Thermal spectra now well-explained!

- quanta of energy key / discretization
- oscillators only emit "packets" of $E = \hbar\omega = hf$
- correct classical result when $h \to 0$!!!

Problem? neon signs or, atomic emission/absorption

2 ways to view interaction of light & sparse atomic matter

(1) sparse gas, send white light in & see what makes it through

$\Rightarrow$ Discrete absorption lines!

- even w/ "quanta" we got a cont. thermal spec
- we miss something yet

(2) excite sparse gas w/ high voltage

$\Rightarrow$ discrete emission, same λ as absorp! (few missing)

same process!

(*) NOT thermal

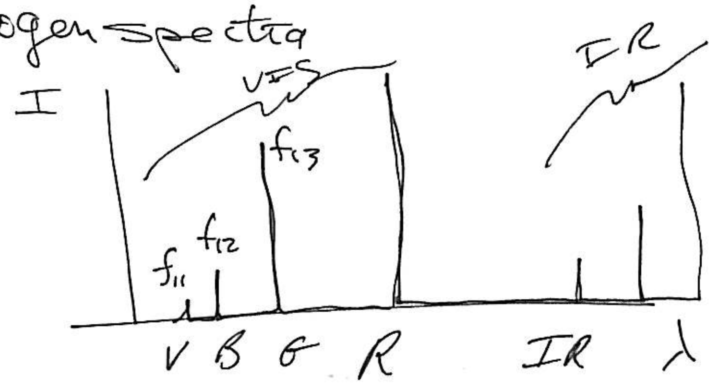
NOT acc chg - eg. cyclotron - contin spec!

Further: stability of atoms still in question!
cannot expl stable neutral matter ...

- this implies something key: somehow atomic energy levels have discreteness too, not just emitted rad!
- discreteness goes beyond Planck's assumption
- Will come back to this in Sect III; for now a sketch

- emission of light as a vibration of sorts?
  - if so, frequency of vibr → rad freq; harmonics
  - already discounted this

Hydrogen spectra



- discrete lines
- char. series that look sim
UV series, Vis, IR, ...

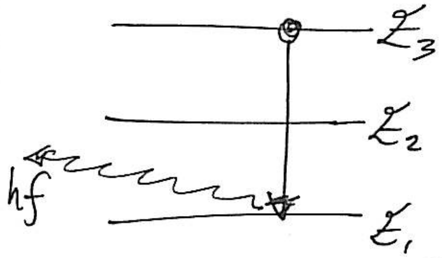
can index frequencies of emission

e.g. f_{11} f_{12} ... f_{21}, f_{22}, ...

Curious: any sum of 2 freq's gives a 3rd observed!

- Strongly implies that allowed energy state of atoms are discrete, not just rad!
- So why is the discharge spectra continuous in intensity i.e. no flicker? MANY atoms!

Bohr had an "expl" - take planck further, atoms only exist in certain discrete states



light emitted in quanta when atom transitions from high → low state

E cons:

$$\underset{(i)}{E_3} = \underset{(f)}{E_1} + \hbar\omega$$

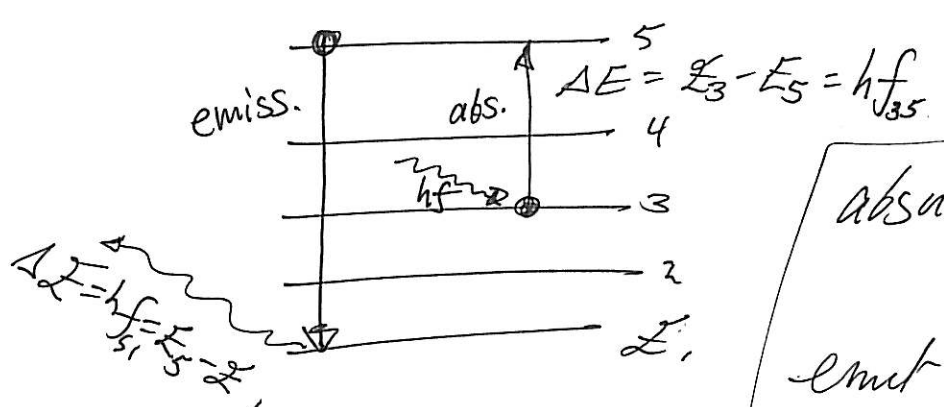
Rad discrete ∴ levels discrete (tautology)

- if $\hbar\omega$ is discrete ... then so must $E_3 - E_1$ or any $E_i - E_j$!
- cant have cont. energy of atom & discrete light!

