Note Title

4/11/2010

Physics 114 - April 21, 2015

- Moving fast
- Last class in 1 week
- Final EXAM

  May 6

  7:15 pm

  Hubbell Auditorium

light is a wave

- Theory well understood
  Maxwell → wave equations → derive laws of optics
  Interference, Diffraction, Refraction → wave characteristics
- Numerous experiments show light behaves exactly like other wave phenomena such as sound, waves on strings, etc.
- Only strangeness is that light is a wave that can travel in a vacuum apparently.

Max Planck

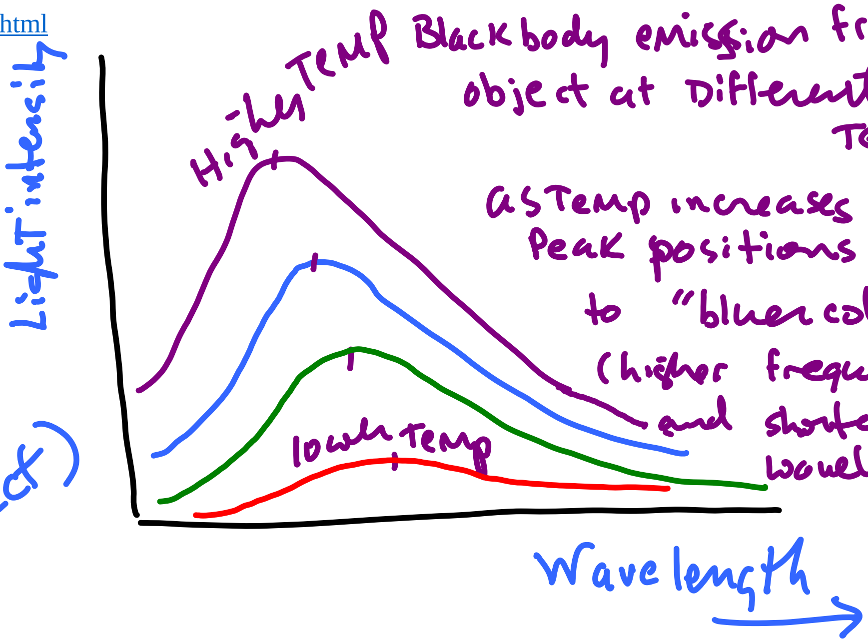
(1858-1947)

German national

http://www-history.mcs.st-andrews.ac.uk/Mathematicians/Planck.html

Awarded 1918 Nobel Prize in physics for analysis of blackbody radiation which contributed to rise of quantum Mechanics

"Blackbody" radiation (emitted by object)



Blackbody emission from object at Different Temps

as Temp increases Peak positions move to "bluer colors" (higher frequency and shorter wavelength)

Planck succeeded in describing
Black body radiation

light exists in packets of energy

Discrete, Particle-like

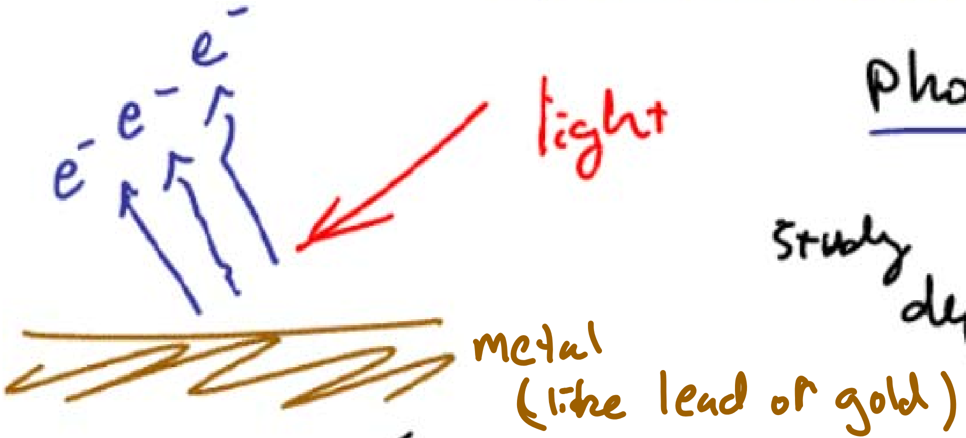
"photons"
Gilbert lewis
~1926

$$\boxed{\underset{\text{Energy}}{E} = \overset{\text{Planck's constant}}{h}\,\underset{\text{frequency}}{\nu}}$$

