Atomic Physics

PHY 215
Thermodynamics and Modern Physics

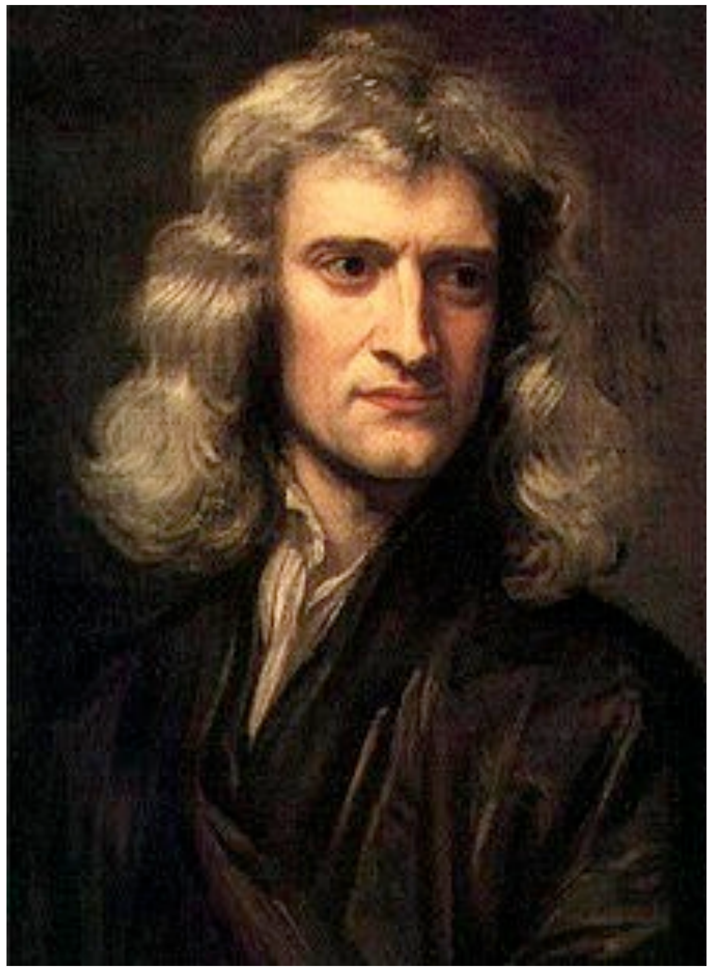
Spring 2026
MSU

Outline: Atomic Physics in “1900”

- Classical Physics in “1900” (and now!)
- What the Chemists Knew
- Brownian Motion - atoms are real!
- Experiments:
  - New Particles: Electrons
  - New Radiation: X-rays & X-ray Diffraction
  - Elemental Transmutation: Radioactivity
- Atoms exist: how are they built?

Images: http://en.wikipedia.org

Classical Physics



Sir Isaac Newton

1643-1727

James Clerk Maxwell

1831-1879

Particles

$$\vec{F} = m\vec{a}$$

$$\vec{F}_G = -\frac{GMm}{r^2}\hat{r}$$

(& Thermodynamics)

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{j}_e$$

Waves

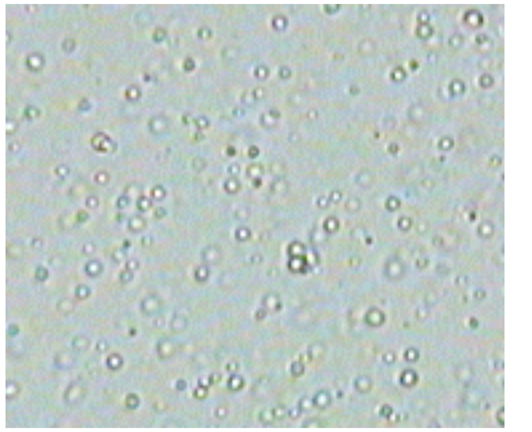
What the Chemists Knew

- Mass conserved in chemical reactions. (Lavoisier)
- Law of Multiple Proportions: Masses of elements that combine, and react completely, form whole-number ratios. (Dalton & Proust)
- Hydrogen is the lightest element.
  - Molecular weight: mass relative to H
- Atomic Hypothesis: everything made of discrete unites, atoms. What is N_A?

Concept Test

- The Modern View: Atomic mass arises mostly from
  - Electrons
  - Protons
  - Neutrons
  - Protons and Neutrons, & $m_p \approx m_n$ ←

Brownian Motion



- Random motion of large particles suspended in a fluid medium.
- Einstein (1905): Average kinetic energy of *large particles* is 3/2 kT! (equipartition!)
- Can't measure K.E. directly. (freq. collisions!)
- Langevin (1909): $$\langle x^2 \rangle = \frac{kT}{3\pi\eta a} t$$

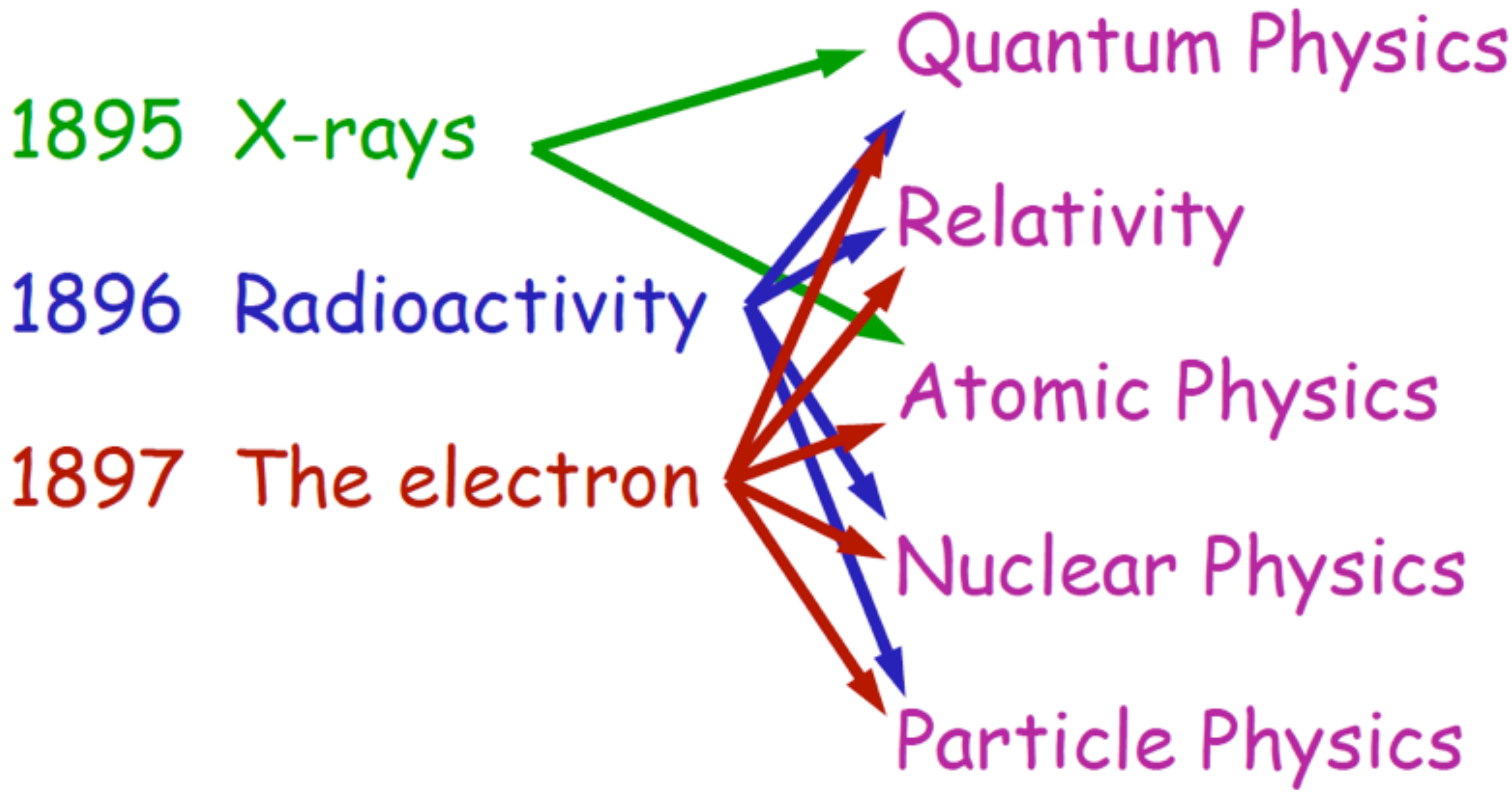
  η=viscosity

  a=particle diameter
- Perrin (1909): measure, find k, deduce $N_A = R/k$.

  Nobel Prize: 1926
- Establishes atomic hypothesis.

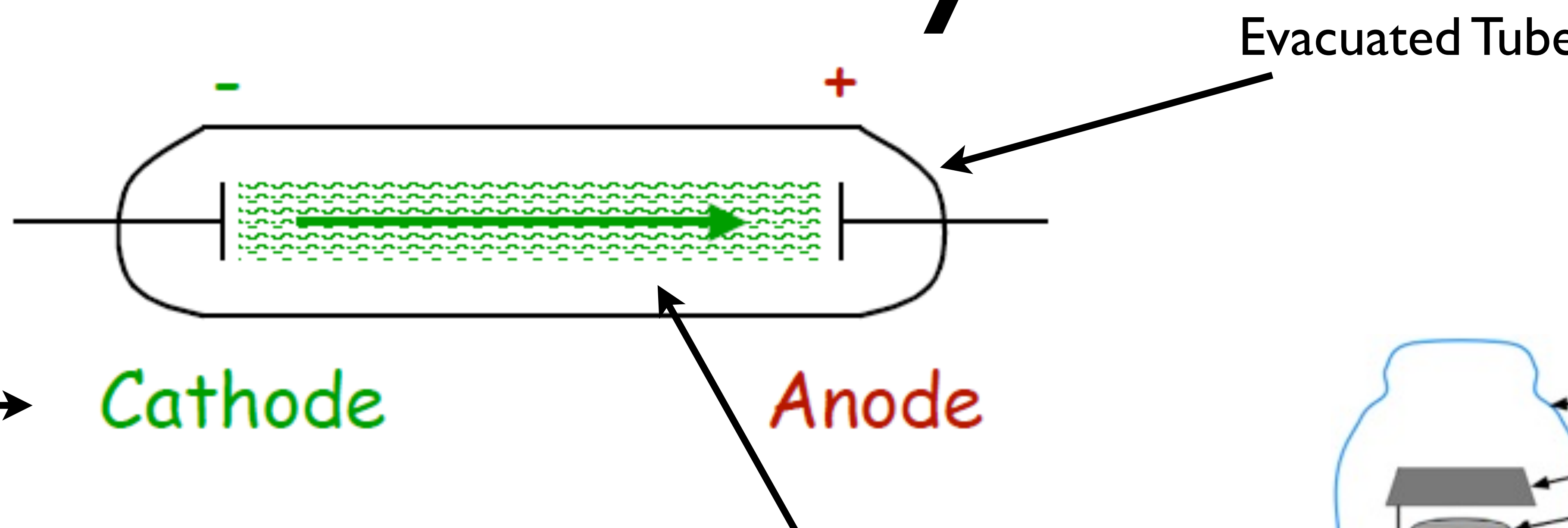
Image: http://www.microscopy-uk.org.uk/dww/home/hombrown.htm

Experiments

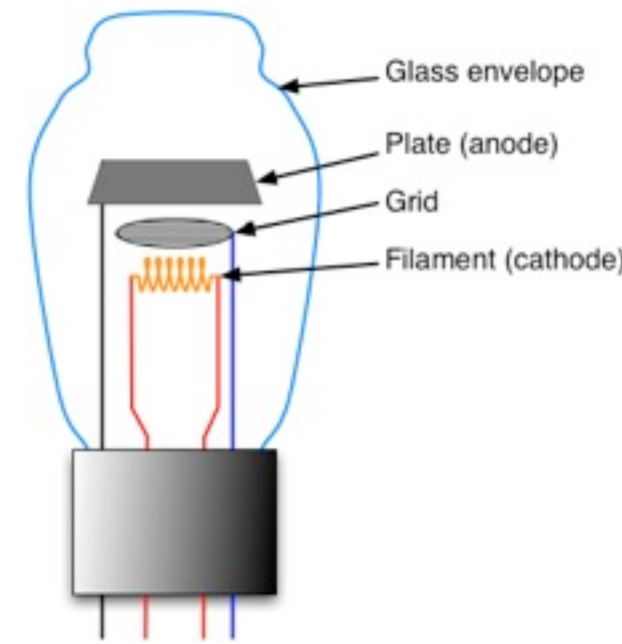


Cathode Ray Tubes

Apply voltage to electrodes



- Plucker (1858-1859) - glow moves with a magnet.
- Hittorf (1869) - objects in front of cathode cast shadows
- Goldstein (1876) coins term "cathode rays"



Vacuum Tube (Triode)

Demo

Concept Test

- Cathode ray tubes used to be common elements of radios, televisions, and computers. Nowadays, these components have been replaced by
  - Resistors
  - Capacitors
  - Transistors ←
  - Power Supplies

The Electron!

J.J. Thomson (1856-1940)

- In 1897 he proved conclusively that cathode rays were indeed streams of negatively-charged particles.

-obtained better vacuum

-deflected the rays by both
electric and magnetic fields.

-able to calculate

$$\frac{\text{Charge}}{\text{Mass}} = \frac{e}{m} = 1.7 \times 10^{11} \text{ Coulombs/kg}$$

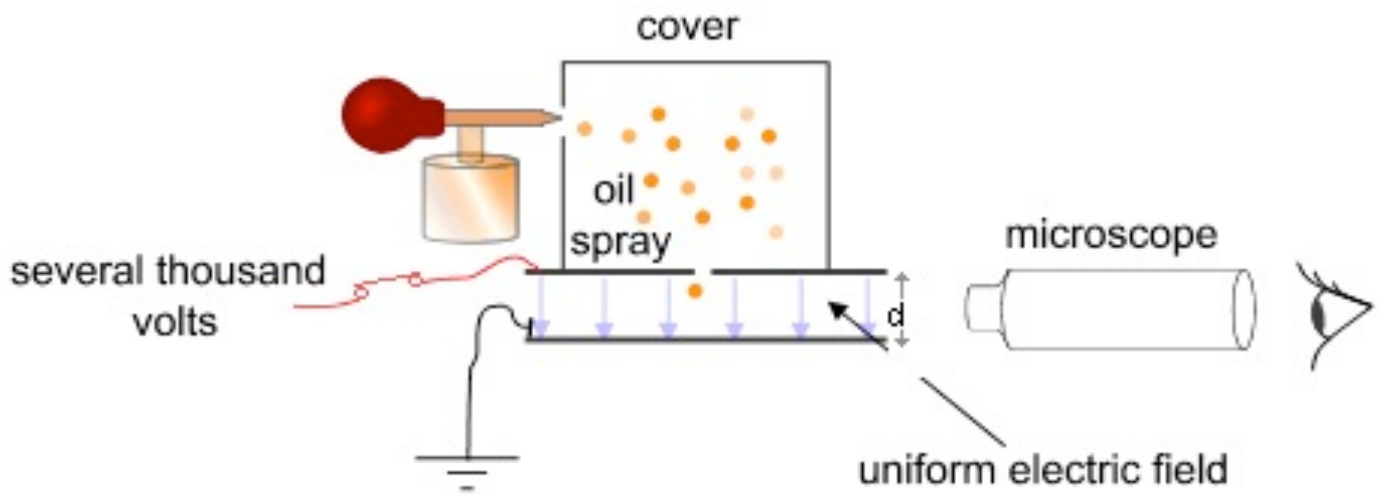
(about 2000 times larger than that of Hydrogen atom)

large charge or small mass!

