Chương IV

TÍNH CHAT NHIET CUA CHAT RAN

I. NHIET DUNG CUA CHAT RAN

1. Nhiet dung

Theo ñònh luat I cua nhiet ñong löc hoc:

$$dQ = dU - dW$$

Trong ño:

dQ : nhiet nang

dU : noi nang

dW : cong, $dW = pdV$

Nhiet dung ñang tích:

$$C_V = \left(\frac{\partial Q}{\partial T}\right)_V = \left(\frac{\partial U}{\partial T}\right)_V$$

Noi nang cua vat ran U:

$$U = U_{mang} + U_{electron}$$

U_{mang} = Nang löông toan phan cua goc nguyen töû dao ñong quanh nut mang

$U_{electron}$ = Nang löông toan phan cua cac electron

$\Rightarrow$ Nhiet dung cua vat ran:

$$C_{VR} = C_{mang} + C_{electron}$$

2. Ket qua thöc nghiem

➢Ô nhiet ño phong (300ºK): gia trò nhiet dung cua hau het cac chat co gia trò khong ñoi $3R = 3Nk_B = 6$ cal/mol.ño.

➢Ô nhiet ño thap: Khi giam nhiet ño nhiet dung giam roi ret va tien ñen gia trò $C_V = 0$ khi $T = 0$

❑ Ñoi vôi chat điện moi

$$C_V \sim T^2$$

❑ Ñoi vôi kim loai

$$C_V \sim T$$

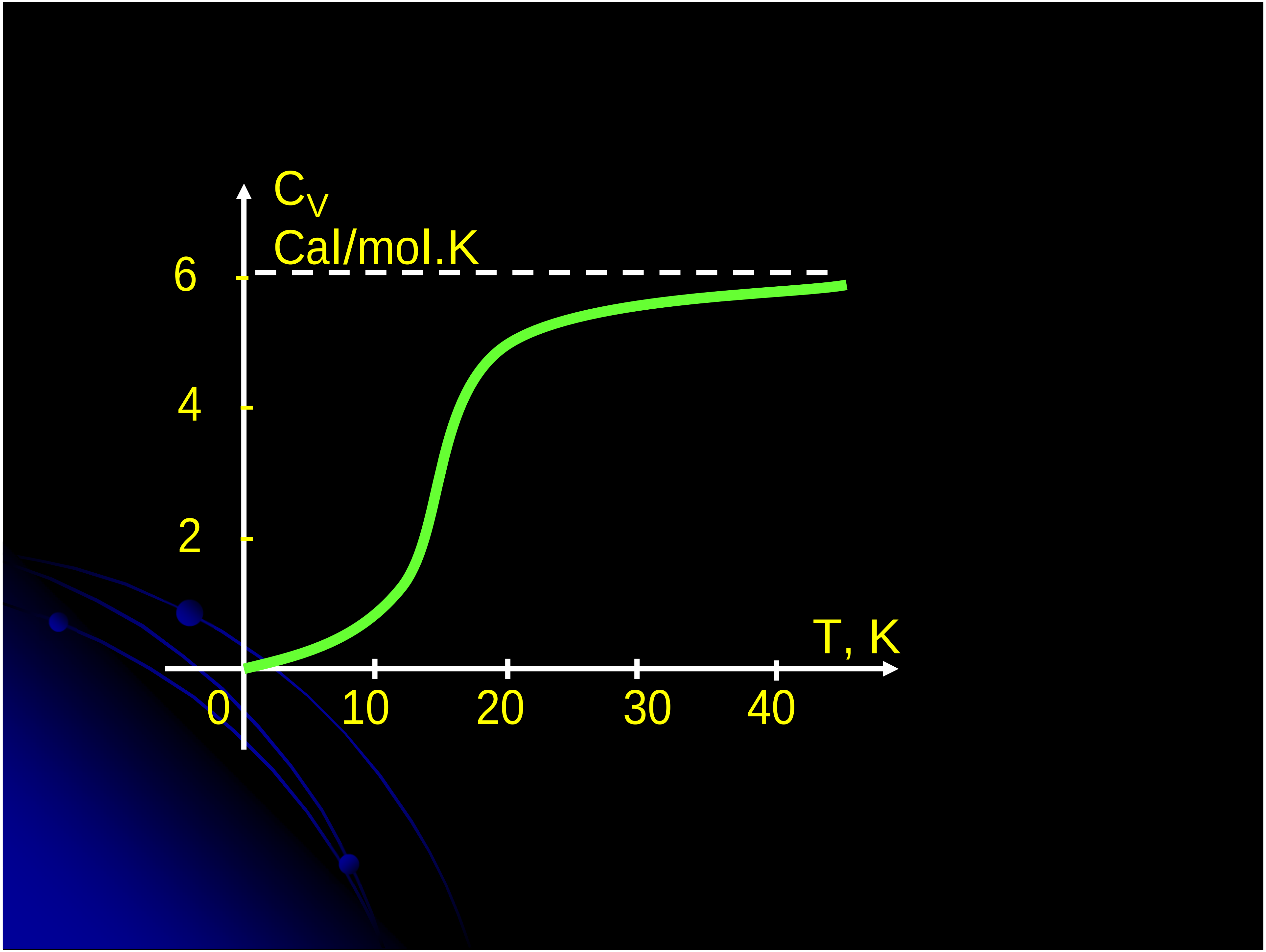
➢Khi T tang : C_V tang dan ñen gia trò khong ñoi