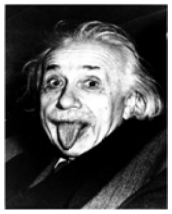
Planck's Theory worked perfectly ... but physicists thought it was a fortuitous Accident ... after all, light is a wave.

Another phenomenon that was NOT understood

Photoelectric effect



Study electric current
depends on Intensity
+ color of light

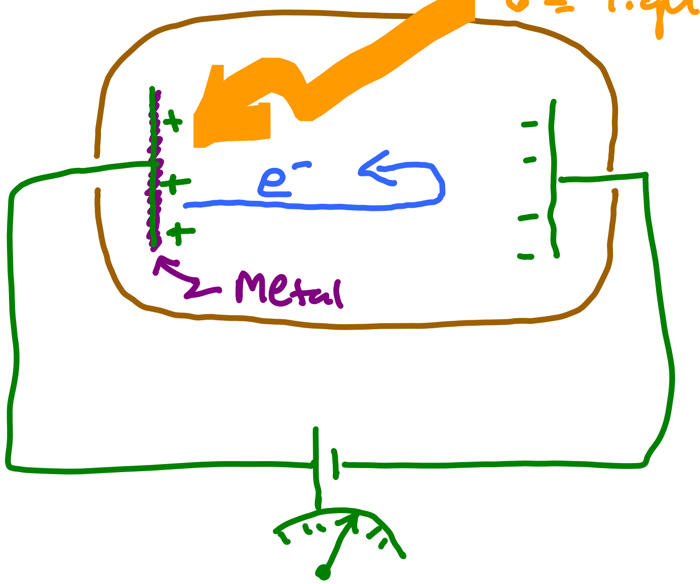


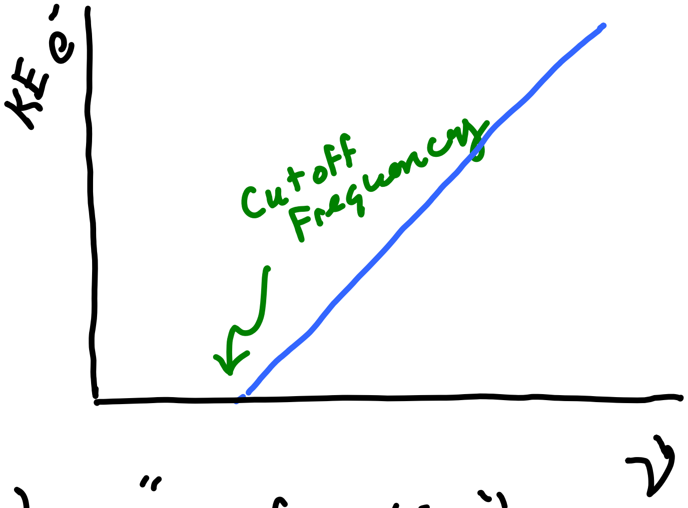
Einstein in 1905

$$\underline{\underline{E = h\nu}}$$

- Einstein able to explain photoelectric effect
  Assuming light to come in little packets
  with energy $E = h\nu$
- Light as wave theory could NOT account for data
- Suddenly world has to face fact that light
  is both a wave and a particle
  ... sounds crazy ... but that's what nature tells us.

Photoelectric effect – Einstein 1905





get current

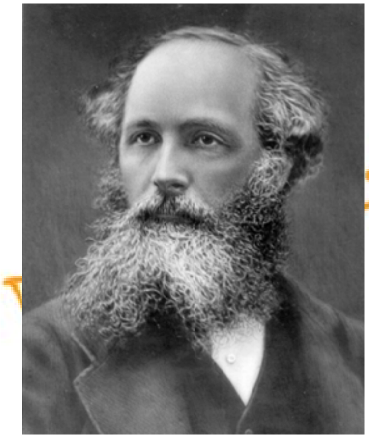
increase potential

until current stops

→ PE = KE

$$KE_{e^-} = h\nu - \underbrace{\text{``work function''}}_{e^-\text{ binding energy in metal}}$$

Constant the same as Needed by Planck!!