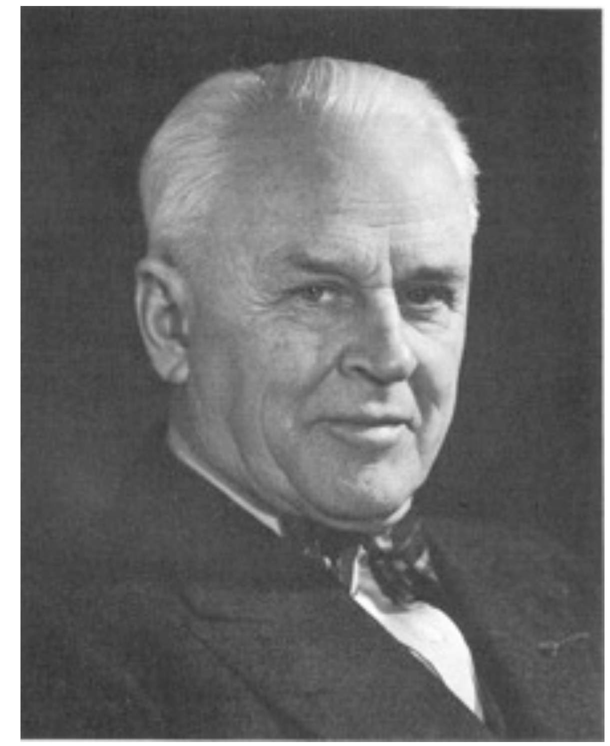
J J Thomson
1856-1940
Nobel Prize: 1906

Image: http://en.wikipedia.org

Charge of the Electron



Oil Drop Experiment (1909)



Robert Millikan
1868-1953
Nobel Prize 1923

Suspend charged oil drops falling in gravity with electrostatic field

- Measure Radius
- Suspend Drop in E field

$e = 1.602\ 176\ 53(14) \times 10^{-19}$ C

electron charge: -e

Image: http://en.wikipedia.org

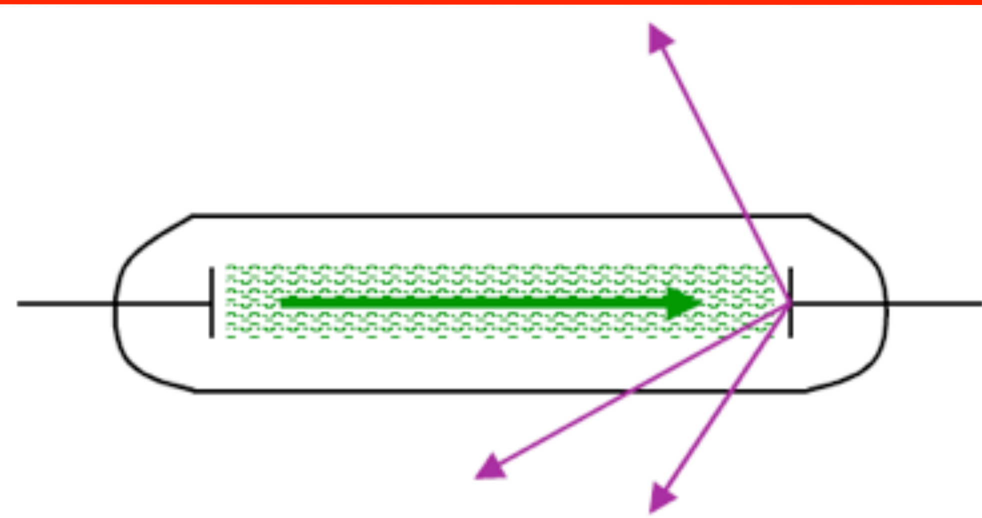
X-Rays

- Roentgen (1895) studying cathode ray tube, noticed glass tubing glowing some distance away.

- He covered the tube with black paper in a dark room. A flourescent screen lit up, even if faced away from the discharge tube.

-Then he placed his hand between the discharge tube and the screen and saw the shadow of his bones!

⇒ X-Rays! (later shown to be high frequency electromagnetic waves)

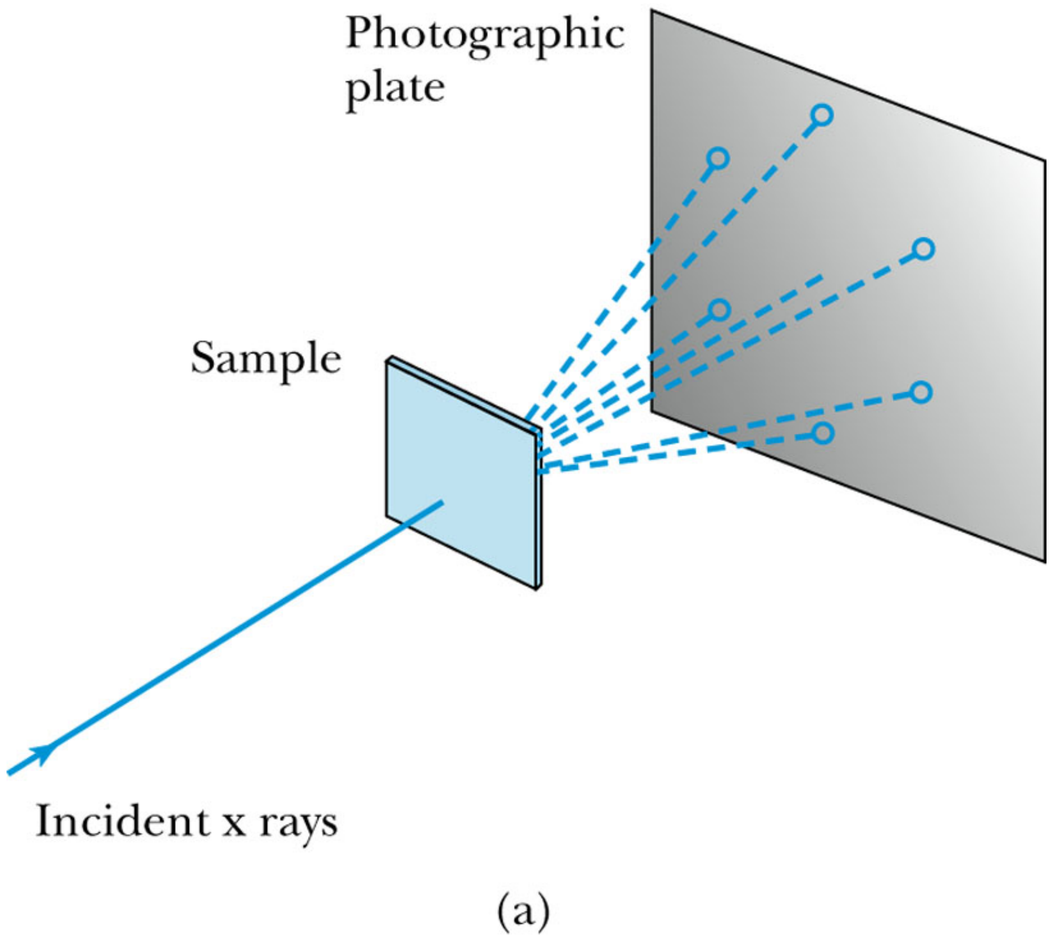


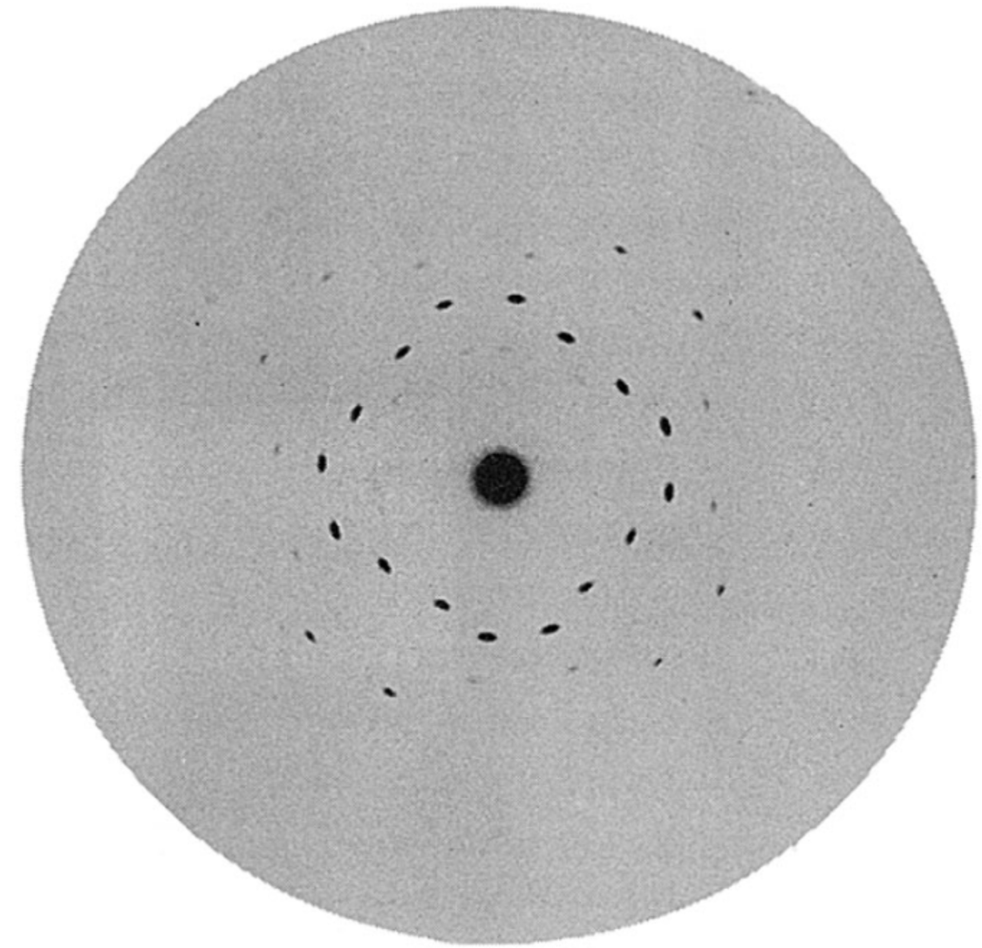
Wilhelm Röntgen
1845-1923
Nobel Prize 1901
(the first one!)

Images: http://en.wikipedia.org

X-Ray Scattering

Max von Laue
1879-1960
Nobel Prize 1914



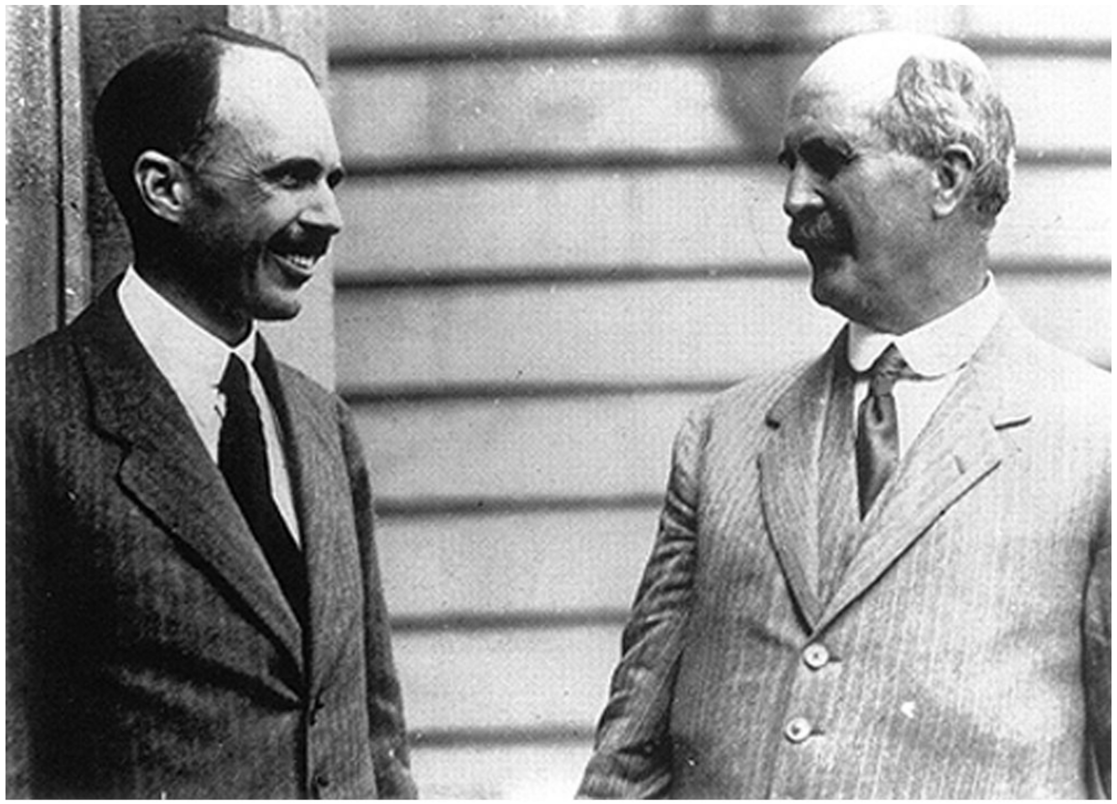


(b)

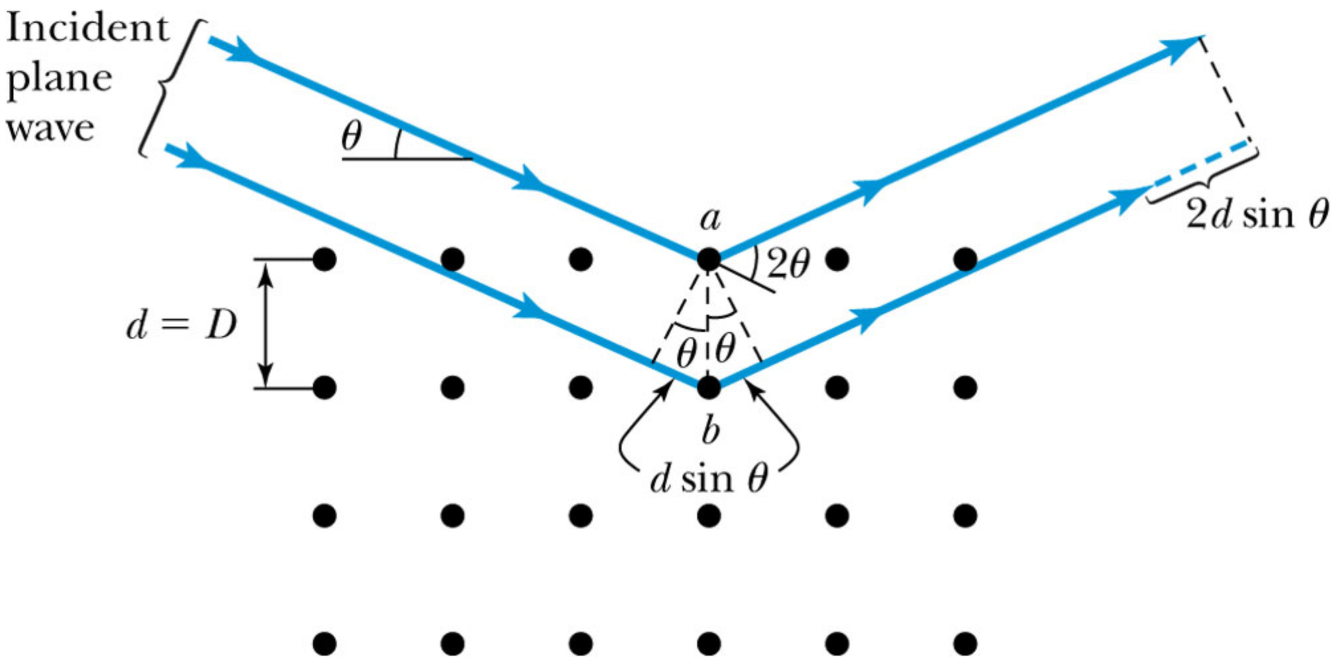
$\lambda_{\text{X-ray}} \approx$ atomic spacing

Images: Thornton and Rex

Bragg Diffraction



William Lawrence Bragg
1890-1972
William Henry Bragg
1862-1942
Nobel Prize 1915



Crystals are a regular array of atoms!

