DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS

IB PHYSICS

LSN 12-1A: INTERACTIONS OF MATTER WITH RADIATION

Questions From Reading Activity?

Essential Idea:

- The microscopic quantum world offers a range of phenomena, the interpretation and explanation of which require new ideas and concepts not found in the classical world.

Nature Of Science:

- Observations: Much of the work towards a quantum theory of atoms was guided by the need to explain the observed patterns in atomic spectra. The first quantum model of matter is the Bohr model for hydrogen.
- Paradigm shift: The acceptance of the wave–particle duality paradox for light and particles required scientists in many fields to view research from new perspectives.

Theory Of Knowledge:

- The duality of matter and tunneling are cases where the laws of classical physics are violated.
- To what extent have advances in technology enabled paradigm shifts in science?

Understandings:

- Photons
- The photoelectric effect
- Matter waves
- Pair production and pair annihilation
- Quantization of angular momentum in the Bohr model for hydrogen

Understandings:

- The wave function
- The uncertainty principle for energy and time and position and momentum
- Tunneling, potential barrier and factors affecting tunneling probability

Applications And Skills:

- Discussing the photoelectric effect experiment and explaining which features of the experiment cannot be explained by the classical wave theory of light
- Solving photoelectric problems both graphically and algebraically

Applications And Skills:

- Discussing experimental evidence for matter waves, including an experiment in which the wave nature of electrons is evident
- Stating order of magnitude estimates from the uncertainty principle

Guidance:

- The order of magnitude estimates from the uncertainty principle may include (but is not limited to) estimates of the energy of the ground state of an atom, the impossibility of an electron existing within a nucleus, and the lifetime of an electron in an excited energy state
- Tunneling to be treated qualitatively using the idea of continuity of wave functions

Data Booklet References:

$$E = hf$$

$$E_{\text{max}} = hf - \Phi$$

$$E = -\frac{13.6}{n^2} eV$$

$$mvr = \frac{nh}{2\pi}$$

$$P(r) = |\Psi|^2 \Delta V$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

Utilization:

- The electron microscope and the tunneling electron microscope rely on the findings from studies in quantum physics
- Probability is treated in a mathematical sense in Mathematical studies SL sub-topics 3.6–3.7

Aims:

- Aim 1: study of quantum phenomena introduces students to an exciting new world that is not experienced at the macroscopic level. The study of tunneling is a novel phenomenon not observed in macroscopic physics.

Aims:

- Aim 6: the photoelectric effect can be investigated using LEDs
- Aim 9: the Bohr model is very successful with hydrogen but not of any use for other elements

Introductory Video:

Wave-Particle Duality

All About Photons

- Light is considered to be an electromagnetic wave
  - Consists of oscillating electric and magnetic fields
- Wave speed is, $c = f\lambda$
- Light behaves as a wave
  - Diffraction
  - Interference
  - Polarization
  - Red and blue shifting

All About Photons

- The photoelectric effect also shows that light behaves as a particle, namely
  - Momentum
  - Energy
- Existence of photon's momentum is supported by Compton effect: deflecting photons off electrons or protons

All About Photons

- Einstein proposed that light should be considered as quanta of energy given by E = hf, moving at the speed of light.
- Photon's momentum:

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

$$E_K = pv$$

$$p = \frac{E_K}{v}$$

$$p = \frac{E}{c}$$

$$E = hf$$

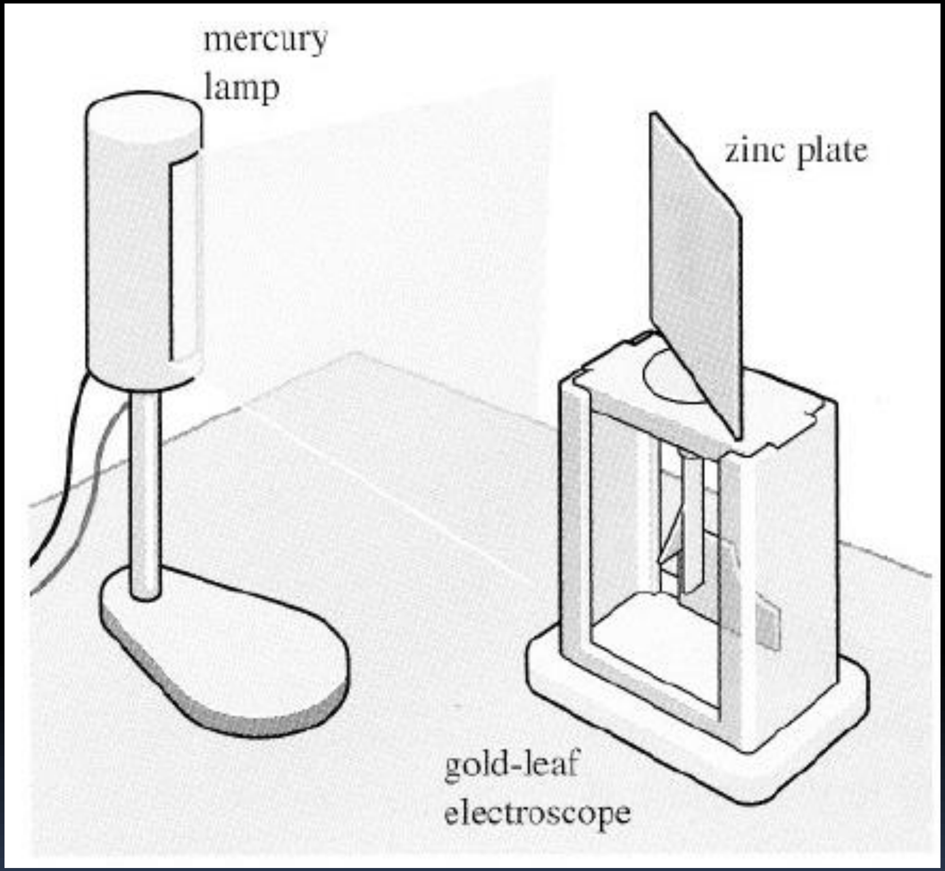
$$c = \lambda f$$

All About Photons

- Even though photons have energy and momentum, they have no mass and zero electric charge
- Einstein's theory of relativity, $E=mc^2$, implies that photons travel at the speed of light
- Because they travel at the speed of light, their momentum is considered relativistic
- Even though we treat light as photon particles, it still exhibits a wave nature

The Photoelectric Effect

- When light or other electromagnetic radiation falls on a metallic surface, electrons may be emitted from that surface