Maxwell's equations

interference

diffraction

Refraction

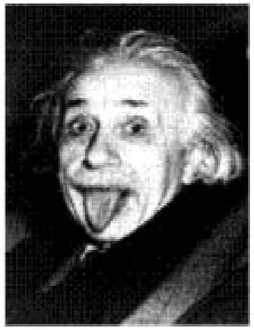
dispersion

⋮

light is a wave!

Planck

Blackbody Radiation



Einstein

Photoelectric effect

1905

light comes in little packets with energy $E = h\nu$

light is a particle!

Louis Victor Pierre Raymond 7th duc de Broglie

mid-1920's

de Broglie hypothesized matter can have wave characteristics with a wavelength given by

So-called de Broglie Wavelength

$$\boxed{\lambda = \frac{h}{p} = \frac{h}{mv}}$$

From special relativity

$$E = \sqrt{p^2c^2 + m^2c^4}$$

Form of "$E = mc^2$" when particle moving

$\longrightarrow$ For photon, $m=0$

$E = pc$ or $\boxed{p = \frac{E}{c}}$

From Blackbody + PhotoElectric

$$E = h\nu \longrightarrow E = \frac{hc}{\lambda} \rightarrow \boxed{\frac{h}{\lambda} = \frac{E}{c}}$$

$v = \lambda\nu$

$\lambda = \frac{h}{p}$ for photon

deBroglie: Perhaps Also true for Particle with Mass

$\lambda = h/p$

baseball at 92 mph

mass 142 g

$\uparrow$ 41 m/s

P of baseball = mv

$p = 5.7 \text{ kg m/s}$

$$\lambda_{\substack{92\text{ mph}\\ \text{baseball}}} = \frac{\overset{h}{6.6\times10^{-34}}\ \text{J}\cdot\text{s}}{5.7\ \text{kg m/s}}$$

$\lambda = 1.\times10^{-34}$ m

incredibly small wavelength — not noticeable to us.

1 eV electron

energy of $\underline{\underline{1.6}}\times10^{-19}$ J

$$= \frac{1}{2}mv^2 \rightarrow v = 596 \, m/s$$

$$p = (9\times10^{-31}\,kg)(596) = 5\times10^{-28}\,kg\,m/s$$

$$\lambda_{e^-} = \frac{6.6\times10^{-34}}{5\times10^{-28}} = 1.3\times10^{-6}\,m$$

$$\sim 1\,\mu m$$

<u>electron Microscope</u>

can use electron waves to image <u>very</u> <u>small</u> objects because electron wavelength is smaller than wavelength of visible light

$\lambda = h/p$

higher Energy or p → smaller λ of electron

Not so incredibly small

careful experiments <u>can</u> see wave effects like diffraction and interference of electrons

Niels Bohr

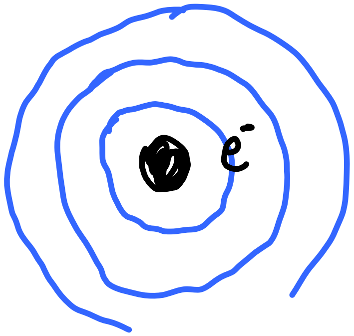
(1885 - 1962) (Denmark)

1922 Nobel Prize in Physics

~1912, 1913
(before deBroglie)