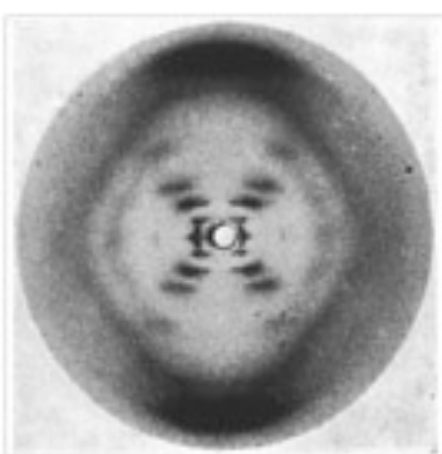
Bragg's Law:

$$n\lambda = 2d\sin\theta$$

Images: Thornton and Rex

Example: DNA

- X-ray crystallography is used to determine the arrangement of atoms in a crystal.
- Sodium salt of DNA:



Franklin & Gosling,
Nature 171: 740-741

Rosalind Franklin
1920-1958

Francis Crick
1916-2004

James Watson
1928 -

Nobel Prize: 1962

Images: http://en.wikipedia.org

Radioactivity I

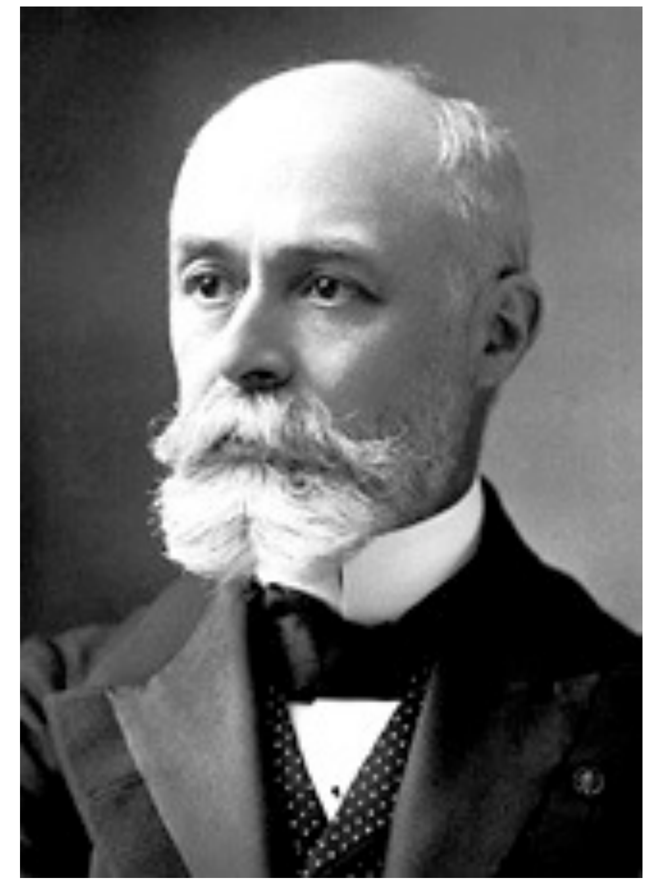
- Becquerel (1896) was testing various flourescent materials to see if they emitted X-rays.

- He sealed a photographic plate in black paper and sprinkled a layer of Uranyl Potassium sulfate onto the paper.

- He wanted to expose the salt to sunlight in order to make it flouresce, but that day Paris was gray and overcast.

-Despite this images exposed with great intensity.

-The new phenomenon was named "radioactivity" by Marie Curie.



Antoine Henri Becquerel
1852-1908
Nobel Prize 1903

Image: http://nobelprize.org

Radioactivity II

β-rays: electrons (Becquerel, 1900). They have a range of energies and are fast and penetrating. Can be absorbed by ~1 mm of lead.

α-rays: Helium nuclei (Rutherford, et al). They are heavy, slow, positively-charged particles. Absorbed by ~few cm of air.

γ-rays: Electromagnetic radiation, with a higher frequency, lower wavelength, even than X-rays.

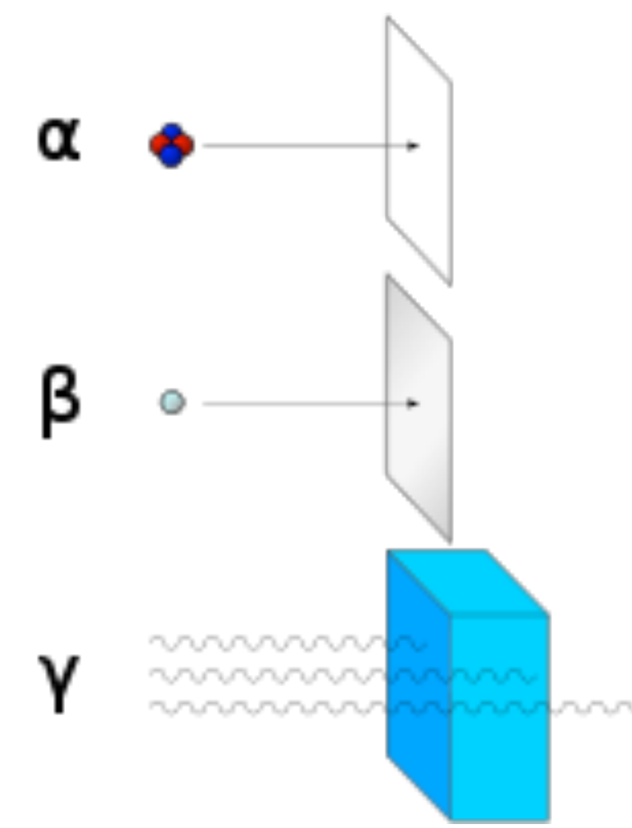


Image: http://en.wikipedia.org

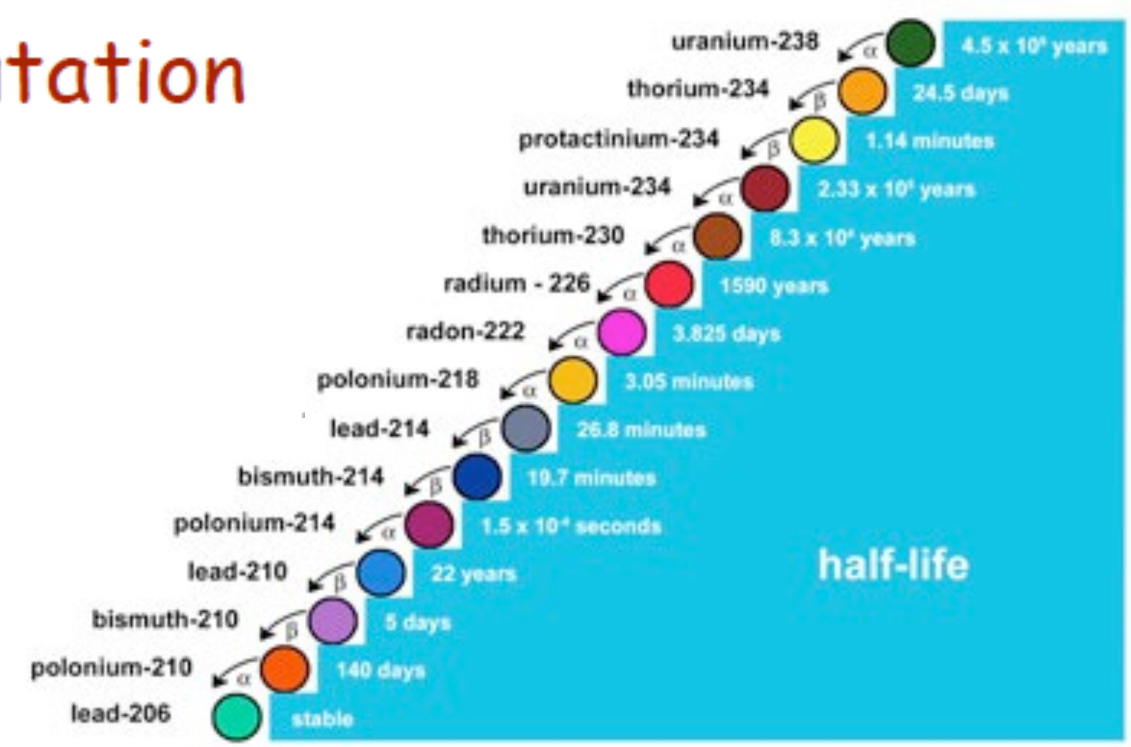
Transmutation

Pierre and Marie Curie found new radioactive elements, including Thorium, Polonium, and Radium.

A considerable amount of chemistry detective work, especially by the Curies, Rutherford, and Soddy led to a remarkable conclusion:

Every Radioactive decay is a transmutation of the elements, a change from one element to another.

Marie Skłodowska-Curie
1867-1934
Nobel Prize 1903, 1911



Images: http://en.wikipedia.org
http://www.ocrwm.doe.gov

Concept Test

- Elemental transmutation is induced on the MSU campus frequently at the following location:
  - Holmes Hall
  - NSCL ← National Superconducting Cyclotron Laboratory
  - Biomedical Physical Sciences Building
  - Administration Building

Atoms Exist: Questions Remain!

- What is the structure of the atom?
  - Electrons and what?
  - Radioactivity and Elemental Transmutation?
- Do the laws of classical physics apply?

Understanding the answers to these questions will take most of the rest of the semester!

Atomic Physics

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Fall 2025
MSU

Outline

- Blackbody Radiation
- Planck’s Formula
- Photoelectric Effect
    - X-Ray Production
- Compton Scattering
- Summary

Blackbody Radiation

As an object gets hot, it radiates energy.

How does the radiation depend on temperature?

What is the distribution among frequencies (or wavelengths)?

$\lambda\downarrow$ as $T\uparrow$

$I(\lambda,T)$ = Intensity as a function of wavelength λ and temperature T

Two experimental facts:

1) $\lambda_{max} T = 2.898 \times 10^{-3}\ m \cdot K$

(Wien's displacement law)

2) Total Power (per unit Area)

$$R(T) = \int_0^\infty I(\lambda,T)\, d\lambda$$

given by

$$R(T) = \varepsilon\sigma T^4$$

with $\varepsilon=1$ for blackbody radiator (Stefan-Boltzmann law)

$\sigma = 5.67 \times 10^{-8}\ W/(m^2 \cdot K^4)$

http://nationalgeographic.com

Concept Test

- A blacksmith heats an iron rod which starts to radiate, beginning red, then orange, then yellow, and ultimately white. As the iron becomes hotter, the color changes because
  - Red light has a longer wavelength than blue light ←
  - Red and blue light have the same wavelength
  - Blue light has a longer wavelength than red light