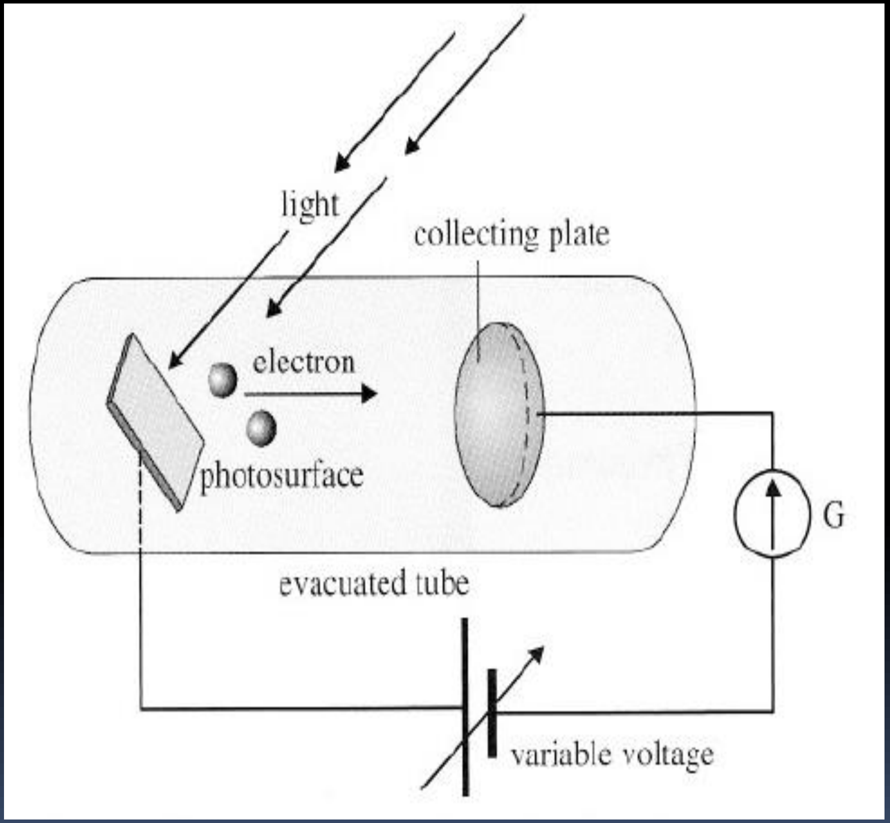


The Photoelectric Effect

- Electromagnetic radiation contains energy that can be transferred to electrons of the atoms of the photosurface, enabling them to pull themselves away from the attraction of the nuclei and leave the surface altogether
- Photons giving electrons enough energy to separate themselves from atoms

The Photoelectric Effect

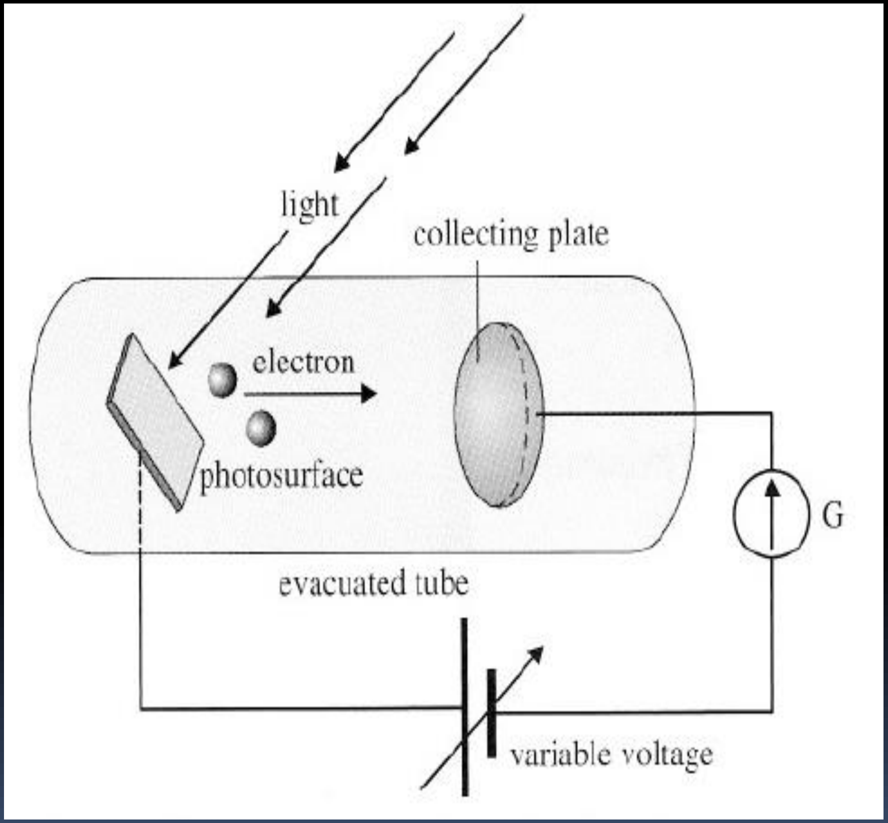
- Millikan experiments
  - Light radiated on a photosurface inside an evacuated tube
  - Reflected onto a collecting plate connected to an electroscope or galvanometer
  - Electrons that make it to the collecting plate create a current