Atomic (planetary) model with fixed orbits

nicely motivated by de Broglie's matter waves in 1924

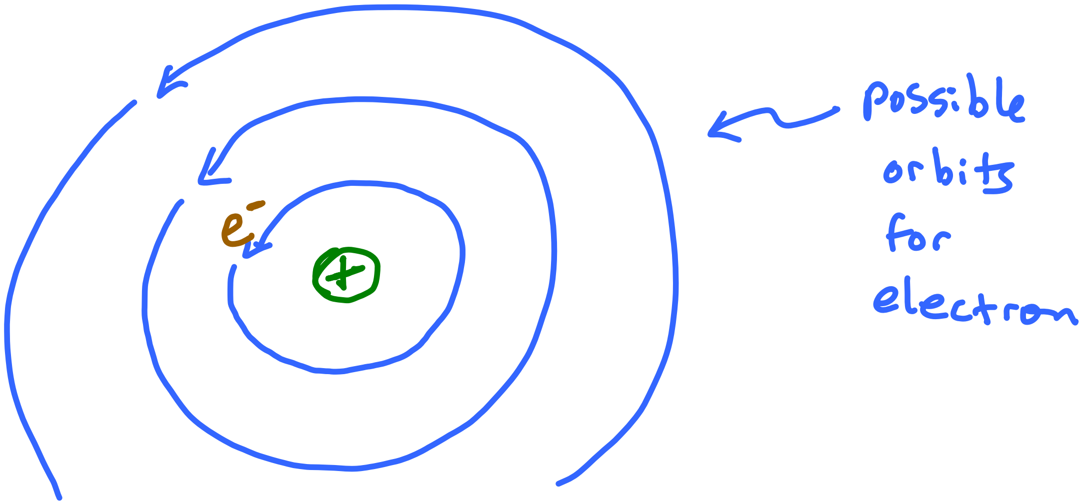


Bohr model of the atom

- Positive Nucleus
- electrons orbit in circles, Proton too heavy to Move
- only particular "discrete" orbits allowed

  ↑ known as quantization

- electric (Coulomb) Force holds electron on Circle as it orbits



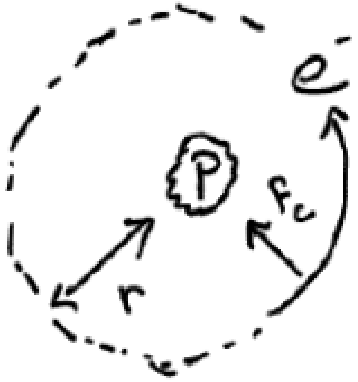
possible orbits for electron

Important pre-quantum mechanics Model of Atom

Bohr ATOM

1913 ↳ impt for giving us intuition about Atoms

Assume e^- orbits proton in a circular orbit



$$F_{cent} = \frac{m_e v^2}{r}$$

$\frac{kZe^2}{r^2}$ if single e^- atom w/ Atomic # Z

$$\boxed{\text{Equation I}}$$

$$\frac{k|e|^2}{r^2} = \frac{m_e v^2}{r} \leftarrow$$

Coulomb attraction between p and e^-

Centripetal force

Since e^- is a wave

Imagine e^- as a Circular STANDing wave

Analogy with drinking STRAWS

only works for certain λ that satisfy

$$2\pi r = n\lambda \qquad n = 1,2,3\ldots$$

From DeBroglie

$$2\pi r = n\frac{h}{p}$$

This is where Things become discrete or quantized

$$\hbar = \frac{h}{2\pi}$$ = called h-bar

So, $pr = n\hbar$

Angular Momentum

$mvr = n\hbar$ same as $L = n\hbar$

So can also say Bohr quantized Angular Momentum

Eqn 2

$$v = \frac{n\hbar}{mr}$$

Substitute into Equation 1 Above

$$\frac{k|e|^2}{r^2} = \frac{mv^2}{r} \longrightarrow \frac{ke^2}{r^2} = \frac{m n^2 \hbar^2}{r\, m^2 r^2}$$ solve for r

$$r_n = \frac{n^2 \hbar^2}{k e^2 m} \qquad n = 1, 2, 3 \ldots$$

SAys that electron only exists at discrete radii

If done for Single e^- ATom of ATomic # Z in initial eqns

$$\frac{ke^2}{r^2} \longrightarrow \frac{k Z e e}{r^2}$$

$$\boxed{r_n = \frac{n^2 \hbar^2}{k Z e^2 m}}$$

good For single e^- ATom w/ At. # Z

r_1 = Ground STATE orbital radius

$$\boxed{r_n = \frac{n^2}{Z} r_1}$$

$$K.E. = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{n\hbar}{mr}\right)^2 = \frac{n^2\hbar^2}{2mr^2}$$