$$3R = 3NkB = 6 \text{ cal/mol.ño}$$

❑ Ñien moi $C \sim T^3$

❑Kim loai $C \sim \gamma T$

vôi $\gamma \approx 10^{-4}$ cal/mol.ño^2



C_V
Cal/mol.K
6
4
2
T, K
0
10
20
30
40

3. NHIET DUNG ÑANG TÍCH CUA MANG TINH THE

LÍ THUYET CO ÑIEN

Mo hình

1 hat ô nut $\rightarrow$ 3 dao ñong tö ñieu hoa.

Tinh the N hat $\rightarrow$ 3N dao ñong tö.

Nang löông cua mot dao ñong tö:

$$E = \frac{1}{2} mv^2 + \frac{1}{2} m\omega^2 x^2$$

vôi $m\omega^2 = f$ = he so cua löc Hooke

Theo phan bo Boltzman:

Khi can bang nhiet, nang löông trung bình cua mot dao ñong töi:

$$\langle E\rangle = \frac{\int\int_0^{\infty} E.e^{-\frac{E}{kT}}dv.dx}{\int\int_0^{\infty} e^{-\frac{E}{kT}}dv.dx}$$

$$\langle E\rangle = \frac{\frac{m}{2}\int\int_0^{\infty}\left(v^2+\omega^2x^2\right)e^{-\frac{m\left(v^2+\omega^2x^2\right)}{2kT}}.dvdx}{\int\int_0^{\infty} e^{-\frac{E}{kT}}dvdx}$$

$$= \frac{\int_0^{\infty}\frac{mv^2}{2}e^{-\frac{mv^2}{2kT}}dv}{\int_0^{\infty}e^{-\frac{mv^2}{2kT}}dv} + \frac{\int_0^{\infty}\frac{m\omega^2x^2}{2}e^{-\frac{m\omega^2x^2}{2kT}}dx}{\int_0^{\infty}e^{-\frac{m\omega^2x^2}{2kT}}dx}$$

Trien khai tính toan:

$$\langle E\rangle = \frac{\int_0^\infty \frac{mv^2}{2}.e^{-\frac{mv^2}{2kT}}.e^{-\frac{m\omega^2x^2}{2kT}}dv}{\int_0^\infty e^{-\frac{mv^2}{2kT}}.e^{-\frac{m\omega^2x^2}{2kT}}dv} + \frac{\int_0^\infty \frac{m\omega^2x^2}{2}.e^{-\frac{mv^2}{2kT}}.e^{-\frac{m\omega^2x^2}{2kT}}dx}{\int_0^\infty e^{-\frac{mv^2}{2kT}}.e^{-\frac{m\omega^2x^2}{2kT}}dx}$$

$$\langle E\rangle = \underbrace{\frac{\int_0^\infty \frac{mv^2}{2}e^{-\frac{mv^2}{2kT}}dv}{\int_0^\infty e^{-\frac{mv^2}{2kT}}dv}}_{\langle E_{\text{ñ}}\rangle} + \underbrace{\frac{\int_0^\infty \frac{m\omega^2x^2}{2}e^{-\frac{m\omega^2x^2}{2kT}}dx}{\int_0^\infty e^{-\frac{m\omega^2x^2}{2kT}}dx}}_{\langle E_t\rangle}$$