Bohr: Planck's bundles are discr trans of atom E levels

<u>transm ↑</u>: absorb hf of light = change in level

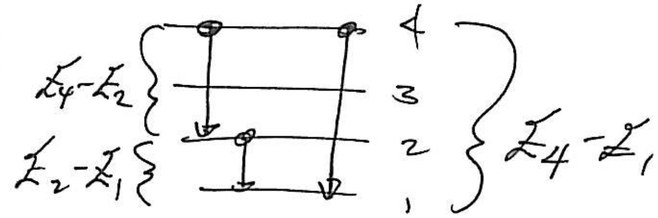
<u>emiss</u> = trans ↓, emit hf to go to lower level



absorb: $E_{init} + hf = E_f$

emit: $E_{init} = E_f + hf$

explains sum rule



$hf_{42} = E_4 - E_2$

$hf_{21} = E_2 - E_1$

$hf_{41} = E_4 - E_1 = (E_4 - E_2) + (E_2 - E_1) = hf_{42} + hf_{21}$

$\rightarrow f_{41} = f_{42} + f_{21} = \frac{E_4 - E_1}{h}$

$f_{nl} = f_{nm} + f_{ml}$

Boltz factor explains why this isn't constantly happening and why there are often more emission than abs lines

- can't absorb radiation to go from $3 \rightarrow 4$ unless its already in 3!
- prob of being in state 3?

$$\frac{N_3}{N_1} = \frac{e^{-E_3/kT}}{e^{-E_1/kT}} = e^{-(E_3 - E_1)/kT}$$

$\Delta E \sim 2\,eV$

$\sim e^{-80}$ ... no way!

at RT, nearly all atoms @ lowest level!

- at RT, expect all emissions possible if excited electrically
- only absorptions from 1 → higher are likely

very high temps: start to see other abs.

2 → higher

3 → higher etc

- Much more on this in Sect III

— main point: making rad discrete has CONSEQ

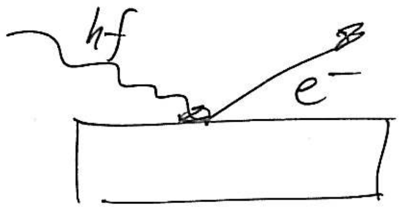
— atom energies also discrete ... what else?

Next: what other empirical prop point toward new phys?

photoelectric effect

basically: shine light on a metal surface

electrons are ejected



- light has momentum, sh
- ∴ consistent w/ wave beh.

problems? in the details...

if light = waves, how is energy discrete?

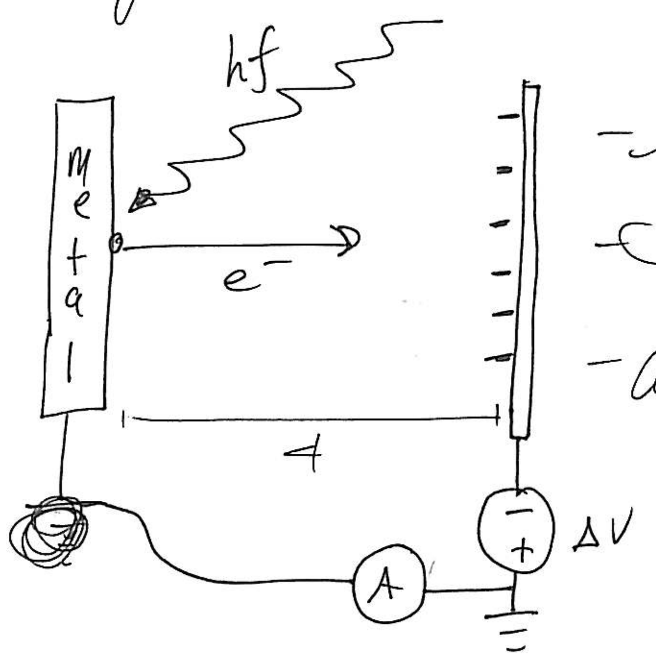
how come discrete chg emitted?