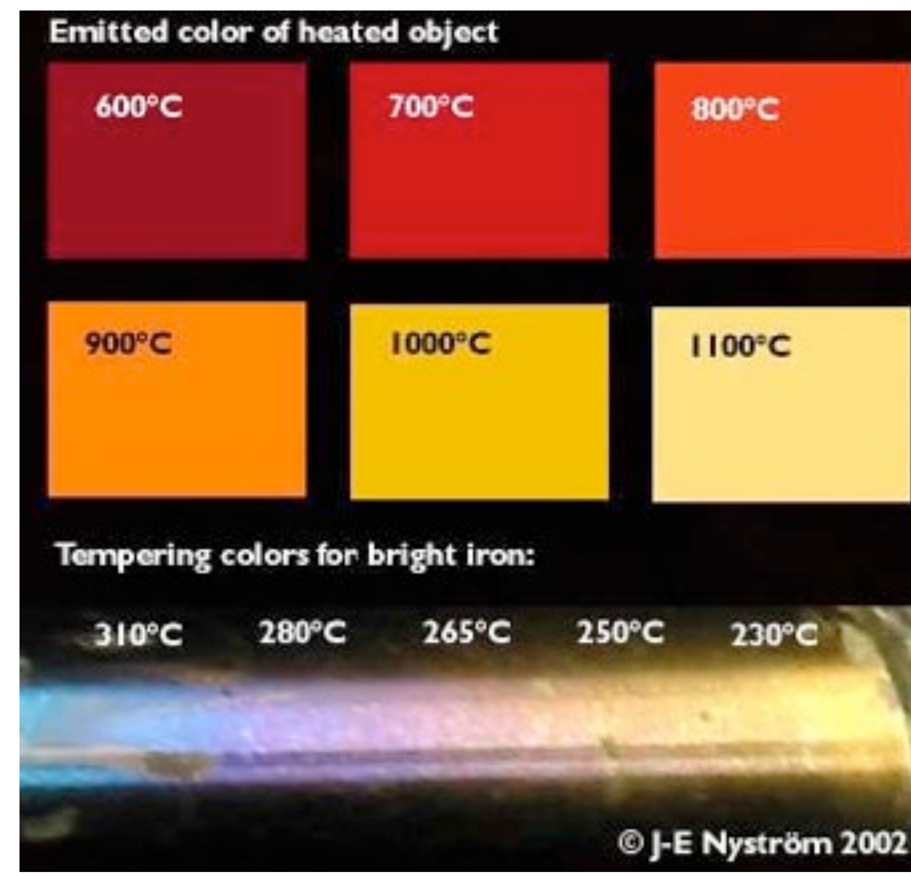
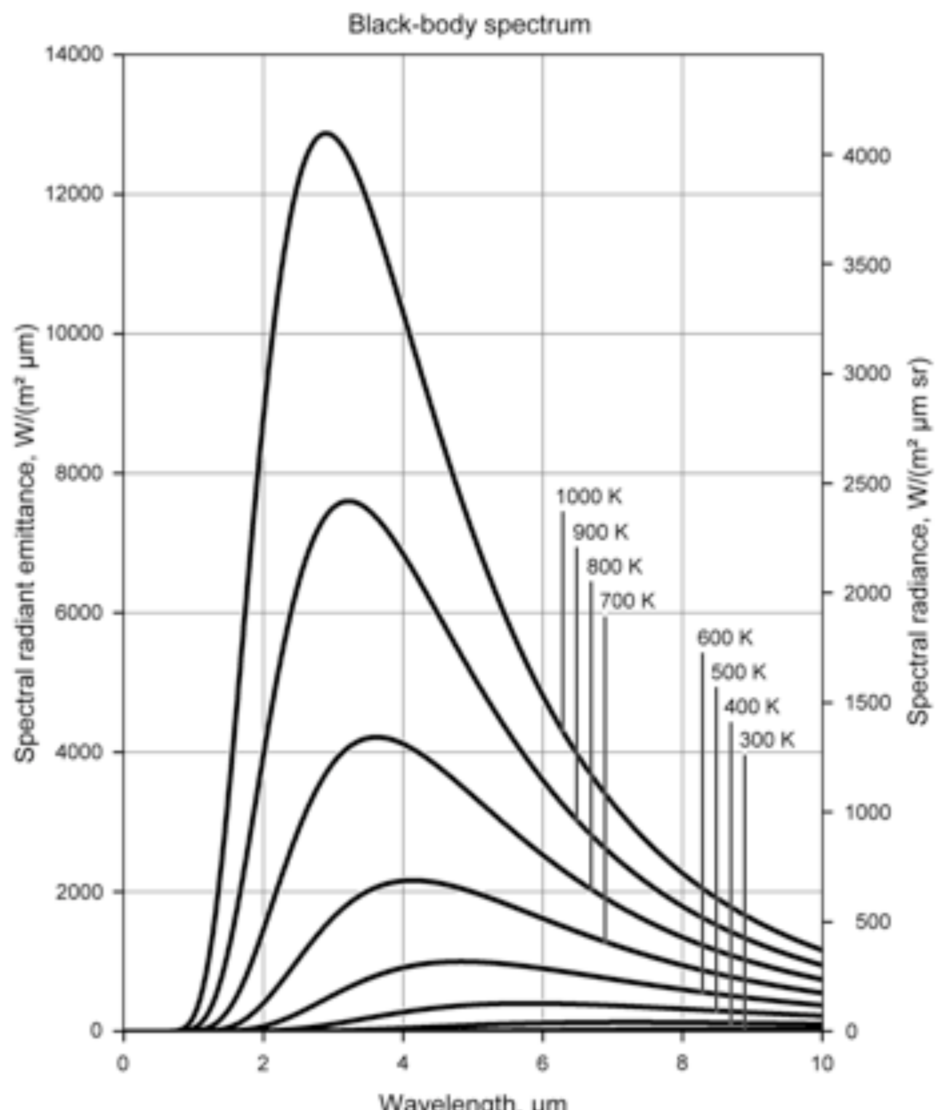
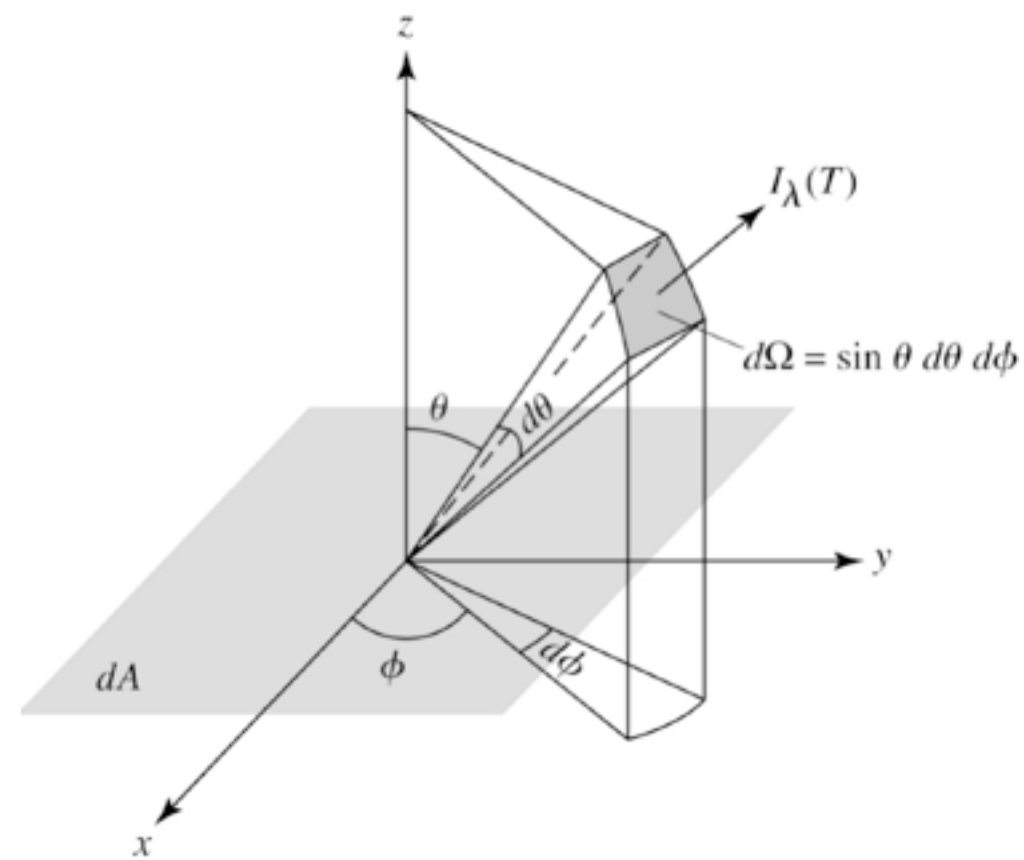


Image: http://www.saunalahti.fi

Blackbody Spectrum

I(λ,T)





$$I(\lambda, T) = \frac{dE}{d\Omega\, dA\, d\lambda\, dt} \neq \frac{2\pi c k T}{\lambda^4}$$

Lord Rayleigh and Sir James Jeans tried to explain the distribution using equipartion of energy: the average energy in each mode of oscillation of the radiation is kT/2.

Image: http://commons.wikimedia.org

Image: http://wesfiles.wesleyan.edu/courses/astr231

Planck's Formula

Each oscillation mode can not absorb just any amount of energy. Each mode can only absorb energy in packets of fixed size.

It described the data perfectly!

The size of each energy packet (now termed a quantum) is proportional to the frequency of the mode:

$E = h\nu$

$E \propto$ Frequency!

The proportionality factor (Planck's constant) is

$h = 6.63 \times 10^{-34}$ J s.

The above formula was first presented at a meeting of the German Physical Society on Dec. 14, 1900.
The birthday of Quantum Physics!

Light comes in discrete quanta! Photons

Max Planck
1848-1947
Nobel Prize 1918

$$I(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Image: http://wikipedia.org

Planck's Constant

The energy in each frequency mode ν can only come in integer multiples of some fundamental unit (quanta):

$$E = h\nu$$

with

$$h = 6.6261 \times 10^{-34}\ \text{J}\cdot\text{s}$$
$$= 4.1357 \times 10^{-15}\ \text{eV}\cdot\text{s}$$

$$1\ \text{V} = 1\ \text{J/C}$$
$$e \approx 1.6 \times 10^{-19}\ \text{C}$$
$$1\ \text{eV} \approx 1.6 \times 10^{-19}\ \text{J}$$

In a cathode ray tube, the change in potential energy of the electron is eV, where V is the voltage difference between cathode and anode.

Thus, eV is the Kinetic Energy of the electron when it hits the anode.

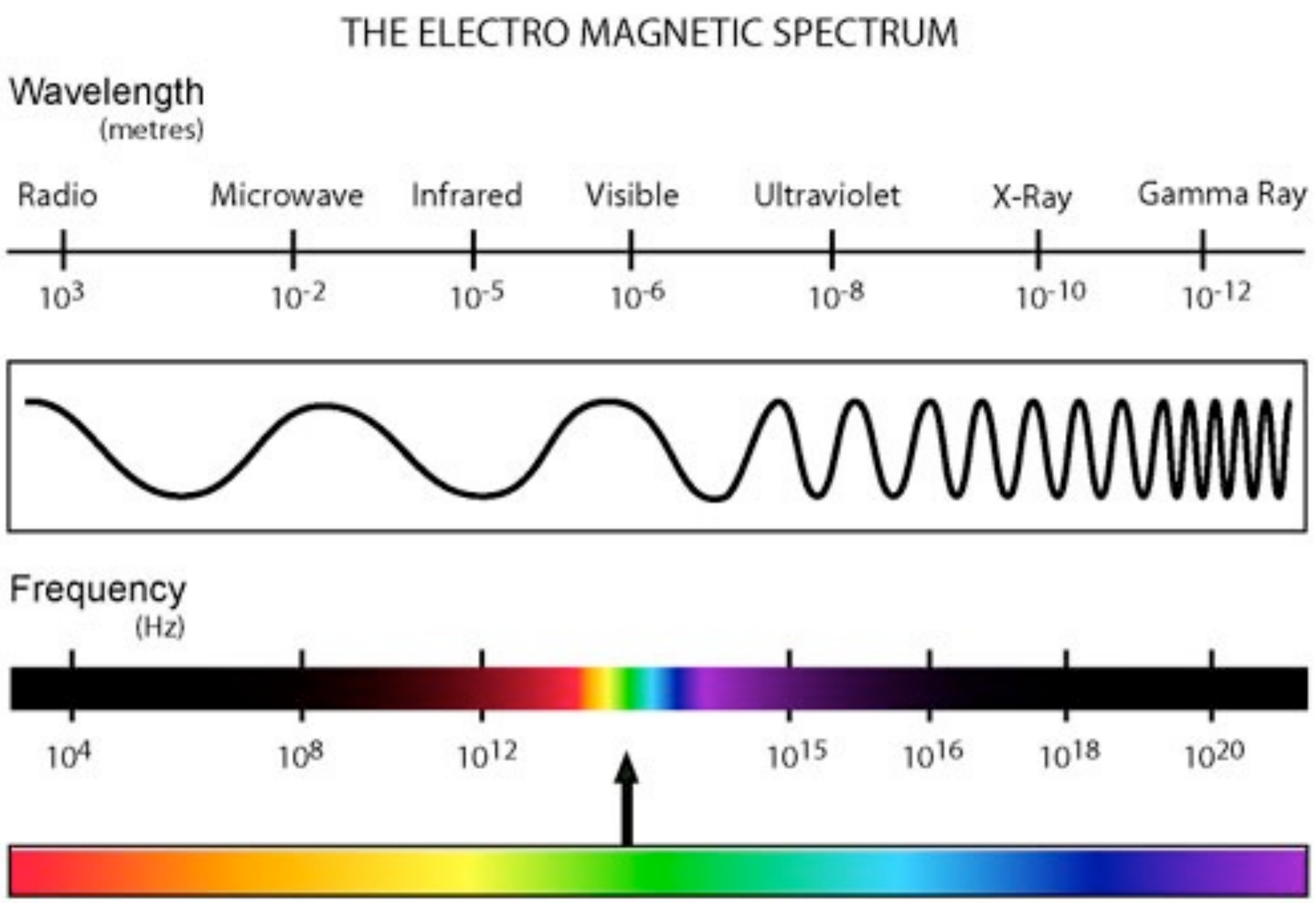
If all of this energy is converted into a single quantum of X-ray radiation (called a photon), then the photon would have a frequency given by

$$\nu = eV/h, \qquad \lambda = c/\nu$$

This is the maximum frequency X-ray that could be emitted in the process.

For example, 2000 V $\longrightarrow$ $\lambda = 0.621$ nm

Light Quanta?



James Clerk Maxwell
1831-1879

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{j}_e$$

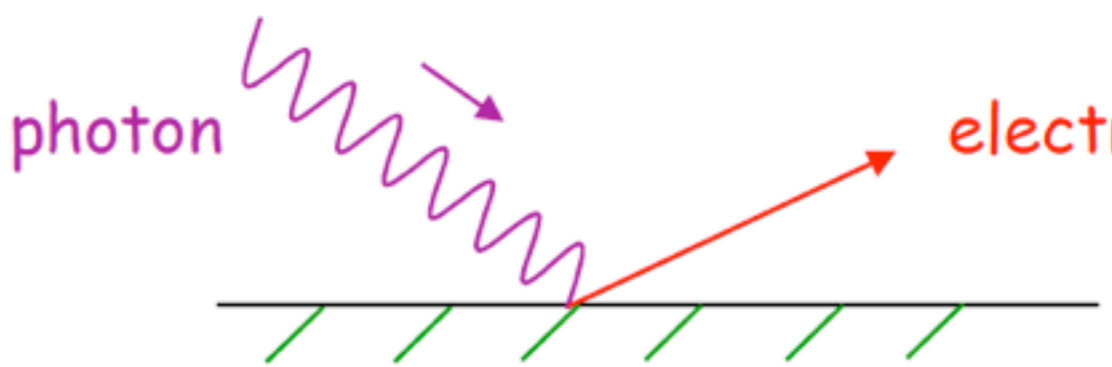
Classically:
EM Radiation = Waves
Energy $\propto$ (Amplitude)^2

Image: http://www.electrical-res.com, wikipedia.org

Photoeletric Effect I

1887 - Heinrich Hertz

Visible or UV light on metal surface may release electrons



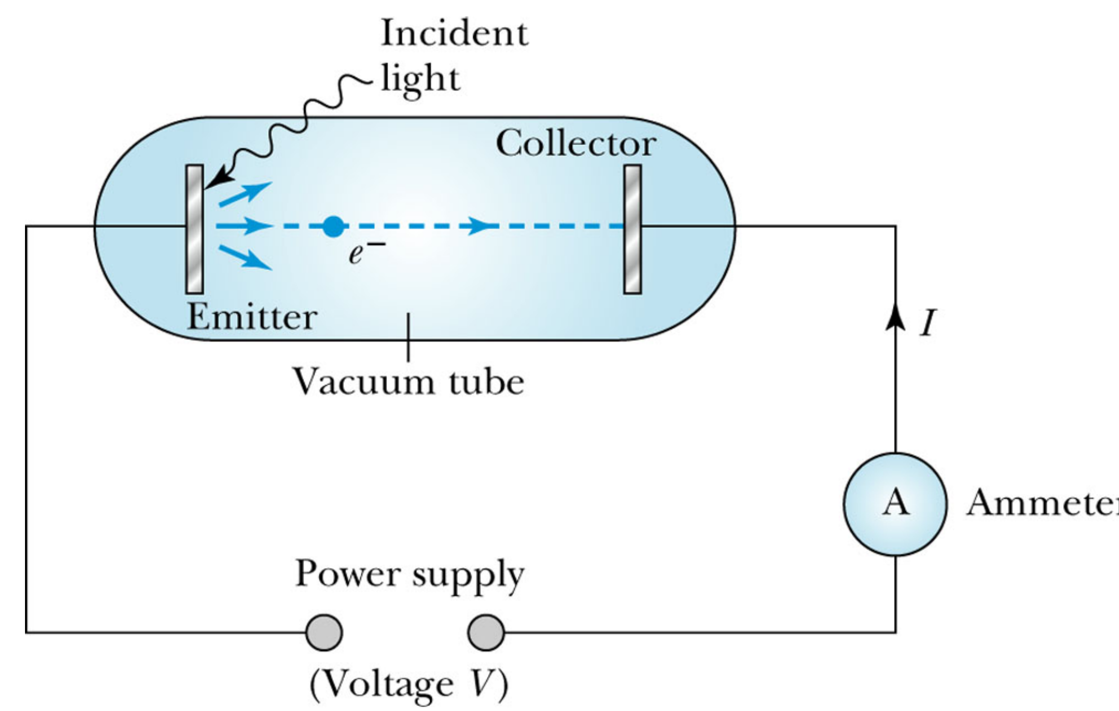
Classical theory says energy of electrons should increase with intensity of light.

However, this was not the case.