Trong dao ñoäng ñieàu hoøa:

ñoäng naêng trung bình = theá naêng trung bình

$$\Rightarrow \langle E_{ñ} \rangle = \langle E_t \rangle$$

$$\langle E \rangle = \frac{\int_0^{\infty} \frac{mv^2}{2} e^{-\frac{mv^2}{2kT}} dv}{\int_0^{\infty} e^{-\frac{mv^2}{2kT}} dv} + \frac{\int_0^{\infty} \frac{m\omega^2 x^2}{2} e^{-\frac{m\omega^2 x^2}{2kT}} dx}{\int_0^{\infty} e^{-\frac{m\omega^2 x^2}{2kT}} dx}$$

Ta ñaët:

$$u^2 = \frac{mv^2}{2kT} = \frac{m\omega^2 x^2}{2kT}$$

$$2udu = \frac{m}{2kT} 2vdv \quad \rightarrow \quad dv = 2kT \frac{udu}{mv} = 2kT. \frac{udu}{\sqrt{\frac{2kT}{m}}.u}$$

$$\langle E\rangle = 2kT\,\frac{\int_0^{\infty} u^2 e^{-u^2}\,du}{\int_0^{\infty} e^{-u^2}\,du}$$

Theo ñònh nghóa vaø tính chaát haøm Gamma:

$$\Gamma(n) = \int_0^{\infty} x^{n-1}e^{-x}\,dx \qquad \Gamma(n) = (n-1)\,\Gamma(n-1)$$

$$\rightarrow \Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}$$

Ñaët $x = u^2 \rightarrow dx = 2udu$

$$\langle E\rangle = 2kT\,\frac{\int_0^{\infty} x.e^{-x}.\dfrac{dx}{2\sqrt{x}}}{\int_0^{\infty} e^{-x}.\dfrac{dx}{2\sqrt{x}}} = 2kT\,\frac{\int_0^{\infty} x^{\frac{1}{2}}.e^{-x}dx}{\int_0^{\infty} x^{-\frac{1}{2}}.e^{-x}dx}$$

$$\langle E\rangle = 2kT.\frac{\Gamma(\frac{3}{2})}{\Gamma(\frac{1}{2})} = 2kT.\frac{(\frac{3}{2}-1).\Gamma(\frac{1}{2})}{\Gamma(\frac{1}{2})} = kT$$

Nang löông cua he gom N hat (3N dao ñong töi ñieu hoa): $U = 3NkT$

→ Nhiet dung ñang tích: $C_V = \dfrac{\partial U}{\partial T} = 3Nk$

→ Nhiet dung ñang tích cua 1 mol:

$$C_V = 3N_A k = 3R = 6 \text{ cal/mol.ñoi}$$

Vay: Lí thuyet coi ñien phu hôïp vôi thöc nghiem ôi nhiet ñoi cao, khong phu hôïp ôi nhiet ñoi thap.

LÍ THUYET EINSTEIN

Moi hình : mot chat ran co N hat la tap hôp cua 3N dao ñong tö ñieu hoa ñoc lap co cung tan so ν

$\rightarrow$ Nang löông cua moi dao ñong tö (1 löông tö)

$E_n = nh\nu$ vôi n la so nguyen.

Nang löông trung bình cua mot dao ñong tö la:

$$\langle E\rangle = \frac{\sum_{n=1}^{\infty} nh\nu.e^{-\frac{nh\nu}{kT}}}{\sum_{n=1}^{\infty} e^{-\frac{nh\nu}{kT}}} = \frac{h\nu\left(e^{-\frac{h\nu}{kT}} + 2e^{-\frac{2h\nu}{kT}} + \ldots\right)}{\left(1 + e^{-\frac{h\nu}{kT}} + e^{-\frac{2h\nu}{kT}} + \ldots\right)}$$

$$\langle E\rangle = \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

Nang löông trung bình cua he gom 3N dao ñong tö:

$$U = 3N.\frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

Ô nhiet ño cao: $kT >> h\nu \Rightarrow x << 1$:

$$e^{-x} \approx 1 + x + x^2 + \ldots$$

$$e^{-\frac{h\nu}{kT}} - 1 \approx 1 + \frac{h\nu}{kT} + \left(\frac{h\nu}{kT}\right)^2 + \ldots - 1 \approx \frac{h\nu}{kT}$$

