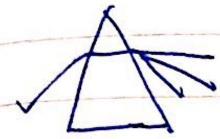
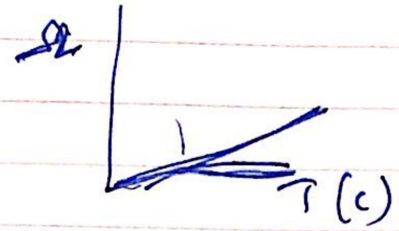


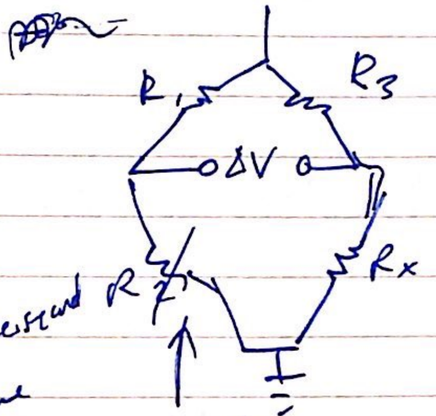
Prism



when temperature ↑
resistance ↑

put black tar around resister.
... when light hits,
resitance goes up

This device lets you detect heat



wheat stone bridge

$$\frac{R_1}{R_2} = \frac{R_3}{R_x} \text{ as}$$

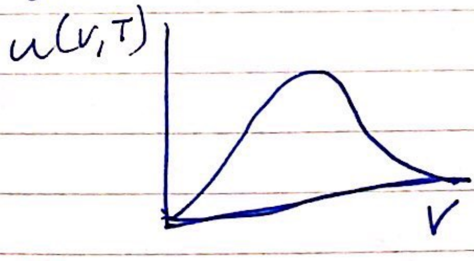
Long as $\Delta V = 0$

Langly?
Can't understand his name

variable.

you vary it until there's no voltage difference

Used this to look at black body



black body spectrum

Can we come up with theory for this curve?

Equations

Maxwell eq'n: free space

$\nabla \cdot \varepsilon_0 \vec{E} = 0 \quad \nabla \cdot \mu_0 \vec{H} = 0$

$\vec{\nabla} \times \vec{E} = -\frac{\partial}{\partial t} \mu_0 \vec{H} \quad \nabla \times \vec{H} = \frac{\partial}{\partial t} \varepsilon_0 \vec{E}$

$W = \int \frac{1}{2} \varepsilon_0 |E|^2 + \frac{1}{2} \mu_0 |H|^2 d^3 r$

think of black body as a box

calculate energy of electromagnetic field & take the average of it.

$\vec{E}(\vec{r},t) = \sum_j e_j(t) \vec{u}_j(\vec{r}) \quad \vec{H}(\vec{r},t) = \sum_j h_j(t) \vec{v}_j(\vec{r})$

$\nabla \cdot \vec{u} = 0 \quad \nabla \cdot \vec{v} = 0 \quad \nabla \times \vec{u}_j = k_j \vec{v} = \frac{\omega_j}{c} \vec{v} = k_j \sqrt{\varepsilon_0 \mu_0} \vec{v}_j$

$\nabla \times \vec{v}_j = k_j \vec{u}_j = \frac{\omega_j}{c} \vec{v}_j = \omega_j \sqrt{\varepsilon_0 \mu_0} \vec{v}_j$

$$\left.\begin{aligned}\frac{d}{dt} e_j(\tau) &= \frac{k_i}{\epsilon_0} h_i(t) \\ \frac{d}{dt} h_j(\tau) &= \frac{-k_i}{\mu_0} e_i(t)\end{aligned}\right\}$$ oscillator!