Classically:

EM Radiation = Waves

Energy $\propto$ (Amplitude)^2



Phillip Lenard
1862-1947
Nobel Prize 1905

Image: Thornton and Rex

Photoelectric Effect II

Experiments (Lenard) showed:

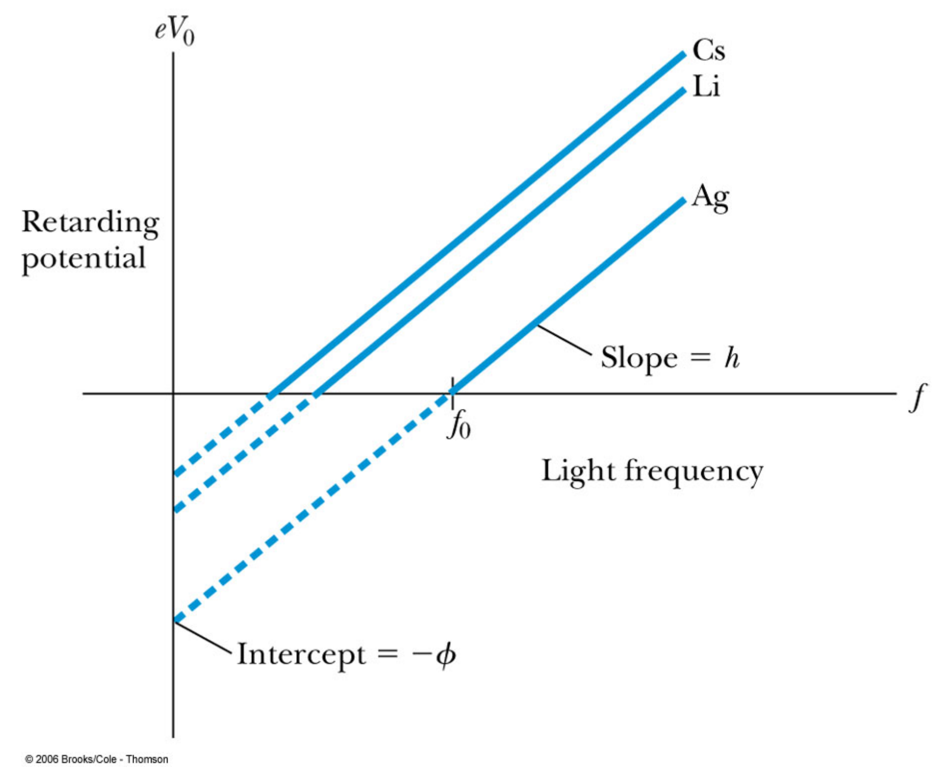
1) KE of photoelectrons depends only on ν (frequency) of light, independent of I (its intensity).

2) # of photoelectrons is proportional to I

3) For a given metal, there is a minimum ν, below which no photoelectrons are emitted.

4) The photoelectrons are emitted instantaneously, independent of I.

Classical theory could not explain these observations.



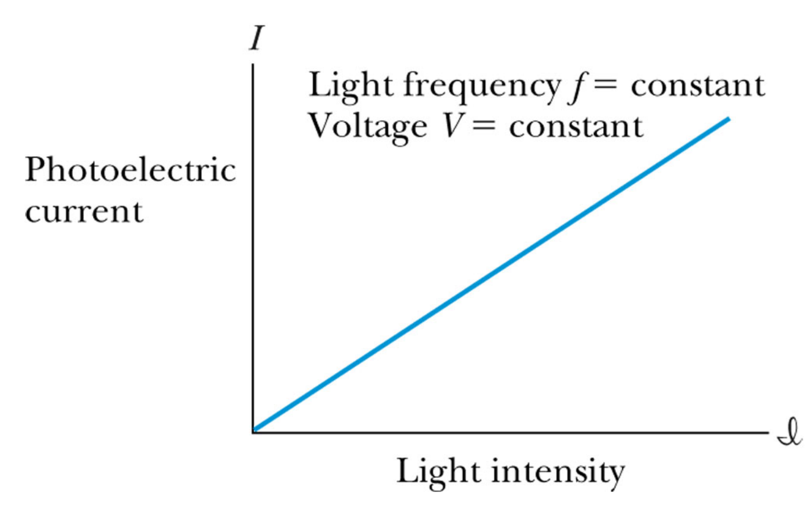


Image: Thornton and Rex

Concept Test

- In the photoelectric effect, if a fixed *frequency* of light shines on a metal, as the intensity of the light is increased
    - the number of electrons ejected increases ←
    - the energy of the ejected electrons increases
    - both the number and energy of the ejected electrons increases

Photoelectric Effect III

1905 - Einstein explained:

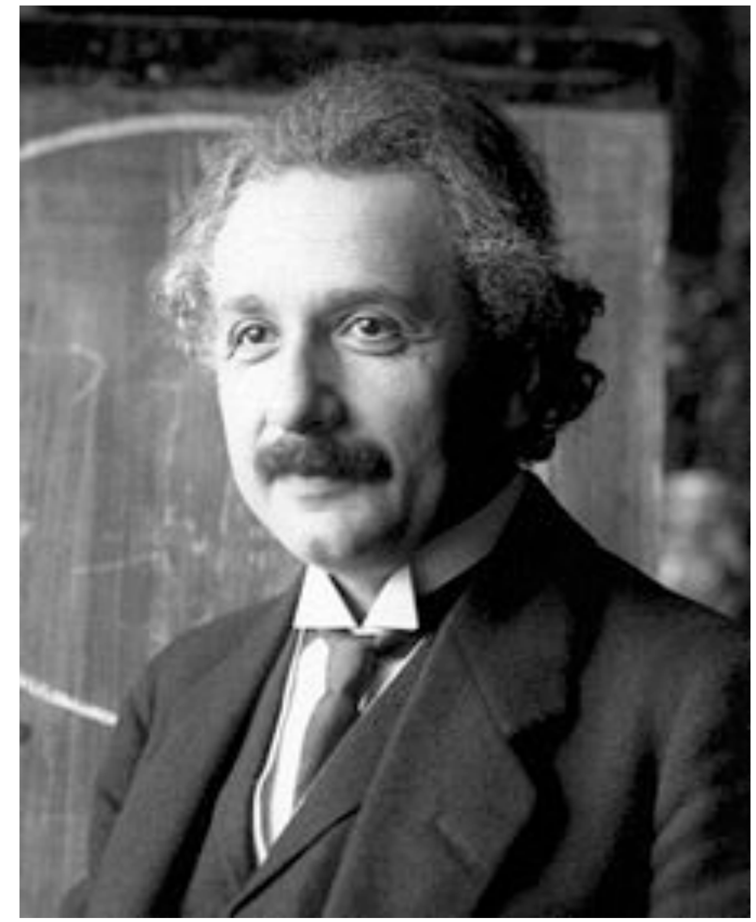
Electromagnetic radiation transferred in discrete bundles of energy ("photons"). The energy of each photon is

$$E = h\nu$$

The KE of an emitted photoelectron is

$$KE = h\nu - \phi$$

- $h\nu$ is Energy of the incident photon
- ϕ is the binding energy of electron to the metal surface (the work function).

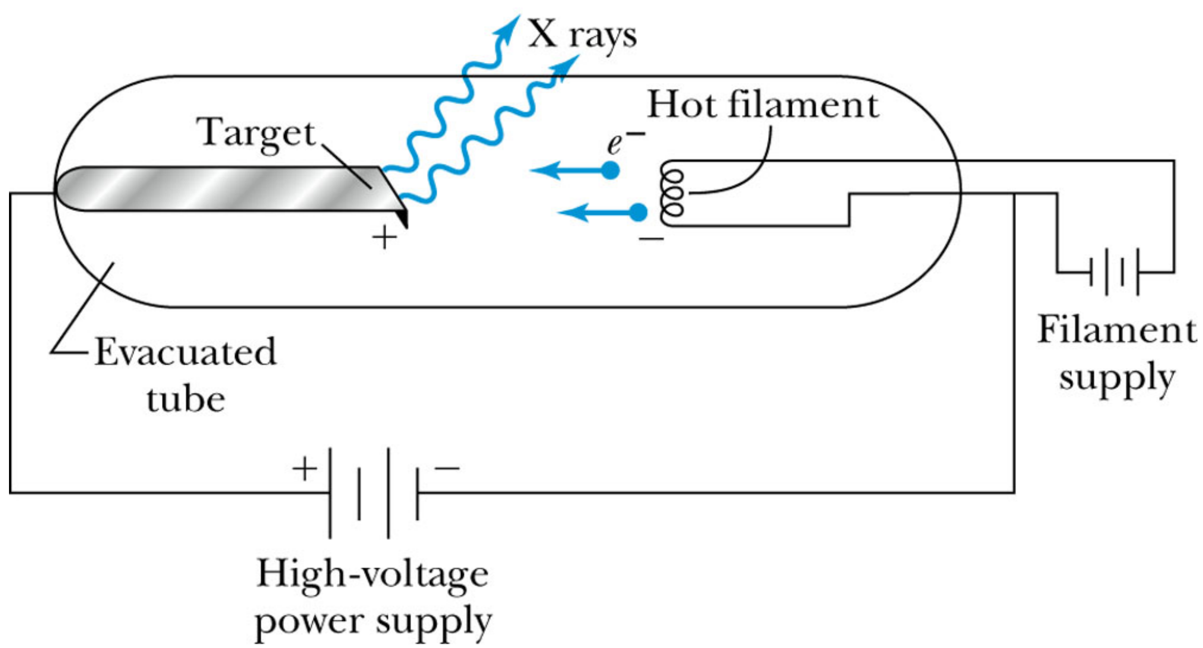


Albert Einstein
1879-1955
Nobel Prize 1921

Einstein extended Planck's hypothesis to explain the photoelectric effect!

X-Ray Production

Inverse photoelectric effect:

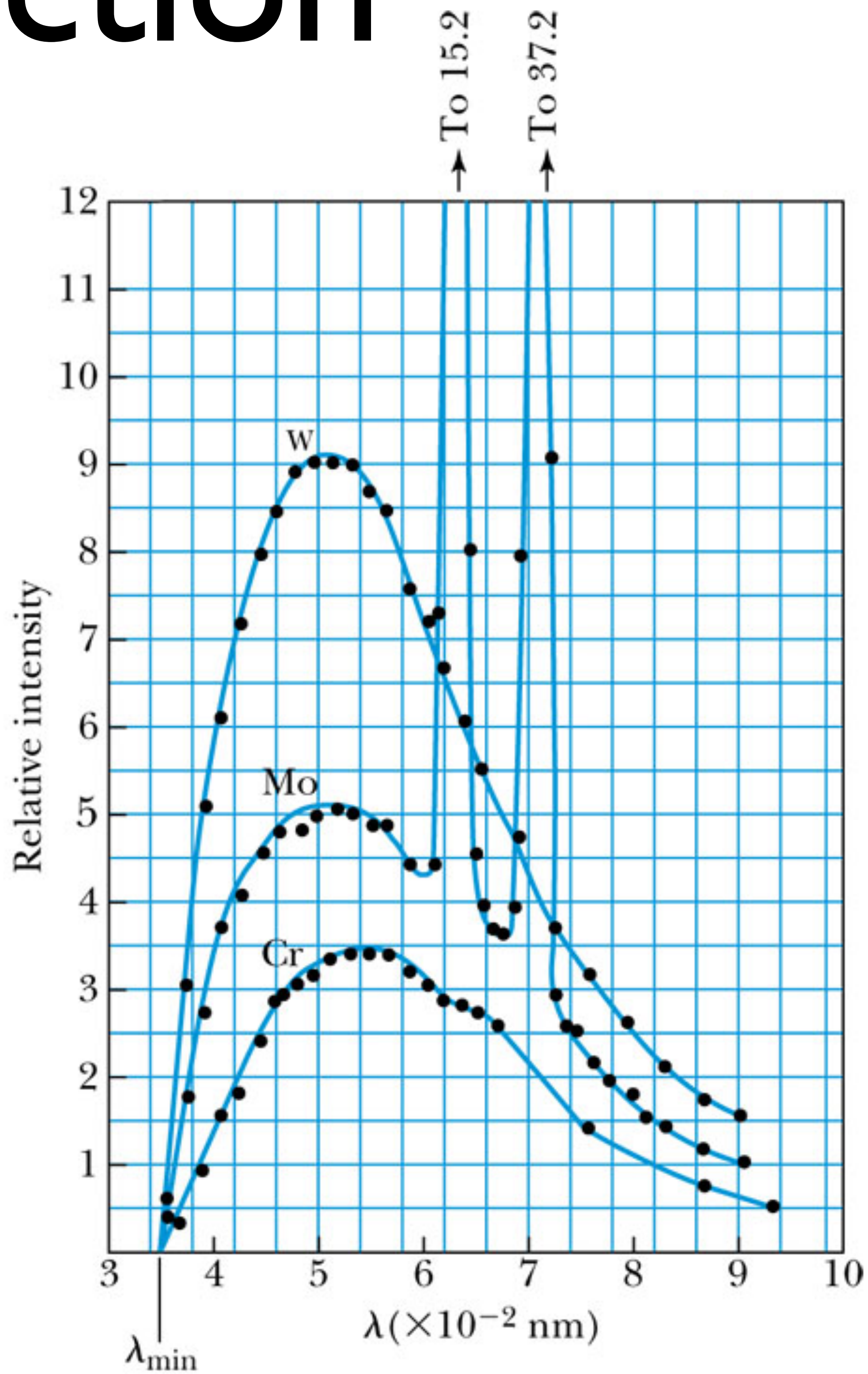


$$eV_0 = hf_{max} = \frac{hc}{\lambda_{min}}$$

Duane-Hunt limit

$$\lambda_{min} = \frac{hc}{e}\frac{1}{V_0} = \frac{1.240\times10^{-6}\ \mathrm{V\cdot m}}{V_0}$$

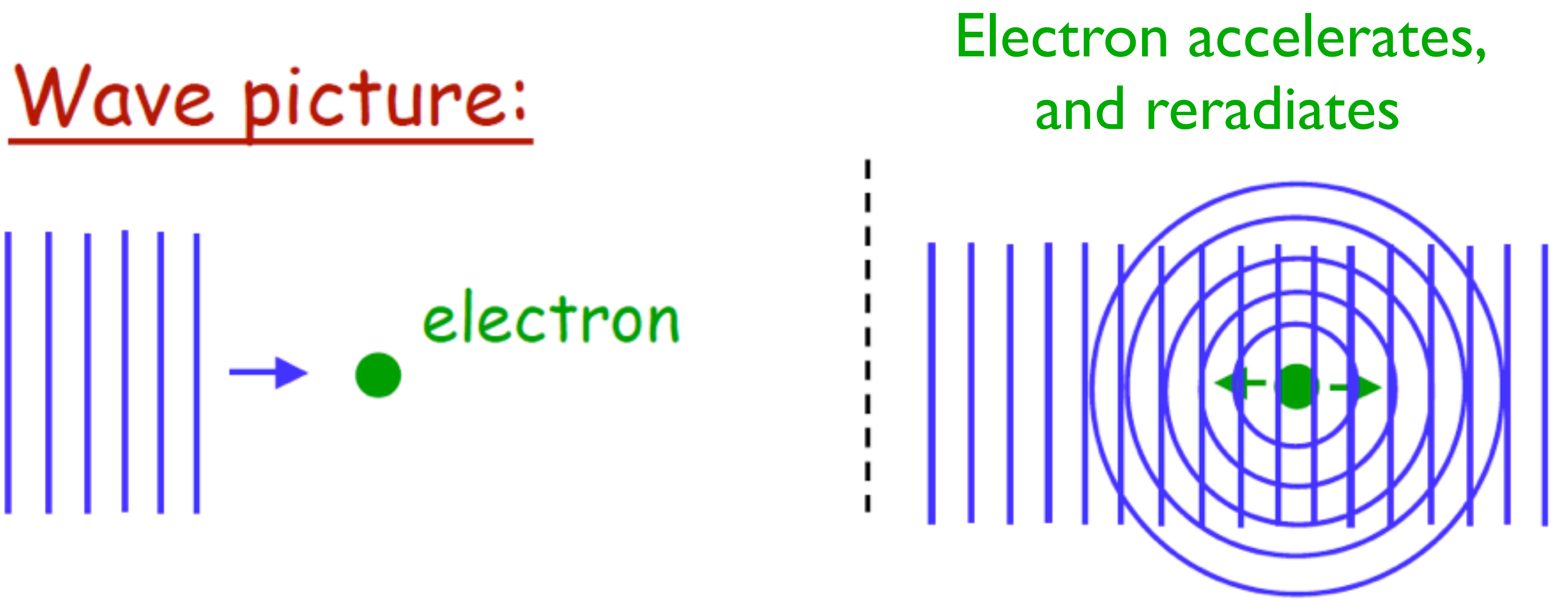
Maximum frequency related to maximum energy✓