$\rightarrow$ $U = 3NkT$

$\Rightarrow$ phu hôp vôi ket qua co ñien

(Ñònh luat Dulong- Petit)

* Ô nhiet ño thap: $kT << h\nu \Rightarrow x >> 1$:

$$\langle E\rangle = \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} \approx h\nu . e^{-\frac{h\nu}{kT}}$$

$$\rightarrow \quad U = 3N<E> \quad \rightarrow \quad C_V = \left(\frac{\partial U}{\partial T}\right)_V = 3Nk\left(\frac{h\nu}{kT}\right)^2 .e^{-\frac{h\nu}{kT}}$$

Ñaët: $\theta_E = \frac{h\nu_E}{k}$: nhieät ñoä Einstein

$$C_V = 3Nk\left(\frac{\theta_E}{T}\right)^2 .e^{-\frac{\theta_E}{T}}$$

$\rightarrow$ C_V giaûm theo nhieät ñoä theo haøm $e^{-\frac{\theta_E}{T}}$ nhanh hôn keát quaû ño ñöôïc baèng thöïc nghieäm.

$\Rightarrow$ Lí thuyet Einstein cho phep giai thích C_V khong ñoi ô nhiet ño cao, ô nhiet ño thap C_V giam khi nhiet ño giam nhöng giam nhanh hôn ket qua thöc

LÍ THUYET DEBYE

MO HÌNH

Chat ran gom cac dao ñong tö; mot dao ñong tö khong bieu thò dao ñong cua töng goc nguyen tö nhö mau cua Einstein ma bieu thò cho dao ñong chuan cua toan tinh the.

Tinh the co N nguyen tö thì co 3N dao ñong chuan: N dao ñong doc va 2N dao ñong ngang.

Nang löông trung bình cua mot dao ñong tö vôi tan so ν la:

$$\langle E_\nu \rangle = \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

- Nang löông cua mang tinh the chat ran la:

$$U = \sum_{i=1}^{N} U_{i\,doc} + \sum_{i=1}^{2N} U_{i\,ngang} = \sum_{i=1}^{3N} \frac{h\nu_i}{e^{\frac{h\nu_i}{kT}} - 1}$$

- Tinh the la mot moi tröông tan sac

→ He thöc tan sac:

$$\omega = qv$$

$$q = \frac{2\pi}{\lambda} \quad : \text{ vectô song}$$

➢ Tinh theå höõu haïn coù caùc caïnh L_x, L_y, L_z.

Ñieàu kieän bieân voøng cho haøm soùng:

$$\exp[iq(r + L)] = \exp iqr$$

$$\rightarrow \quad q_x = \frac{2\pi}{L_x} n_x; \quad q_y = \frac{2\pi}{L_y} n_y; \quad q_z = \frac{2\pi}{L_z} n_z$$

Vôùi n_x, n_y, $n_z \in Z$

$$q = \sqrt{q_x^2 + q_y^2 + q_z^2}$$

Tröông hôp ñôn gian
Tinh the lap phöông canh L

- Moi tröông ñang höông.
- Van toc truyen cac song lay trung bình la v_o.

$\rightarrow$ He thöc tan sac:

$$\omega_0 = v_0 q_n = v_0 \frac{2\pi}{L} n = v_0 \frac{2\pi}{L} \sqrt{n_x^2 + n_y^2 + n_z^2}$$

Xet trong khong gian q

- Cac gia trò ñöôc phep cua q xac ñònh vò trí cac nut cua mang.
- O nguyen to cua mang nay co dang lap phöông canh $\frac{2\pi}{L}$ $\rightarrow$ The tích o mang:

$$\left(\frac{2\pi}{L}\right)^3 = \frac{8\pi^3}{V}$$

V = the tích cua tinh the, $V = L^3$.