~~damonte~~

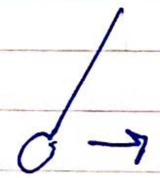
$$W = \int \frac{1}{2} \epsilon_0 \Big|\sum_i e_j \vec{u}_j\Big|^2 + \frac{1}{2}\mu_0 \Big|\sum_j h_j \vec{v}_j\Big|^2 d^3\vec{r} =$$

$$\sum_j \frac{1}{2}\epsilon_0 \underbrace{\int |\vec{u}_j|^2 d^3 r}_{L^3}\, e_j^2 + \frac{1}{2}\mu_0 \underbrace{\int |\vec{v}_2|^2 d^3\vec{r}}_{L^3}\, h_j^2$$

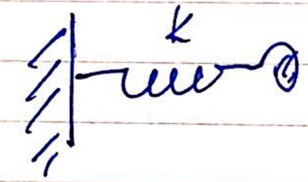
$$W = \sum_j \frac{1}{2}\epsilon_0 L^3 e_i^2 + \frac{1}{2}\mu_0 L^3 h_j^2$$

now need to take thermal average

$$e^{-E/kT}$$



$$\frac{d}{dt} x(t) = v(t) = \frac{p(t)}{m} \qquad \frac{d}{dt} p(t) = -kx(t)$$



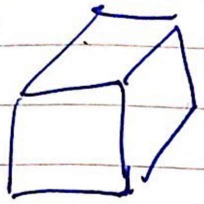
$$E = \frac{p^2}{2m} + \frac{1}{2}kx^2 \qquad \langle\langle E \rangle\rangle = \frac{\iint E(x,p)\, e^{-\frac{E(x,p)}{k_B T}}\, dx\, dp}{\iint e^{-\frac{E(x,p)}{k_B T}}\, dx\, dp}$$

$$= \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left(\frac{p^2}{2m} + \frac{1}{2}kx^2\right) e^{\frac{-\frac{p^2}{2m} + \frac{1}{2}kx^2}{k_B T}}\, dx\, dp}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{\frac{-\left(\frac{p^2}{2m} + \frac{1}{2}kx^2\right)}{k_B T}}\, dx\, dp}$$

average ~~[illegible]~~ over all degrees of freedom

$$= \frac{k_B T}{2} + \frac{k_B T}{2}$$

equal partition theorem



$$\langle\langle w \rangle\rangle = \langle\langle \sum_j \tfrac{1}{2}\varepsilon_0 L^3 e_j^2 + \tfrac{1}{2}\mu_0 L^3 h_j^2 \rangle\rangle$$

$$\langle\langle w_j \rangle\rangle = \frac{\iint \left(\tfrac{1}{2}\varepsilon_0 L^3 e^2 + \tfrac{1}{2}\mu_0 L^3 h_j^2\right) e^{-\frac{\frac{1}{2}\varepsilon_0 L^3 e_j^2 + \frac{1}{2}\mu_0 L^3 h_j^2}{k_B T}}\, de_j\, dh_j}{\iint e^{-\frac{\frac{1}{2}\varepsilon_0 L^3 e_j^2 + \frac{1}{2}\mu_0 L^3 h_j^2}{k_B T}}\, de_j\, dh_j}$$

2 degrees of freedom, energy is quadratic

$$= \frac{k_B T}{2} + \frac{k_B T}{2} = k_B T$$

$$\langle\langle w \rangle\rangle = \sum_j \langle\langle w_j \rangle\rangle$$

$$= \sum_j k_B T \qquad \frac{\langle\langle w \rangle\rangle}{L^3} = \frac{1}{L^3}\sum_j \langle\langle w_j \rangle\rangle$$

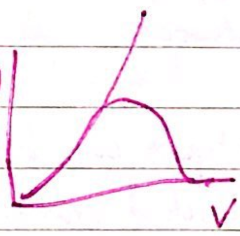
$$\boxed{u(\nu, T) = \frac{8\pi\nu^2}{c^3}\cdot k_B T} \longrightarrow \int_0^\infty \frac{8\pi\nu^2}{c^3}\langle\langle w(\nu)\rangle\rangle\, d\nu$$

thermal energy mode

# of modes / freq

Classical Prediction for the spectrum

results



matches perfectly until top of curve

response take this & add an exponential to it

$$\Rightarrow u(\nu, T) = \frac{8\pi\nu^2}{c^3} k_B T e^{-\frac{\text{const}\,\nu}{k_B T}}$$