Planck's energy quanta were a formality - not taken literally!

- light still viewed as a wave
  ... so how is energy discrete?
- deeply confusing times :-)

<u>Einstein</u> - take Planck literally!

- if energy is discrete, then so is light itself!
- why? <u>the expt</u>



- light ejects e^- (ONLY! emp.)
- ~~ΔV accelerates~~
- absorbs light via KE
  - NEG metal plate
    if $KE < e\Delta V$, NO I

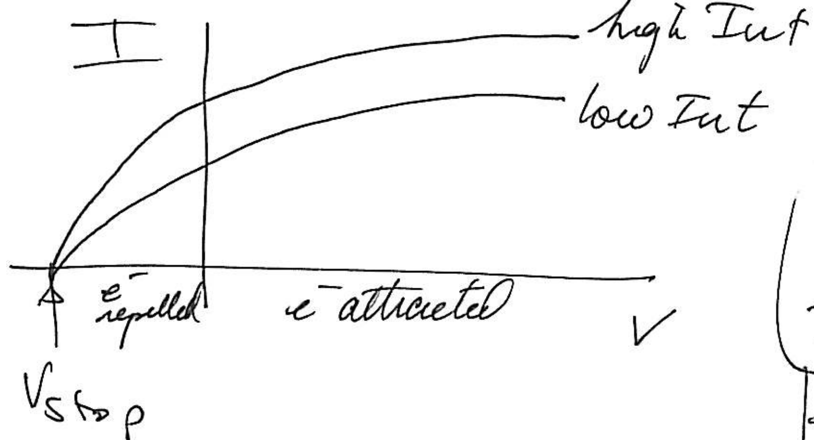
° checks E distr of electrons, cf light freq!

$K_{e^-} = \frac{1}{2}mv^2 = hf$ photon → electron KE

if $\frac{1}{2}mv^2 \geq e\Delta V$ e^- collected, current!

ΔV_{Stop} measures e^- KE!

vary ΔV for given f; at some cut $\Delta V < 0$
no e^- make it any more — STOPPING POTENTIAL



problem?

Stopping potential INDEP of intensity!

higher intensity should mean more energy?

Conclusion: Light energy is NOT related to intensity! energy always SAME given f

if it were, expect $V_{stop} \sim$ Intensity!

Classical expect	Reality
e^- absorb EM waves energy continuously ~~current~~ } so intensity↑ means KE↑ means higher ΔV_{stop}	KE_{max} indep of intensity
time delay - turn light on, wait for e^- to absorb enough E varies w/ intensity	NIKS. $\ll 10^{-9}$ sec

e^- ejected @ any f so long as intensity high enough	e^- only come out if f > crit. value!
KE and f unrelated	KE ↑ as f ↑

major FAIL!

Einstein's model: incident light *is* quanta!

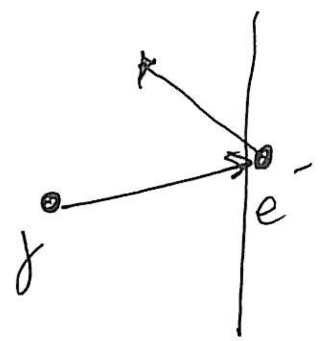
- light emitted (absorbed as quanta AND) travels as such!
- light = bundles, massless particles! photons
  - $\frac{1}{r^2}$ intensity drop OK ... particles spread out
  - if $m=0$, travel at $v=c$ in straight lines
  - energy ≠ intensity

    intensity = more particles of same energy each

    $E_{ph} = hf$ as Planck said

now its a mechanics problem!