The Photoelectric Effect

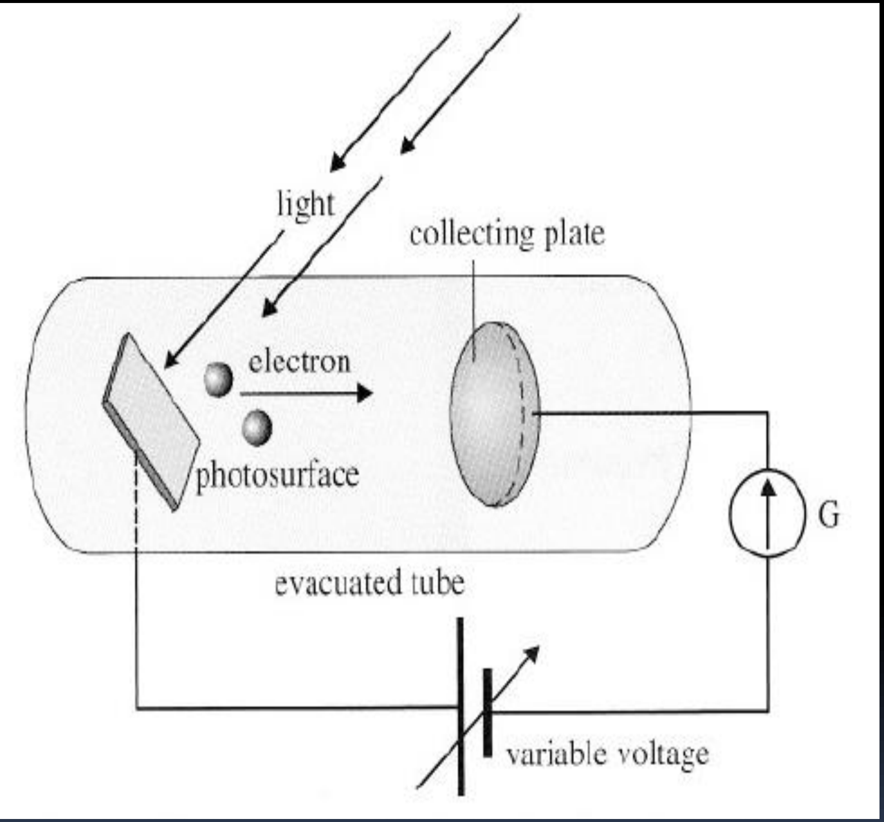
As the intensity of the radiation increases, induced current increases – intensity and current are directly proportional

- May be due to larger number of electrons emitted per second, OR;
- Electrons with higher speed emitted, OR;
- Both