Images: Thornton and Rex

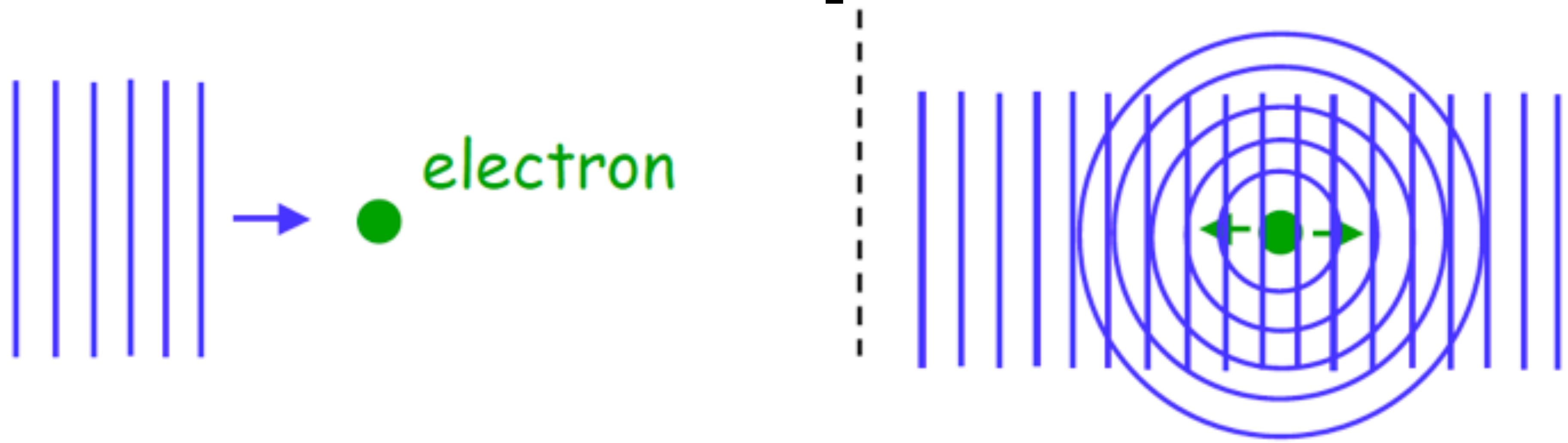
Compton Scattering I

Classical Picture of Scattering of Light:



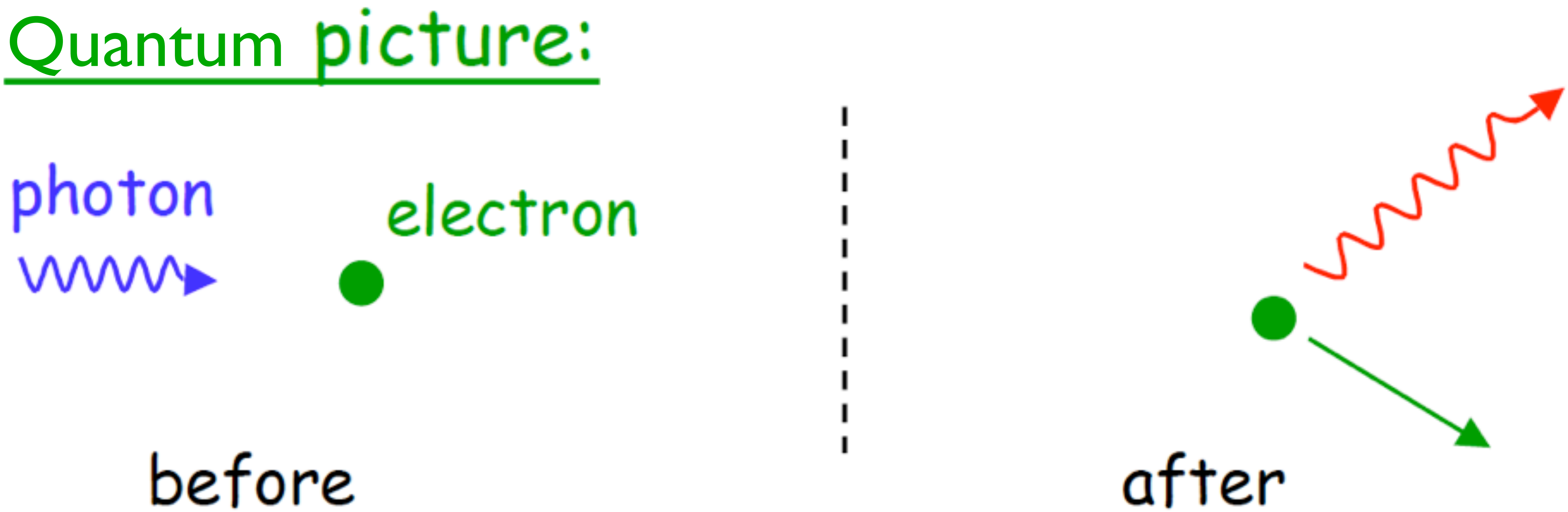
Light scatters off all electrons in metal, and scattered frequency same as incident frequency

Concept Test



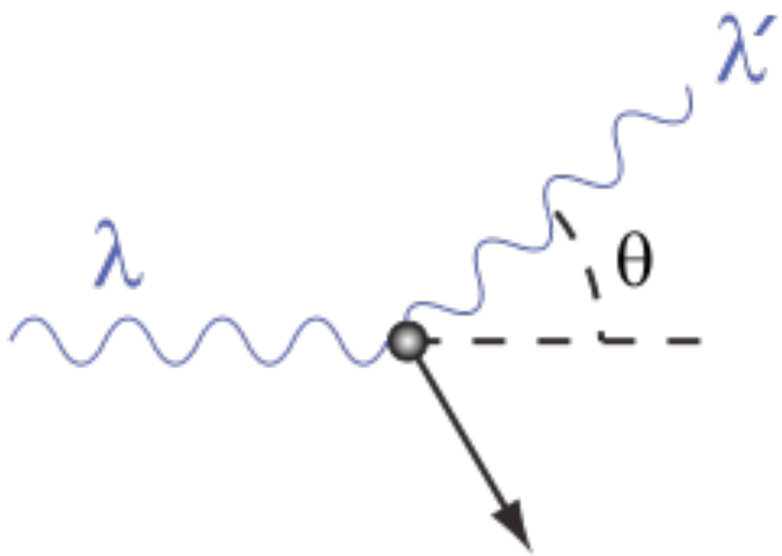
- Light is a transverse wave: the direction of the oscilliating E and B fields is perpendicular to the direction of propagation. What is wrong with the diagram above?
  - Light doesn't have to be blue
  - The electron is moving in the wrong direction ←
  - The scattered light is not a spherical wave
  - Electrons aren't green

Compton Scattering II



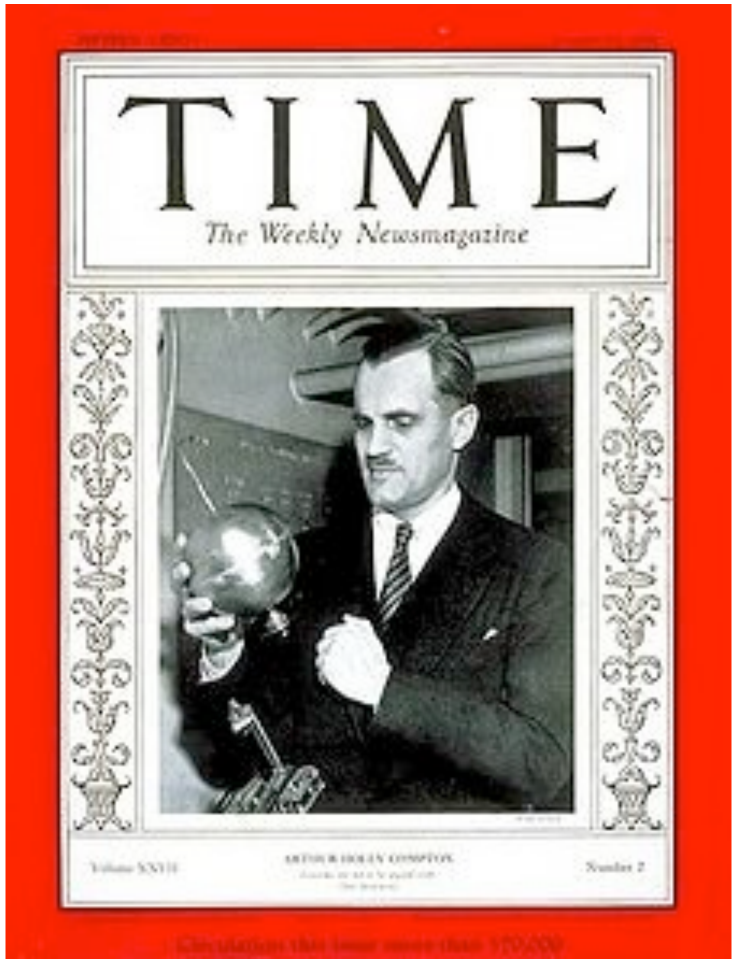
A quantum of light scatters of an electron, and can change energy and hence frequency

Compton Formula



$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

$$\frac{1}{E_\gamma} - \frac{1}{E'_\gamma} = \frac{1}{m_e c^2}(1 - \cos\theta)$$



Arthur Holly Compton
1892-1962
Nobel Prize 1927

Image: http://wikipedia.org

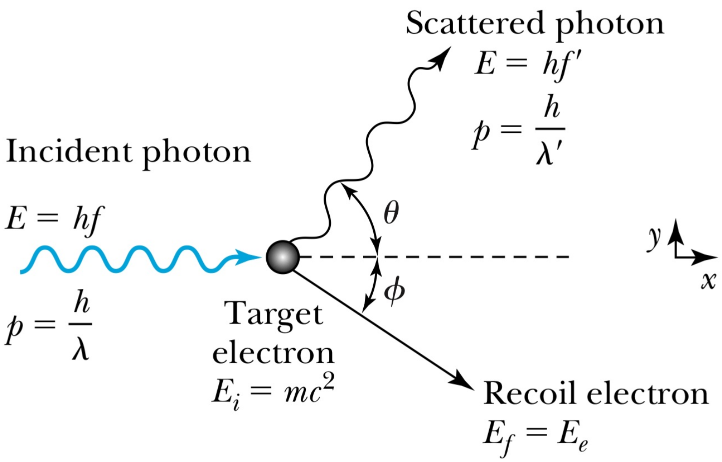


Table 3.4 Results of Compton Scattering

Energy or Momentum	Initial System	Final System
Photon energy	hf	hf'
Photon momentum in x direction (p_x)	$\frac{h}{\lambda}$	$\frac{h}{\lambda'}\cos\theta$
Photon momentum in y direction (p_y)	0	$\frac{h}{\lambda'}\sin\theta$
Electron energy	mc^2	$E_e = mc^2 + \text{K.E.}$
Electron momentum in x direction (p_x)	0	$p_e\cos\phi$
Electron momentum in y direction (p_y)	0	$-p_e\sin\phi$

In the final system the electron's total energy is related to its momentum by Equation (2.70):

$$E_e^2 = (mc^2)^2 + p_e^2c^2 \tag{3.39}$$

We can write the conservation laws now, initial = final, as

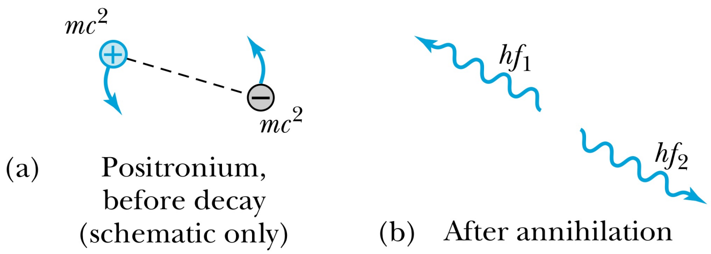
$$\text{Energy} \quad hf + mc^2 = hf' + E_e \tag{3.40a}$$

$$p_x \quad \frac{h}{\lambda} = \frac{h}{\lambda'}\cos\theta + p_e\cos\phi \tag{3.40b}$$

$$p_y \quad \frac{h}{\lambda'}\sin\theta = p_e\sin\phi \tag{3.40c}$$

momentum Conservation

Positronium (e^-e^+) decay at rest



(a) Positronium, before decay (schematic only)

(b) After annihilation

$$(e^-e^+)_{atom} \rightarrow \gamma + \gamma$$

two photons

ignore binding energy

e^+: positron; anti-particle of e^-

$$m_{e^+} = m_{e^-}$$

Energy $\quad 2m_e c^2 \approx hf_1 + hf_2$

Momentum $\quad 0 = \dfrac{hf_1}{c} - \dfrac{hf_2}{c}$

$$2m_e c^2 = 2hf$$

$$hf = m_e c^2 = 0.511 \text{ MeV}$$

A useful process for PET

Positron-Emission-Tomography

Summary

- Planck's formula, E=hν, explains
  - Blackbody Spectrum
  - Photoelectric Effect
  - X-ray Production
  - Compton Scattering

Light behaves both like a particle and a wave!