γ = photon



relativity: if $m=0$, $\vec{p} = \frac{E}{c} = \frac{hf}{c} = h/\lambda$

- photons still have momentum
- they hit e^-, eject them **if** their energy > Binding E

Simplest: light quanta (photon) gives all energy to e^- ($\vec{p}$ too). if its enough, e^- ejected

- electrons are bound to crystal
- mostly e^- near surface (no scatter/recapture)
- mostly ejected w/ $\vec{v} \perp$ surface ($\vec{p}$ consv.)

E balance:

$$\underset{(i)}{E_{photon}} = \underset{(f)}{KE_{e^-} + BE_e} = KE + W$$

$E_{photon} = hf$; BE_e = binding energy aka W = work fn

or, $\boxed{K_{e^-} = hf - W}$

this explains it all!

- have to have $\boxed{hf > W}$ for any ejection!
  exceed binding energy of e^- to crystal
- KE linear in freq above that
- $\boxed{\text{instantly}}$ – each photon gives all its energy
  one photon → one e^-
- $\boxed{\text{intensity is irrelevant,}}$ has nothing to do w/ E
  classical optics: not true... but not concerns.

$$E_{light} = (\#\text{photons})(\text{energy per photon})$$
$$= Nhf$$

$$\text{intensity} \sim N/\Delta t$$

- weak beam does the same, just less photons/sec!

- Since W depends on material, so does freq required for e^- emission ✓

- Why film less sensitive to red light ... less E per photon!

? what more does this imply

? why do ray diagrams work AND wave interference ?

Scale of probe

relev dist $\lesssim \lambda$ wave-like 

relev dist $\gg \lambda$ ray/particle-like wavepacket ↕ RAY

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really, neither!!! ... just our lack of imagination. MORE TO COME

Impl from relativity

$E_{ph} = hf = \hbar\omega$ Planck-Einstein

$$\left.\begin{array}{l} E^2 = m^2c^4 + p^2c^2 \\ v_{light} = c \end{array}\right\} \text{Relativity}$$

- Only consistent if $m_{photon} = 0$!

- implies $E_{ph}^2 = c^2p^2$ or $|\vec{p}| = \frac{E_{ph}}{c}$

or $$|\vec{p}| = \frac{hf}{c} = \frac{h}{\lambda}$$

- So, wacky: momentum w/o mass by virtue of energy
- however: emission of photon means a body loses energy E_{ph}, requiring its mass to decrease by E/c^2!
- absorb photon: mass-energy equiv ⇒ <u>mass increase</u>

  tiny though. green photon ~ 2eV

  electron mass: 511,000 eV

- also: <u>radiation pressure</u> (also classically)

  consistent w/ classical E&M

? how to prove photons have momentum

Collide them with stuff.

COMPTON EFFECT

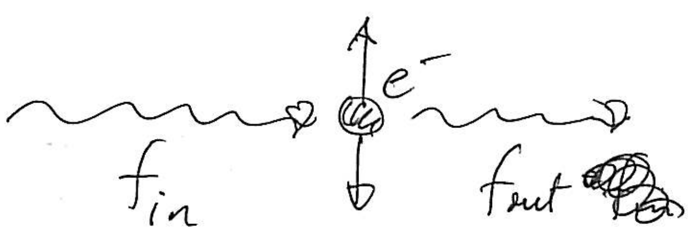
experiment: shoot high energy (gamma or x) light at e^-

• photon ejects e^- ... scattered

– if e^- acquires KE, photon LOSES energy!

– $f_{in} > f_{out}$

Classical

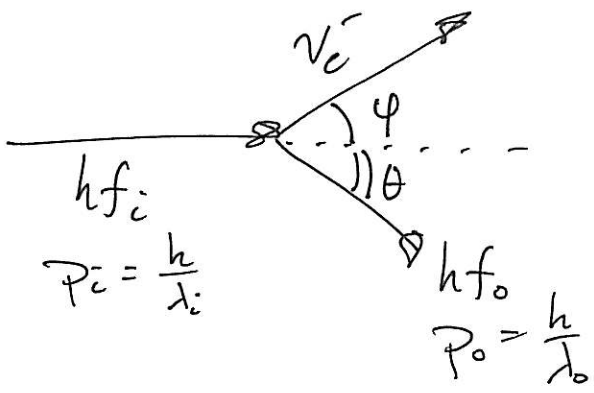


e^- just oscillates...