☆ In the future, look ahead so you can participate more in class ☆

Planck (1900)

$$u(\nu, T) = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{e^{\frac{h\nu}{k_B T}} - 1}$$

managed to get to percent level

$e_j = E\cos\phi$

$h_j = E\sin\phi$

$$\langle W_j \rangle \to \frac{\int_0^\infty E_j e^{-E_j/k_B T} dE_j}{\int_0^\infty e^{-E_j/k_B T} dE_j} = k_B T$$

planck thought this would be easier to calculate. make more obvious re: mode.

$$\int_0^\infty E e^{-E/k_B T} dE \to \sum_n E_n e^{-E_n/k_B T} \quad E = h\nu$$

$$\int_0^\infty e^{-E/k_B T} dE \to \sum_n e^{-E_n/k_B T}$$

this means that energy is discrete because it's summing instead of integrating

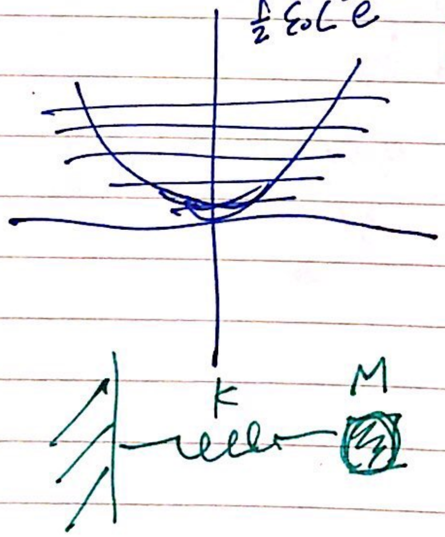
Planck & Einstein argument:

Planck: ways emitting discrete energy packets

Einstein: radiation field is an oscillator

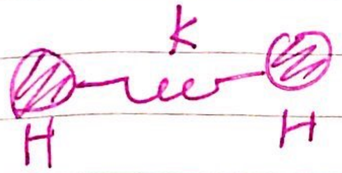
goal of the class: develop quantum mechanics?

$\frac{1}{2}\varepsilon_0 L^3 e^2$



trying to figure out how much energy each individual modes are.

electromagnetic field is an oscillator. If this oscillator works this way then all oscillators work this way



In thermal equilibrium,

$$\langle\langle E \rangle\rangle = \langle\langle \frac{p^2}{2m} + \frac{1}{2}Kx^2 \rangle\rangle$$

$$\rightarrow \frac{h\nu}{e^{\frac{h\nu}{k_B T}} - 1}$$

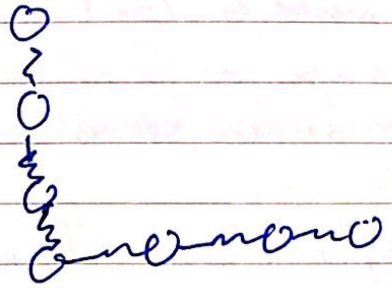
Cannot measure thermal ~~energ~~ energy. In order to prove Einstein was right, compare heat something pressure ... something couldn't hear.

$$\frac{\partial}{\partial T} \sum_K \langle\langle E_K \rangle\rangle$$

+ Rotation

Einstein made a mistake → he neglected rotational momentum

he needed one that doesn't rotate



$$\frac{\langle\langle E \rangle\rangle}{L^3} = \sum_i \frac{\langle\langle E_i \rangle\rangle}{L^3} = \frac{3Nk_BT}{L^3}$$

→ Einstein plugs in einstein oscillator energy

Dulong-Petit (1819) heat capacity for solids

~~ei~~

einstein's oscillator equation ~~is~~ still used?

$$\Rightarrow \frac{1}{L^3} \sum_j \frac{h\nu_j}{e^{h\nu_j/k_BT} - 1}$$

don't know why... ?