- Cac ñiem co cung mot gia trò cua q thuoc cung mot mat cau co ban kính q $\rightarrow$ the tích mat cau $\frac{4}{3}\pi q^3$

→So cac gia trò ñöôc phep cua q bang so dao ñong töø co so song töø 0 → q:

$$N(q) = \frac{\frac{4}{3}\pi q^3}{\frac{8\pi^3}{V}} = V\frac{q^3}{6\pi^2} \Rightarrow q = \frac{2\pi}{L}.\sqrt[3]{\frac{3N(q)}{4\pi}}$$

He thöc tan sac: $\omega = v_o q = v_o.\frac{2\pi}{L}.\sqrt[3]{\frac{3N(q)}{4\pi}}$

Sö cac dao ñong töø co tan so ν töø $0 \to \nu$:

$$N(q) = \frac{V}{6\pi^2}\left(\frac{2\pi\nu}{v_o}\right)^3 = V.\frac{4\pi}{3v_o^3}\nu^3$$

Vôi $q = \dfrac{2\pi}{\lambda} = \dfrac{2\pi\nu}{v_o}$

Soi dao ñoing töi coi gia trò q trong khoaing $q \to q + dq$:

$$dN(q) = V.\frac{q^2}{2\pi^2}dq$$

$$\to \quad g(q) = \frac{dN(q)}{dq} = V\frac{q^2}{2\pi^2} \qquad (1)$$

Soi dao ñoing töi coi ν trong khoaing $\nu \to \nu + d\nu$:

$$dN(\nu) = V.\frac{4\pi}{v_o^3}\nu^2 d\nu \;\to\; g(\nu) = \frac{dN(\nu)}{d\nu} = V\frac{4\pi}{v_o^3}\nu^2 \quad (2)$$

(1) va (2) : goi la ham mat ñoi traing thai (mat ñoi mode dao ñoing).

Noi nang cua he:

$$U = \int \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} dN(\nu) = \int_0^{\nu_{max}} \frac{h}{e^{\frac{h\nu}{kT}} - 1} .\nu . \frac{4\pi}{v_o^3} \nu^2 d\nu$$

Dung gia trò trung bình cua van toc theo cong thöc:

$$\frac{1}{v_o^3} = \frac{1}{v_d^3} + \frac{2}{v_{ng}^3} = const$$

$$V . \frac{4\pi}{v_o^3} \int_0^{\nu_{max}} \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} .\nu^2 d\nu = V . \frac{4\pi}{v_o^3} \int_0^{\nu_{max}} \frac{h\nu^3}{e^{\frac{h\nu}{kT}} - 1} d\nu$$

ν_{max} : tan so cöc ñai cua dao ñong chuan, ñöôc tính tö

$$\int_0^{\nu_{max}} dN(\nu) = 3N$$

$$\rightarrow V.\frac{4\pi}{v_o^3}\underbrace{\int_0^{\nu_{max}} \nu^2 d\nu}_{\frac{\nu_{max}^3}{3}} = 3N$$

$$\Rightarrow \nu_{max} = \sqrt[3]{\frac{9N}{4\pi V}}.v_0$$

Ñaët: $x = \dfrac{h\nu}{kT} \rightarrow x_{max} = \dfrac{h\nu_{max}}{kT} = \dfrac{\theta_D}{T}$

$\rightarrow \theta_D = \dfrac{h\nu_{max}}{k}$: nhieät ñoä Debye.

$$\rightarrow \nu = \frac{kT}{h}x \rightarrow d\nu = \frac{kT}{h}dx$$

$$\rightarrow U = V.\frac{4\pi}{v_o^3}\int_0^{x_{max}} \frac{h.\left(\frac{kT}{h}x\right)^3}{e^x - 1}.\frac{kT}{h}dx$$

$$\rightarrow U = V.\frac{4\pi}{h^3 v_o^3} k^4T^4 \int_0^{x_{max}} \frac{x^3}{e^x - 1}dx$$

* Ô nhiet ño cao: $kT >> h\nu \rightarrow x << 1$

$$e^x = 1 + x + x^2 + \ldots \approx 1 + x$$

$$U = V.\frac{4\pi}{h^3 v_o^3} k^4 T^4 \frac{x_{max}}{3}$$

$$\Rightarrow U = V.\frac{4\pi}{h^3 v_o^3} k^4 T^4 \left(\frac{h\nu_{max}}{kT}\right)^3$$

$$\rightarrow U = V.\frac{4\pi}{h^3 v_o^3} k^4 T^4 \underbrace{\int_0^{x_{max}} \frac{x^3}{1 + x - 1} dx}_{\int_0^{x_{max}} x^2 dx = \frac{x_{max}^3}{3}}$$

$$\Rightarrow U = V.\underbrace{\frac{4\pi}{h\nu_o^2}}_{\frac{9N}{4\pi V}.\nu_o^3}kT.\nu_{max}^3 = 3NkT$$

U = 3NkT : trung vôi ket qua co ñien.