From Eqn 2

Subsititute in for r

$$K.E. = \frac{n^2\hbar^2}{2m}\,\frac{k^2Z^2e^4m^2}{n^4\hbar^4} = \frac{mk^2Z^2e^4}{2n^2\hbar^2}$$

$$E_{TOTAL} = KE + PE$$

What is P.E.? recall Potential $= \frac{\text{work}}{\text{chg}}$

$$P.E. = -\frac{kZe^2}{r}$$

"–" because ATTRACTIVE

Sub in for r

$$P.E. = -\frac{kZe^2}{n^2\hbar^2}\,kZe^2m = -\frac{k^2Z^2e^4m}{n^2\hbar^2}$$

$$E_{TOTAL} = KE + PE = \frac{1}{2}\frac{mk^2z^2e^4}{n^2\hbar^2} - \frac{mk^2z^2e^4}{n^2\hbar^2}$$

$$\boxed{E_{n\,(TOTAL)} = -\frac{mk^2z^2e^4}{2n^2\hbar^2}}$$

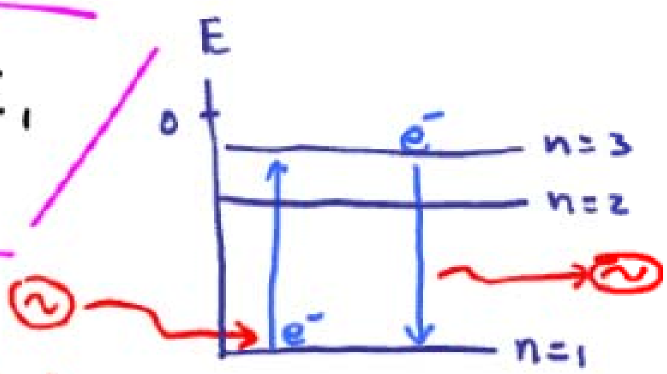
What is meant by the negative sign here?

for $Z=1$, $n=1$ → Most tightly bound Energy level for H

$$E_1 = -13.6\,eV$$

$$\boxed{E_n = -\frac{Z^2}{n^2}E_1}$$

Discrete Spectra!!



photons emitted or Absorbed as e^- shifts levels $E_\gamma = h\nu$

Discrete Atom
Emission + Absorption
lines come from
e^- transitions
between discrete
Energy levels