Light "particle" - Photon

Outline

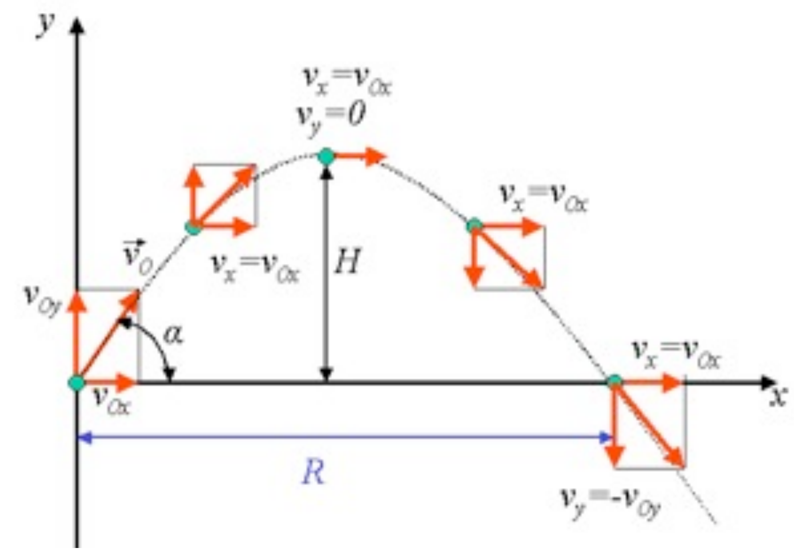
- Waves vs. Particles
    - Review of Wave Diffraction
- deBroglie Waves
- Davison and Germer
- Electron Double Slit

  Electrons Behave Like Waves!
- Complementarity

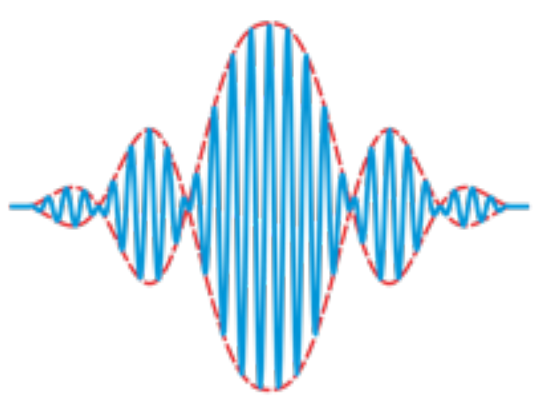
Particles vs. Waves

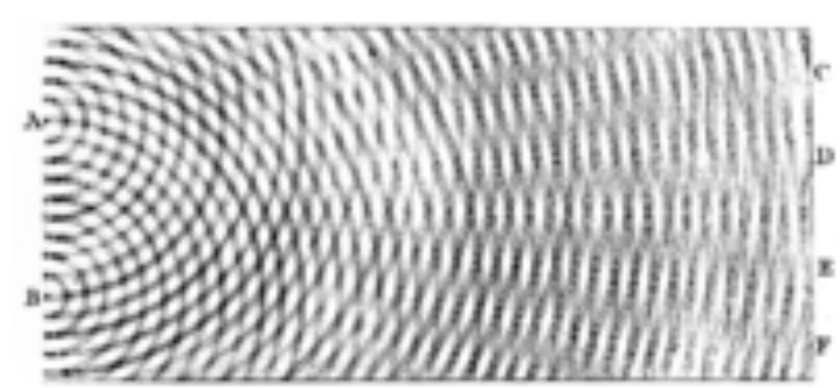
Property	Particle	Wave
Location	Definite	Indefinite
Momentum	Definite	Indefinite
Interference	No	Yes

Particle



Wave

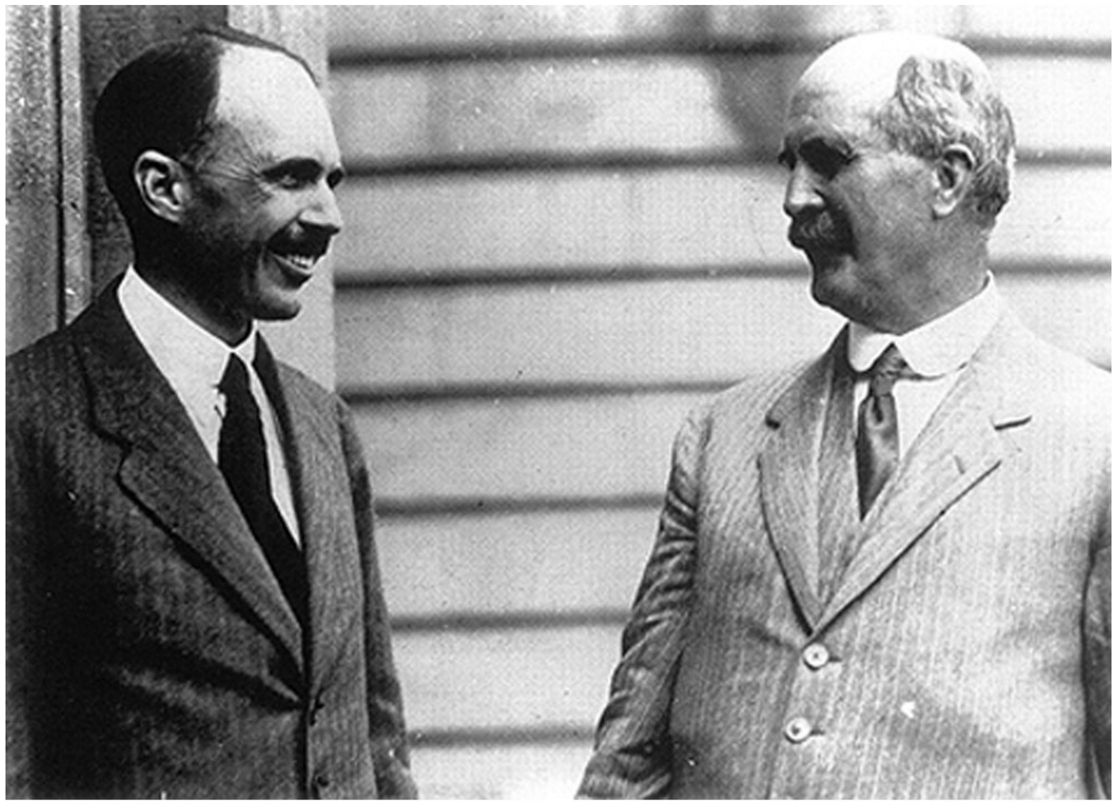




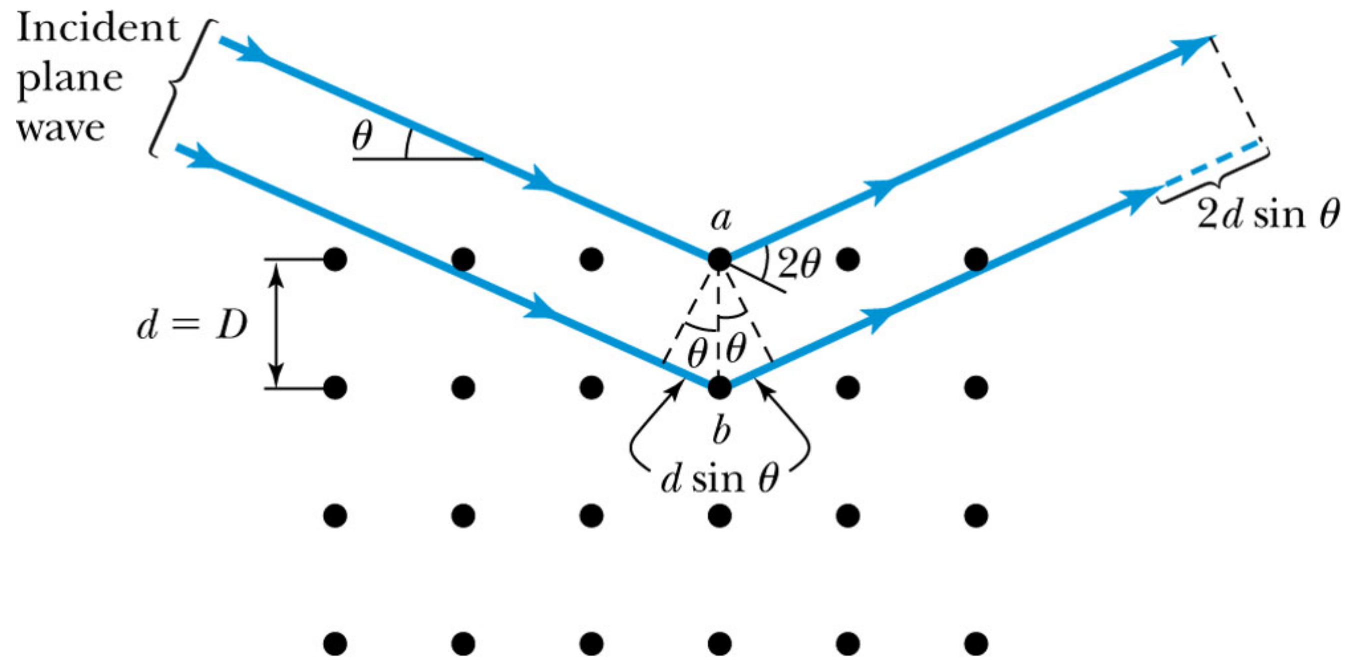
Diffraction, Thomas Young (1803)

Images: http://en.wikipedia.org
http://www.staff.amu.edu.pl
http://micro.magnet.fsu.edu

Bragg Diffraction



William Lawrence Bragg
1890-1972
William Henry Bragg
1862-1942
Nobel Prize 1915



Bragg's Law:

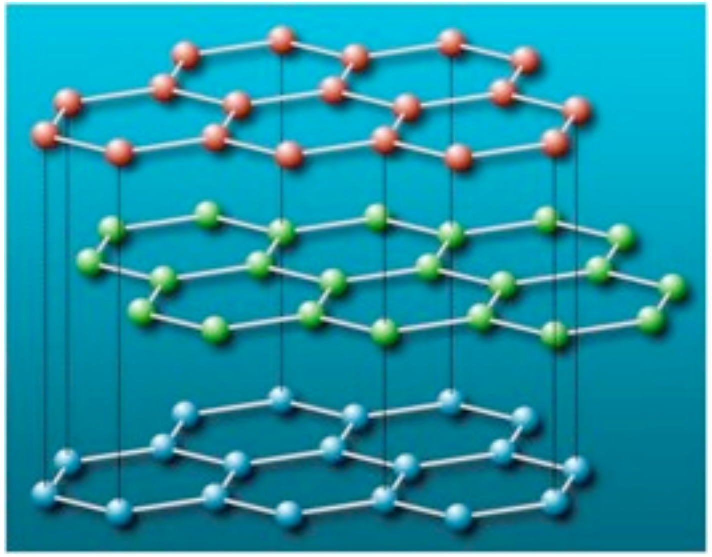
$$n\lambda = 2d\sin\theta$$

Classically, light behaves as a wave!

Images: Thornton and Rex

Electrons

- Are parts of an atom.
- Atoms are particles. →
- Ergo, electrons are particles.
- Or are they...



Graphite

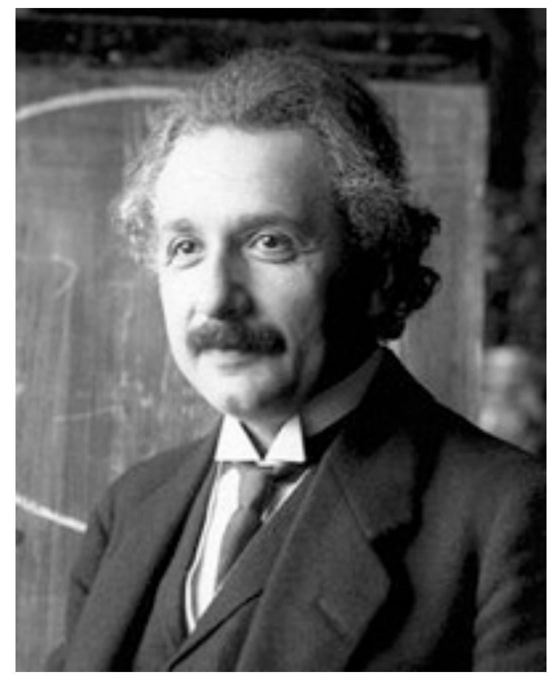
Concept Test

- For a light wave with wavelength λ and frequency ν, the following relation is always true (in a vacuum):
  - $\lambda\nu = c$ ← $$[c] = \frac{\mathrm{m}}{\mathrm{s}} = [\lambda] \cdot [\nu]$$
  - $\lambda c = \nu$
  - $\nu c = \lambda$

where c is the speed of light.

For Light

- $\lambda\nu=c$
- $E=pc$ (Einstein)
- $E=h\nu$ (Planck)
- $pc=h\nu=hc/\lambda$
- $\therefore\ \lambda=h/p$



Images: http://www.wikipedia.org

A Crazy Idea...

Matter waves

An electron with momentum p "has" a wavelength

$\lambda = h/p$!

Louis de Broglie
1892-1987
Nobel Prize: 1929

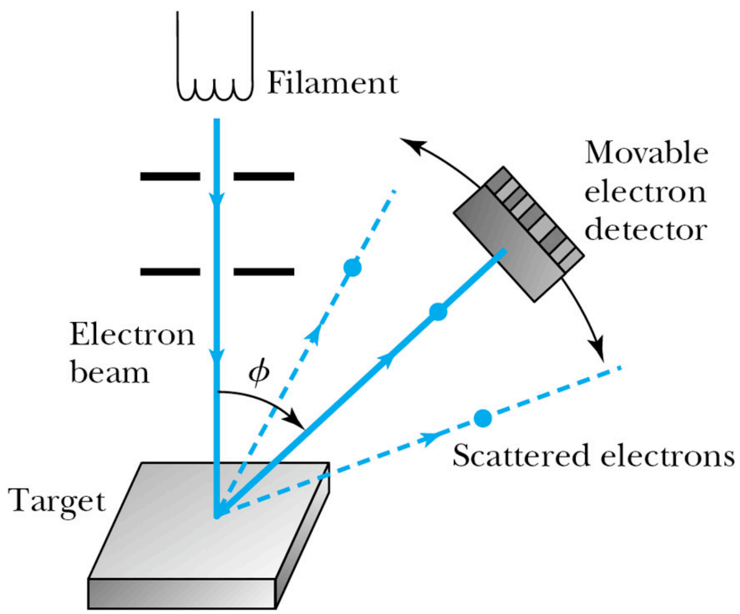
Quantum "fuzziness": a wave is hard to localize within a size of order λ

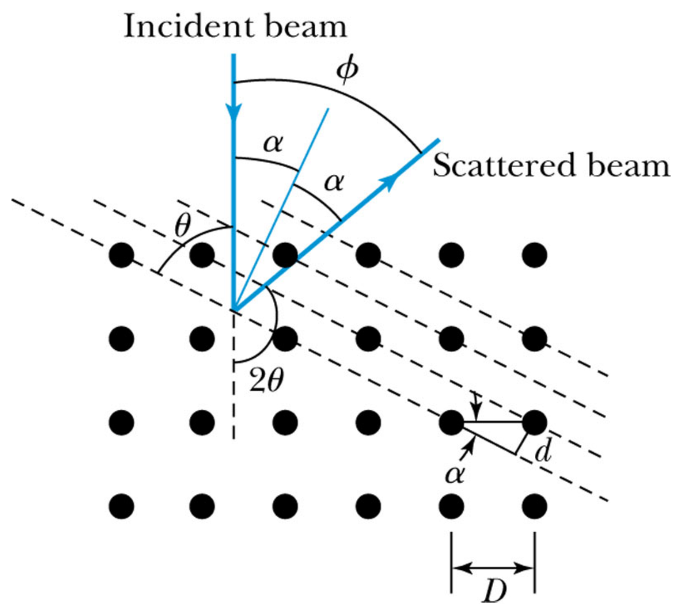
Heisenberg will make this more precise!

Image: http://www.wikipedia.org

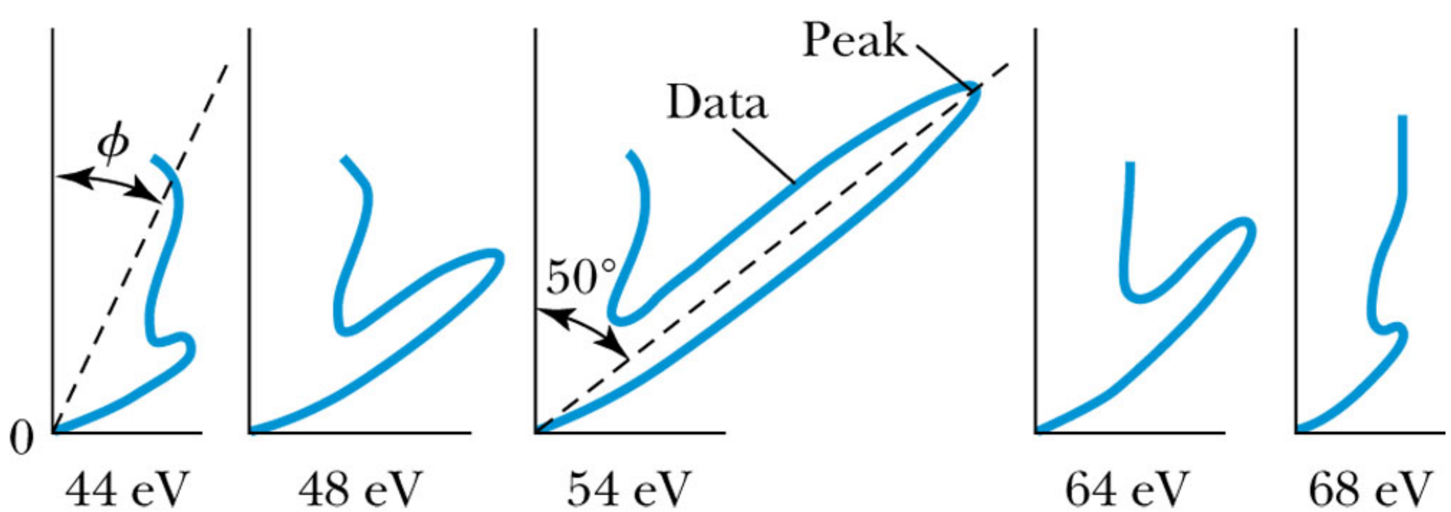
Experimental Proof!