- Ôû nhieät ñoä thaáp: $x = \dfrac{h\nu}{kT} >> 1$

$$\Rightarrow \int_0^\infty \frac{x^3dx}{e^x - 1} = \frac{\pi^4}{15}$$

$$U = \frac{4\pi V}{h^3 v_o^3} k^4T^4 \frac{\pi^4}{15} = \frac{4\pi V}{h^3 \dfrac{4\pi V}{9N} \nu_{max}^3} \frac{\pi^4}{15} k^4T^4$$

$$\Rightarrow U = \frac{9N\pi^4k^4T^4}{15h^3\nu_{max}^3}$$

Nhiet dung

$$C_V = \frac{\partial U}{\partial T} = \frac{12N\pi^4 k^4}{5h^3\nu_{max}^3}T^3 = \frac{12N\pi^4 k}{5}\left(\frac{T}{\theta_D}\right)^3$$

$$\Rightarrow C_V = \left(\frac{T}{\theta_D}\right)^3$$

$C_V \sim T^3 \quad \rightarrow \quad$ phu hôp vôi thöc nghiem.

$\Rightarrow$ Lí thuyet Debye trung vôi ket qua thöc nghiem ôi ca nhiet ño cao vôi nhiet ño thap.

II. LÍ THUYEÁT PHONON VEÀ NHIEÄT DUNG

Aùnh saùng coù löôõng tính:

- Tính chaát soùng ñaëc tröng bôûi böôùc soùng

$$\lambda = \frac{2\pi}{k}$$

- Tính chaát haït ñaëc tröng bôûi naêng löôïng photon

$$\varepsilon = h\nu$$

hay xung löôïng $\vec{p} = \hbar\vec{k}$

$\vec{k}$ = vectô soùng.

⇒Sö löông tö hoa song anh sang la photon.

Töông tö, sö löông tö hoa cua song ñan hoi trong tinh the la phonon co nang löông va xung löông.

Photon co the ton tai trong chan khong, nhöng phonon chæ co trong cac moi tröông co the truyen song ñan hoi.

$$\rightarrow \begin{cases} \text{photon : hat thöc} \\ \text{phonon : chuan hat} \end{cases}$$

Naíng lööïng trung bình cuûa moät dao ñoäng töû trong tinh theå laø:

$$\langle E_\nu \rangle = \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} = \langle n \rangle h\nu$$

vôùi $\langle n \rangle = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$: soá phonon trung bình coù naíng

lööïng $h\nu$.

Ôû nhieät ñoä xaùc ñònh, soá phonon coi nhö xaùc ñònh.

* Ô nhiet ño cao: $x = \dfrac{h\nu}{kT} << 1$

$$\rightarrow e^x - 1 \approx 1 + x - 1 \approx x = \frac{h\nu}{kT}$$

$$\rightarrow \langle E \rangle = kT = \langle n \rangle h\nu$$

$$\rightarrow \langle n \rangle = \frac{kT}{h\nu}$$

$$q = \frac{2\pi}{\lambda} = \frac{2\pi\nu}{v_o} \rightarrow \nu = \frac{q v_o}{2\pi}$$

$$\rightarrow \langle n \rangle = \frac{kT}{h.\dfrac{q v_o}{2\pi}} = \frac{kT}{\hbar q v_o}$$

Số phonon trong thể tích V:

$$N_p = \int_o^{q_{max}} \langle n \rangle . \underbrace{\underbrace{dN(q)}_{\frac{dN(q)}{dq}.dq}}_{g(q)} = \int_o^{q_{max}} \frac{kT}{\hbar v_o q} . V \frac{q^2}{2\pi^2} dq$$

Với $g(q) = \dfrac{dN(q)}{dq} = V \dfrac{q^2}{2\pi^2}$ $\quad q_{max} = \dfrac{2\pi\nu_{max}}{v_o}$

$$\rightarrow N_p = \frac{kT}{\hbar v_o} V \frac{q_{max}^2}{4\pi^2}$$

$$\text{Ma}\quad N_p(q) = V\,\frac{q_{max}^3}{4\pi^2} = \frac{V}{4\pi^2}\cdot\frac{2\pi\nu_{max}}{v}$$

$$\rightarrow\ N_p = 3N\left(\frac{3}{2}\frac{T}{\theta_D}\right) \sim T$$

$$\Rightarrow C_V = \frac{\partial U}{\partial T} = \text{const}$$

$$\rightarrow\ \theta_D = \frac{h\nu_{max}}{k}$$: nhiet ño Debye.