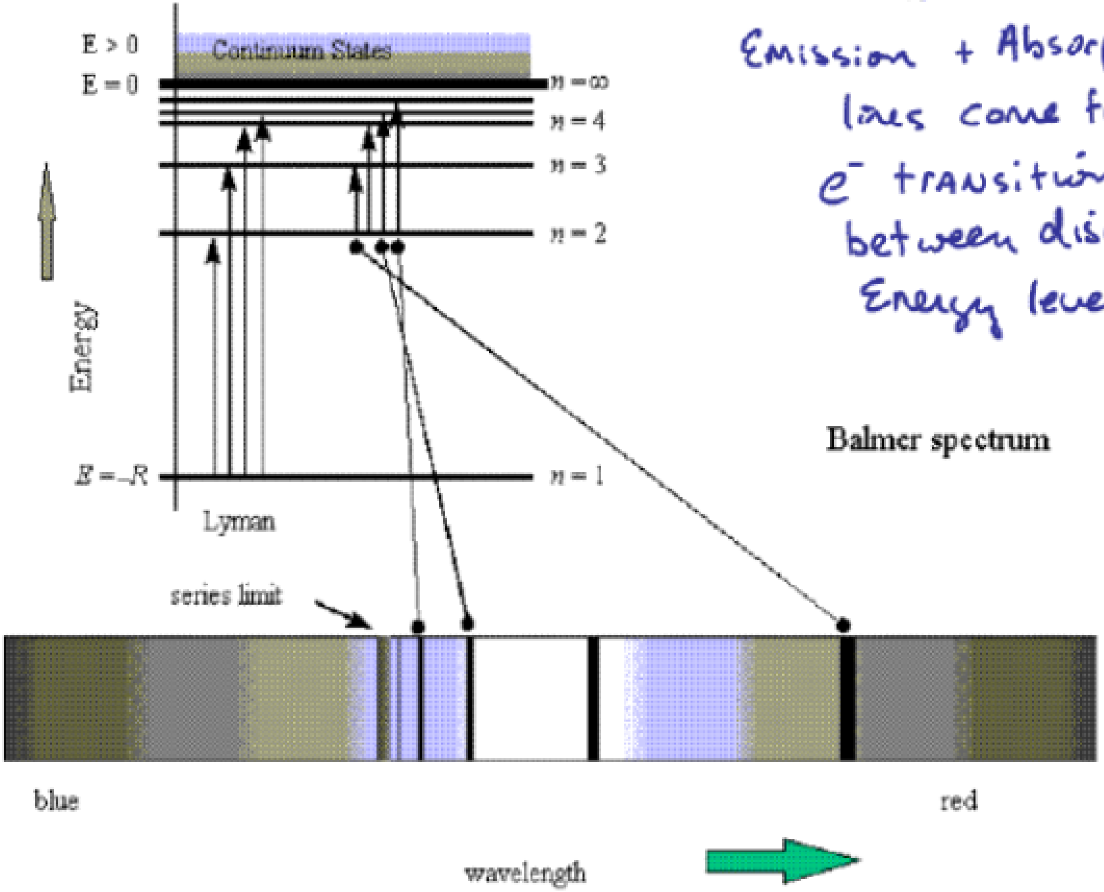
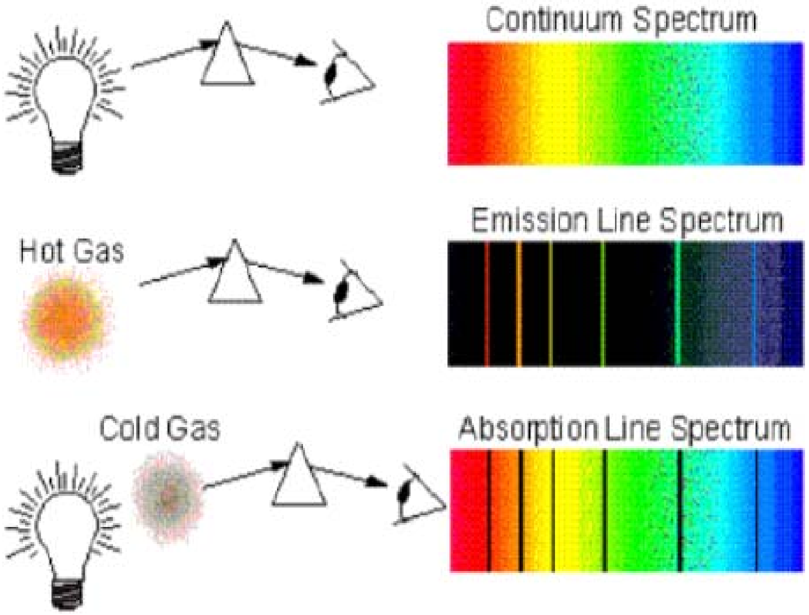


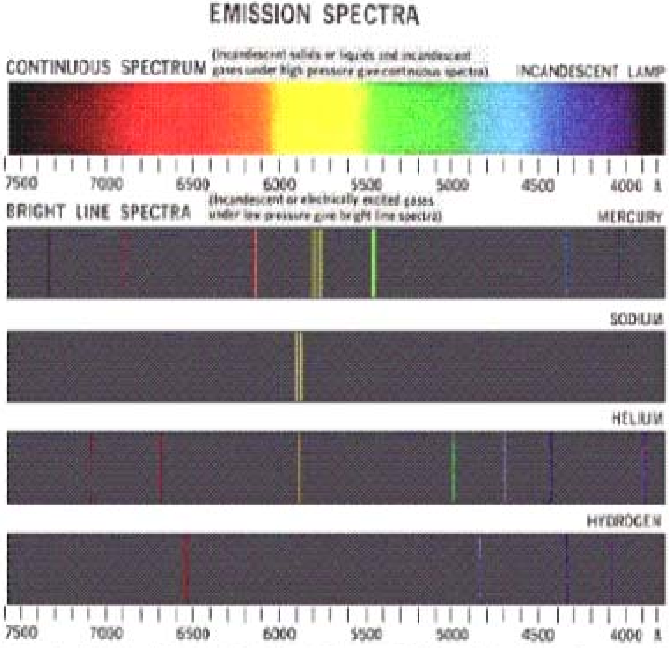
Figure from
http://www.uclan.ac.uk/facs/science/physastr/x99/PAM98/UCert/Ch06/6_6ato~1.htm

