ also $C = \frac{N\alpha}{e^{\alpha} - e^{-\alpha}}$

$$\boxed{M = N\mu_B\left[\coth\alpha - \frac{1}{\alpha}\right]}$$

where $\alpha = \frac{\mu_B B}{KT}$

$$\boxed{M = \underbrace{N\mu_B}_{M_S}\left[\coth\left(\frac{\mu_B B}{KT}\right) - \frac{1}{\left(\frac{\mu_B B}{KT}\right)}\right]}$$

M_S = saturation magnetisat^n.

$\Rightarrow$ $\boxed{\frac{M}{M_S} = L(\alpha)}$ $\rightarrow$ Langevin's function.

for $\alpha << 1$ (high T & low B)

12/20

प्रश्न संख्या (Question No.)

U.P.S.C.

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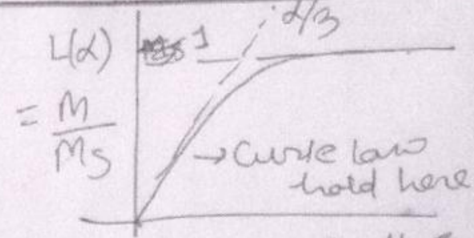
$$L(\alpha)\Big|_{\alpha\to 0} \approx \alpha/3 = \frac{\mu B}{3KT}$$



$\Rightarrow$

$$\alpha = \frac{\mu_0 B}{kT}$$

$$M = N\mu\left(\frac{\mu B}{3KT}\right) = \frac{N\mu^2\mu_0 H}{3k_B T}$$

$$\Rightarrow \frac{M}{H} = \chi = \frac{N\mu^2\mu_0}{3k_B T} = \frac{C\mu_0}{T}$$

$$\Rightarrow \boxed{\chi = \frac{C\mu_0}{T}}$$ Curie's law.