1925: Diffraction of Electrons by a Nickel Crystal





Intensity = radial distance along dashed line to data at angle ϕ



Clinton Davission (R)

(1881-1958)

Nobel Prize 1937

Lester Germer

(1896-1971)

Images: Thornton and Rex

What is the wavelength of a tennis ball?

60 mph

$$\begin{aligned}\lambda &= \frac{6.63 \times 10^{-34}\,\mathrm{J\,s}}{60\,\frac{\mathrm{mi}}{\mathrm{hr}} \cdot 1600\,\frac{\mathrm{m}}{\mathrm{mi}} \cdot \frac{1}{3600}\,\frac{\mathrm{hr}}{\mathrm{s}} \cdot 0.1\mathrm{kg}} \\ &= 2.5 \times 10^{-34}\ \mathrm{m} \\ &= \mathcal{O}\left(10^{-24}\right) \times \text{size of atom}\end{aligned}$$

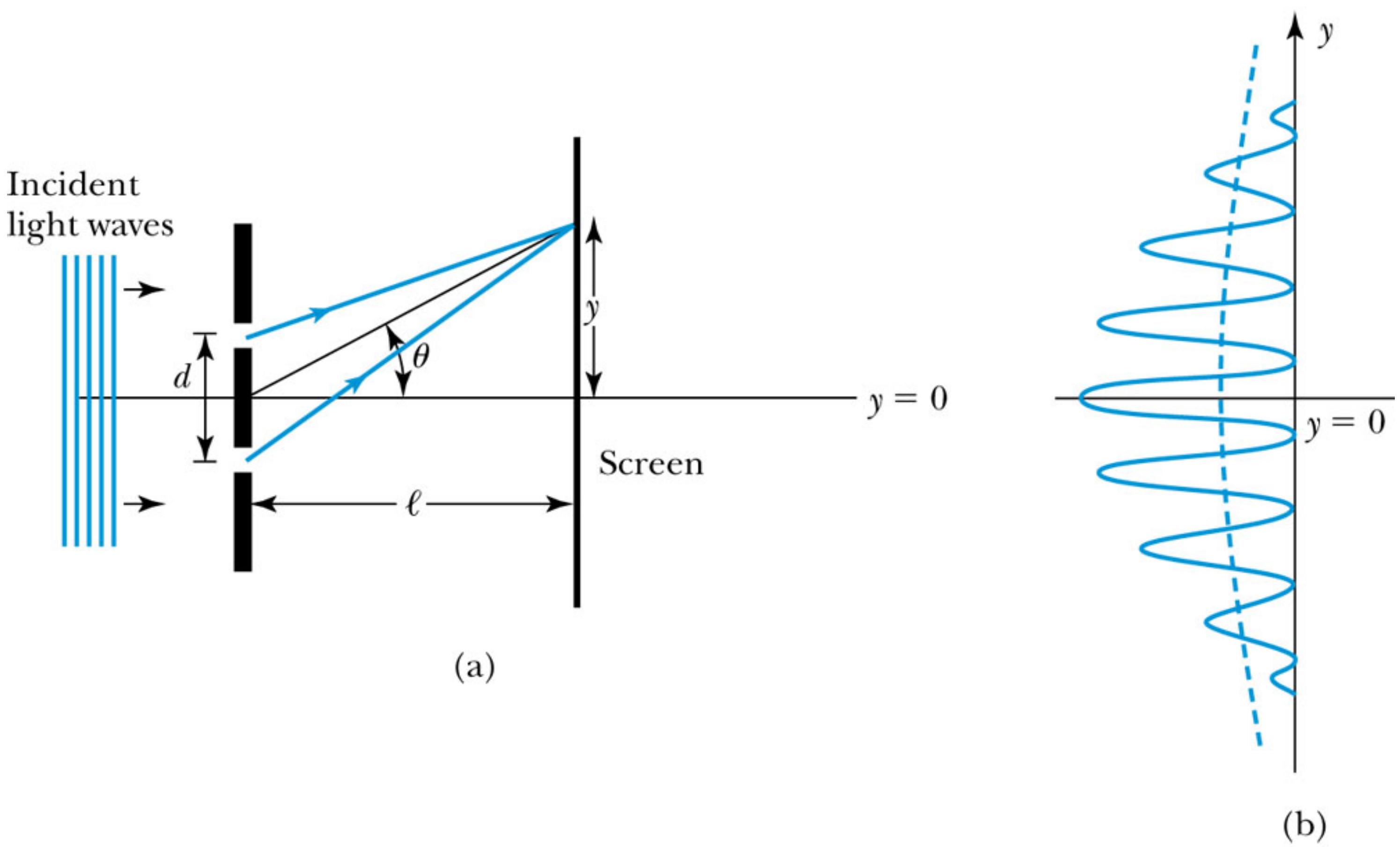
Quantum “fuzziness” of tennis ball is *very* small!

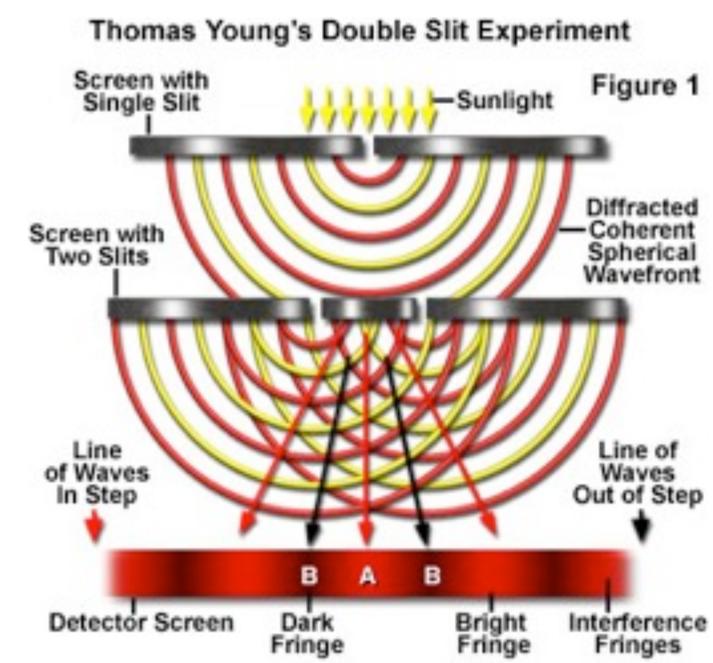
(I can’t blame my inability to hit a tennis ball to quantum effects.)

Concept Test

- The de Broglie wavelength of a tennis ball, $\lambda=h/p$, goes to ∞ (the "fuzziness" of the ball) as $p \rightarrow 0$. Why doesn't this prevent us from picking up tennis balls left on the court?
  - de Broglie's formula doesn't apply
  - $h \rightarrow 0$ when the ball isn't moving
  - p is never exactly 0 ←

Double Slit Experiment
Light

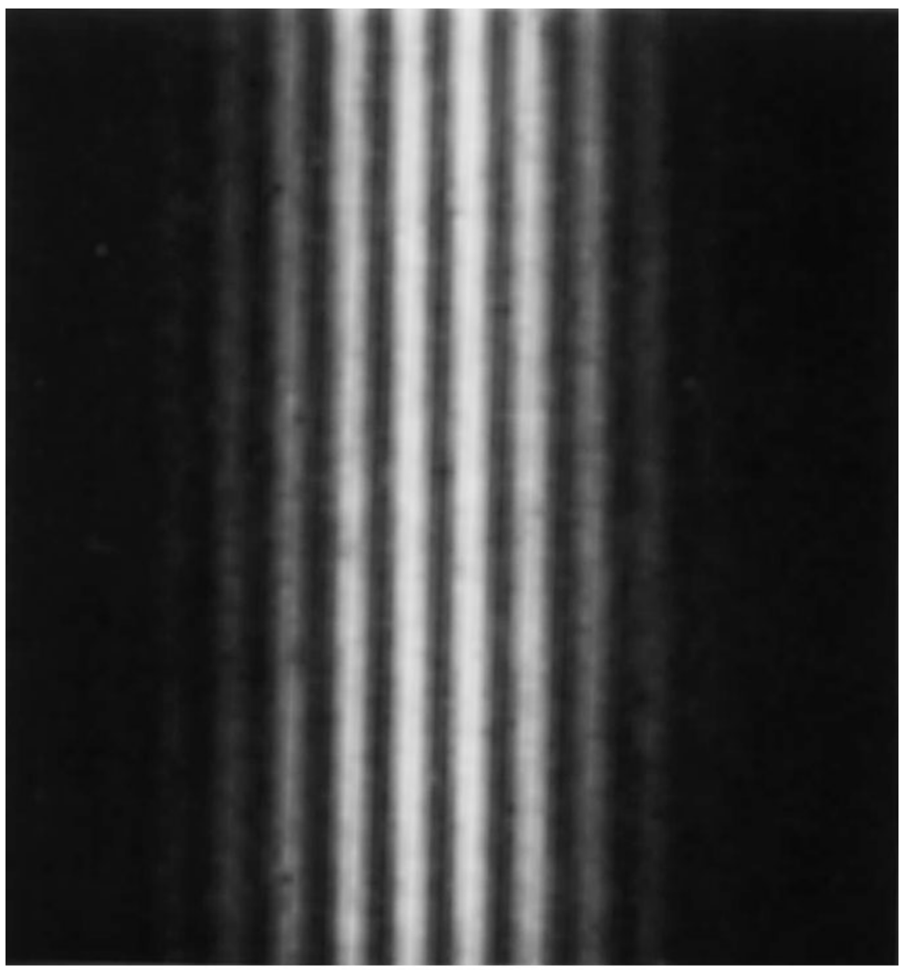




Diffraction, Thomas Young (1803)

Images: Thornon and Rex
http://micro.magnet.fsu.edu

Double Slit Experiment: Electrons!



C. Jönsson, 1961

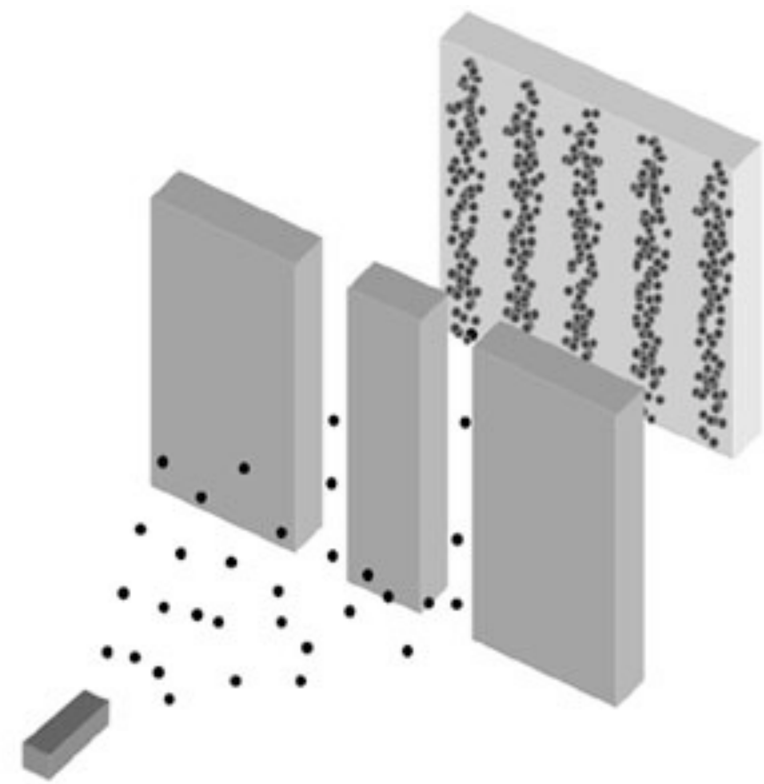
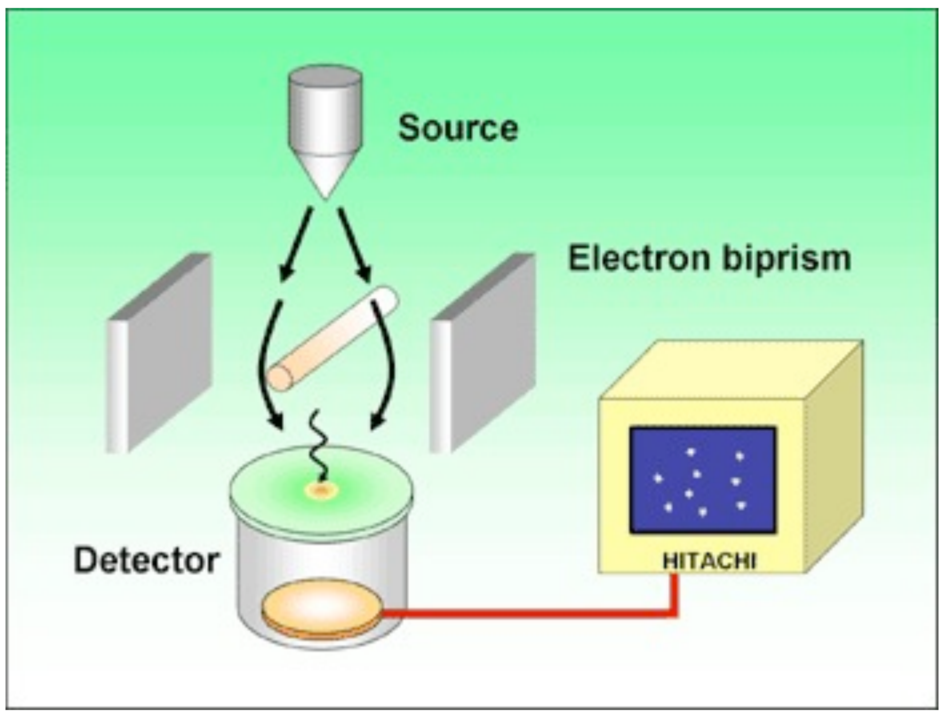


Image: Thornon and Rex
http://stephenwhitt.files.wordpress.com

One electron at a time!



Electrons, even one at a time, behave like waves!

Hitachi Laboratories
Dr. Tonomura Akiro

Movie: www.hitachi.com

Duality and Complementarity

- Wave-Particle Duality: all matter and energy exhibits *both* wave and particle like properties!
- Complementarity: a single quantum-mechanical system can behave like a wave or a particle, *but not both simultaneously!* (Bohr)

Summary, so far

- Light is classically a wave, but can behave like a particle (e.g. the photoelectric effect).
- Electrons are classically described as particles, but can behave like waves (e.g. the Davisson-Germer experimet).
- We need a description that unifies the particle and wave aspectsof natural systems!