Emission vs, Absorption



Different Atoms

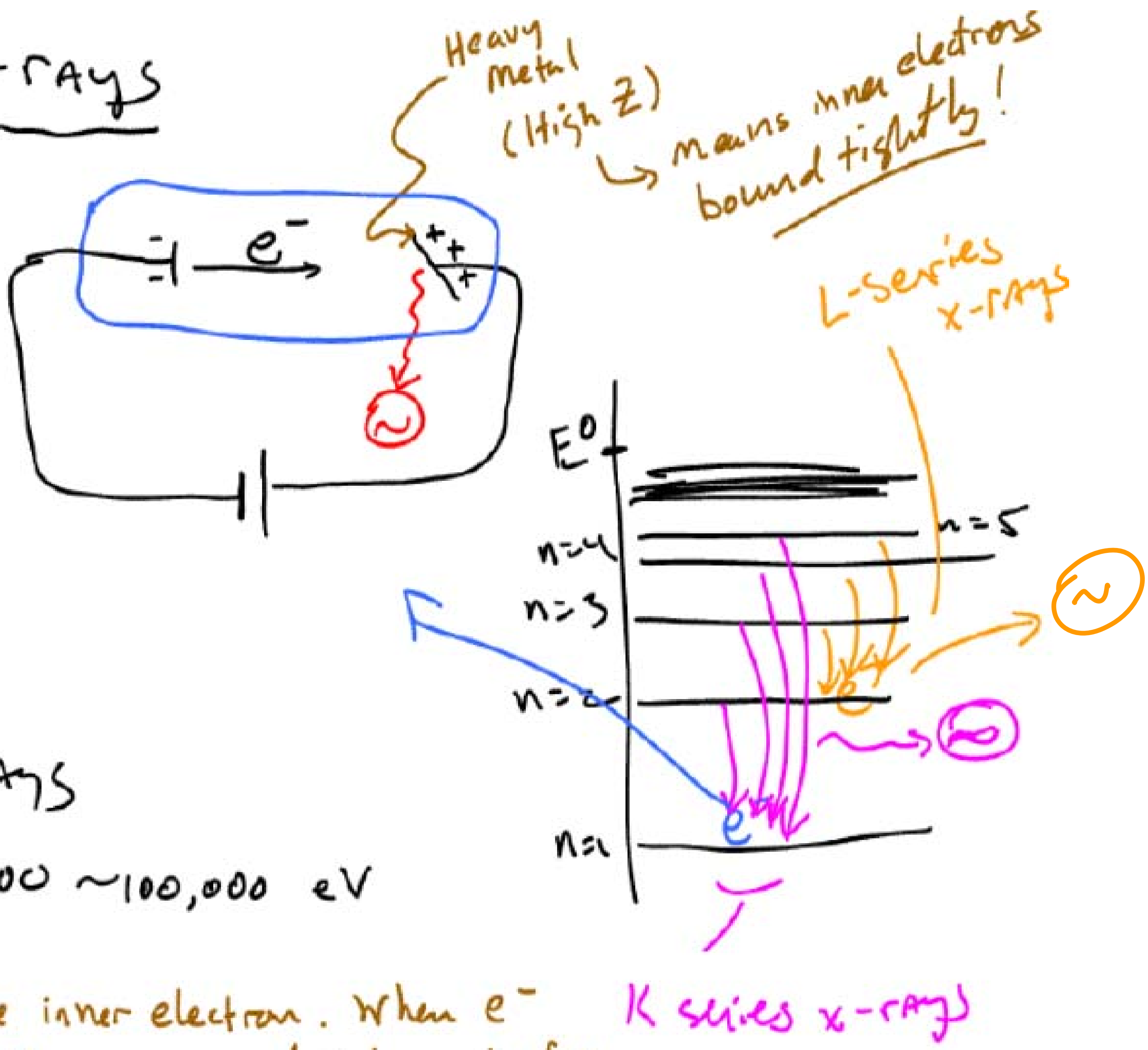
→ different discrete frequency pattern



© 1986 Saunders Publishing, "Physics for Scientists and Engineers with Modern Physics, 2/e" by Raymond A. Serway

Atomic Fingerprinting

X-rays



X-rays

100 ~100,000 eV

Remove inner electron. When e⁻ from higher n cascades down to fill open place in inner shell, high energy γ is emitted

Werner Karl Heisenberg
(1901 - 1976)

Nobel Prize in physics -1932
for "the creation of quantum Mechanics"
(Max Born, Pascual Jordan - co-workers)

Erwin Rudolf Josef Alexander Schrödinger
(1887 - 1961) AUSTRIA

1933 Nobel Prize in physics

1926 - Paper on wave Mechanics of Matter
Annalen der Physik