* Ô nhiet ño thap:

$$Np \sim \left(\frac{T}{\theta_D}\right)^3 \sim T^3$$

va $C_V \sim 234Nk \left(\frac{T}{\theta_D}\right)^3 \sim T^3$

$\Rightarrow$ Ly thuyet phonon ve nhiet dung phu hôp vôi ket qua thöc nghiem.

TOÙM LAÏI

- Tính theå chaát raén coù theå coi nhö laø moät hôïp chöùa khí phonon coù soá phonon thay ñoåi theo nhieät ñoä cuûa chaát raén.

- Phonon vaø photon ñeàu tuaân theo phaân boá Bose – Einstein vaø ñöôïc goïi laø caùc haït Boson.

III. SÖ DAN NHIET VA NÔ NHIET CUA CHAT RAN

SÖ DAN NHIET

Trong cac vat ran ñien moi qua trình dan nhiet chu yeu la do cac phonon.

Theo thuyet ñong hoc chat khí: He so dan nhiet trong chat khí la:

$$k = \frac{1}{3} C_V \langle v \rangle .\lambda$$

C_V : nhiet dung cua mot ñôn vò the tích khí.

$\langle v \rangle$: van toc trung bình cua cac phan tö khí.

$\langle \lambda \rangle$: quang ñöông tö do trung bình cua cac hat.

Trong chat ran: Coi nhö mot hop chöùa khí phonon

Debye ñaõ duøng coâng thöùc treân cho tinh theå, vôùi:

C_V : nhieät dung cuûa maïng tinh theå.

$\langle v \rangle$: vaän toác cuûa phonon (vaän toác truyeàn aâm) = v_o.

$\langle \lambda \rangle$:quaõng ñöôøng töï do trung bình cuûa caùc phonon ñöôïc xaùc ñònh bôûi hai quaù trình:

+ Taùn xaï hình hoïc:

Taùn xaï treân maët tinh theå, sai hoûng, …

+ Taùn xaï phonon – phonon.

Quang ñöông töi do trung bình λ_p cua phonon tæ le nghòch vôi nong ño phonon n_p va tiet dien tan xa hieu dung σ_p:

$$\lambda p = \frac{1}{n_p \sigma_p}$$

$$\Rightarrow K = \frac{1}{3} C_V \langle v \rangle \frac{1}{n_p \sigma_p}$$

Ô Nhiet ño cao ($T >> \theta_D$):

$$C_V = const; \; n_p = 3n \; \frac{3}{2}\left(\frac{T}{\theta_D}\right)$$

$$\Rightarrow K = \frac{const}{T}$$

$\Rightarrow$ K se giam khi nhiet ño tang. Phu hôp ñònh tính vôi ket qua thöc nghiem.

- Ô Nhiet ño thap (T << θ_D):

$$C_V \sim \left(\frac{T}{\theta_D}\right)^3;\ n_p = \left(\frac{T}{\theta_D}\right)^3 \Rightarrow K = const.$$

- Thöc te K tiep tuc tang khi ha nhiet ño.
- Giai thích la do khi nhiet ño giam thì bien ño dao ñong cua nguyen tö giam $\Rightarrow$ quang ñöông tö do trung bình λ_p cua cac phonon tang cho ñen khi quang ñöông tö do trung bình bò han che bôi tan xa hình hoc tren cac nut mang tinh the.

SÖÏ NÔÛ NHIEÄT

- Coi maïng tinh theå nhö moät heä caùc dao ñoäng töû (DÑT) dao ñoäng ñieàu hoøa.

- Khi nhieät ñoä taêng bieân ñoä dao ñoäng cuûa caùc DÑT taêng $\Rightarrow$ Khoaûng caùch giöõa caùc nguyeân töû taêng $\Rightarrow$ Nôû nhieät.

- Nhöõng pheùp tính toaùn chính xaùc cho ta keát quaû heä soá nôû nhieät $\alpha \sim C_V$

ÔÛ nhieät ñoä cao: $C_V = const \Rightarrow \alpha = const \Rightarrow$ khoâng phuï thuoäc vaøo nhieät ñoä.

Ôû nhieät ñoä thaáp: $C_V \sim T^3 \Rightarrow \alpha \sim T^3$.