– result "proves" photon model has truth momentum + particle-like scattering

– high energy → short λ → particle-like

(low energy → long λ → wave like) depending on relevant scale



- conserve $\vec{p}$, E
- use relativistic E formulas (see text)

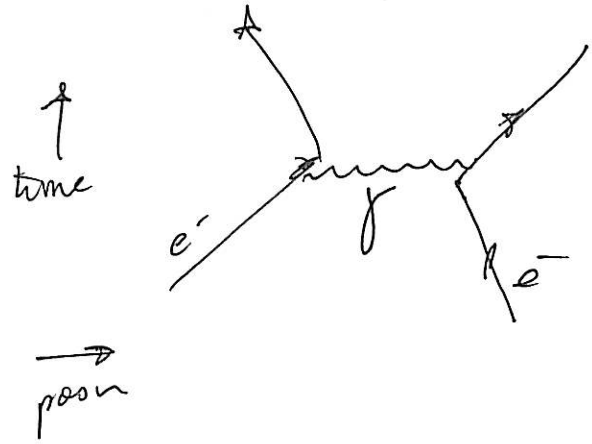
$$\Rightarrow \boxed{\lambda_o - \lambda_i = \left(\frac{h}{mc}\right)(1-\cos\theta)} = \lambda_c (1-\cos\theta)$$

$\lambda_c \approx 2.4 \times 10^{-12}\,m$

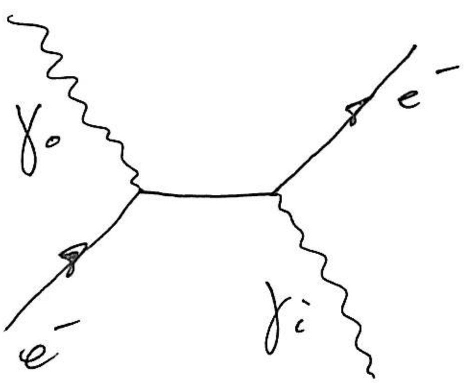
- frequency $\downarrow$, $\lambda \uparrow$ ... photon loses energy
- explicit appearance of h!
  - $\Rightarrow$ goes away in "classical limit"
  - intrinsic to quantum hypothesis
- Observation of Compton scattering = stunning confirmation of photon model! (and rel.)
- only for SMALL λ ... x-rays, gammas

Better: 2-step process
1. absorb photon of $E_i = hf_i$, $p_i = h/\lambda_i$
2. emit photon of $E_o = hf_o$, $p_o = h/\lambda_o$

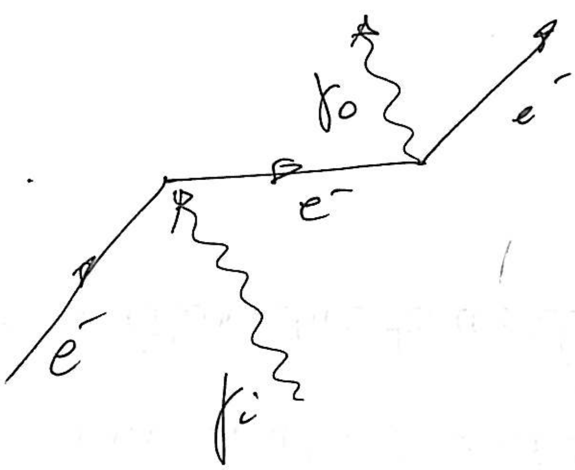
Actually: all interactions of charged particles can be thought of as photon interaction!



- one e^- emits γ, recoils
- 2^{nd} absorbs later, scatters!
- equiv to COULOMB!



Compton: e^- emits photon, recoils, absorbs 2^{nd} one
(time ordering observer-dep)



~~e^- emits~~

e^- absorbs photon, recoils, emits 2^{nd} photon