"For discovery of new and productive forms of atomic theory"

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} + U\psi(x) = E\psi(x)$$

Schrödinger's EQUATION → 1d

1-d

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} + U\psi(x) = E\psi(x)$$

Potential energy function

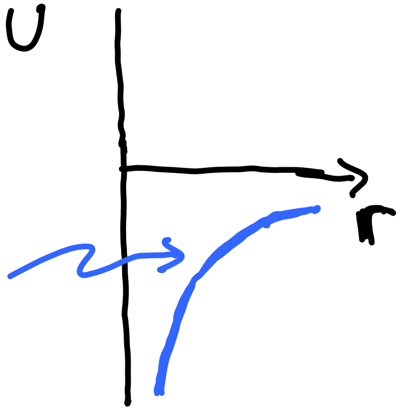
Pop in different U's

Solve for E and ψ

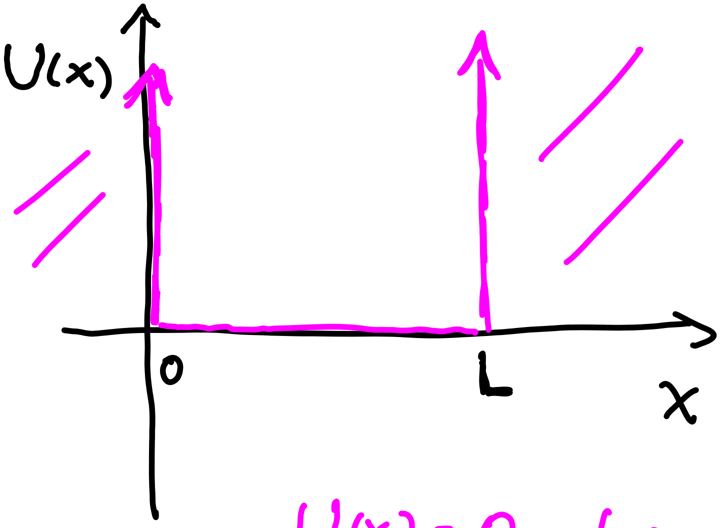
Example

Q· ·q

$$U = \frac{kQq}{r}$$



infinite Square Well potential



$$\frac{d^2\psi(x)}{dx^2} = -\underbrace{\boxed{\frac{2mE}{\hbar^2}}}_{\equiv k^2}\psi(x)$$

$U(x) = 0$ for $0 < x < L$

$U(x) = \infty$ for $x < 0$, $L < x$

$$\frac{d^2\psi(x)}{dx^2} = -k^2\psi(x)$$

SHM-ish

$F = -kx \rightarrow d^2x/dt^2 = -k/m\, x$