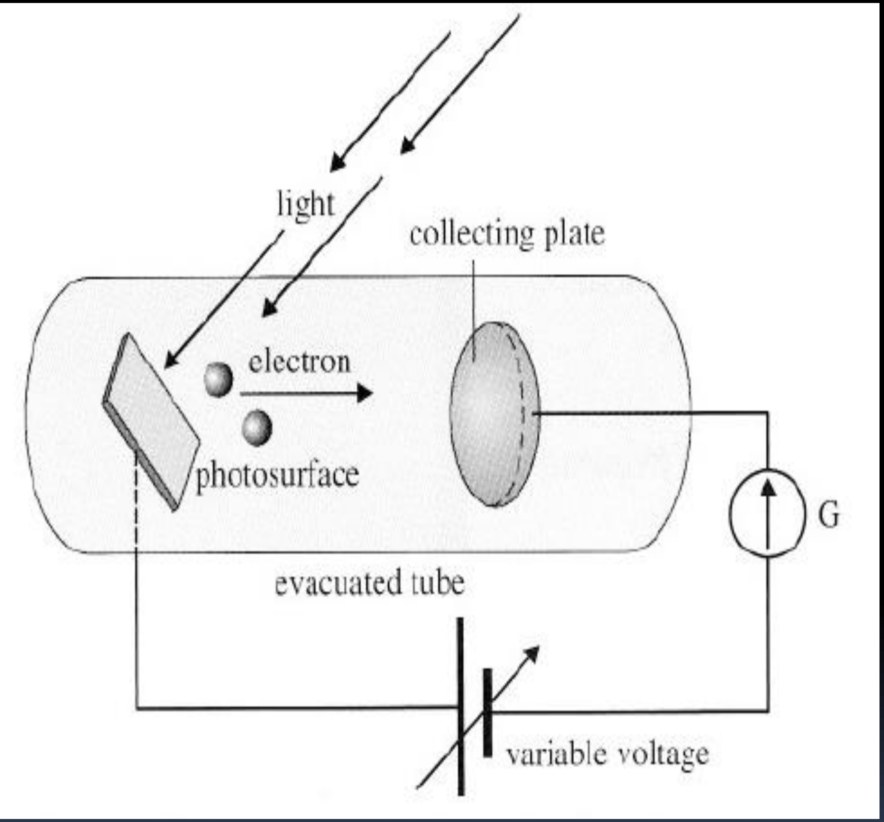
The Photoelectric Effect

To determine which, you connect up a voltage source to the circuit to make the current drop to zero – a <u>*stopping voltage (V_s)*</u>



The Photoelectric Effect

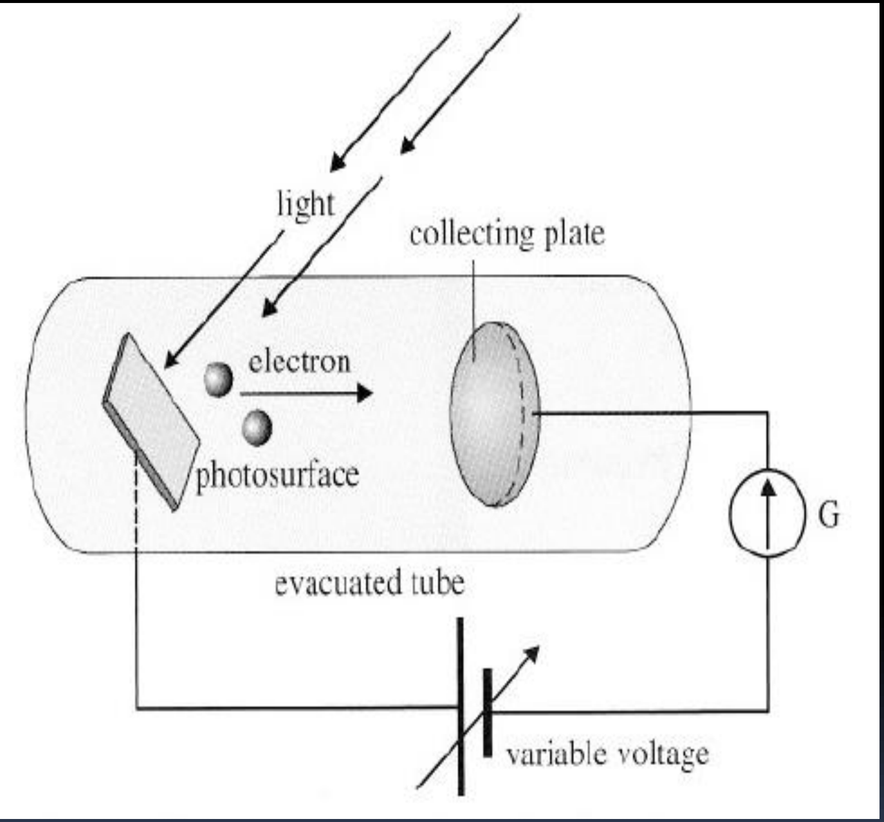
The energy of the stopping voltage, eV_s, must then be equal to the work done in moving the electrons from the cathode to the collecting plate, which is the same as the maximum kinetic energy of the electrons, E_k



$$E_k = eV_s$$

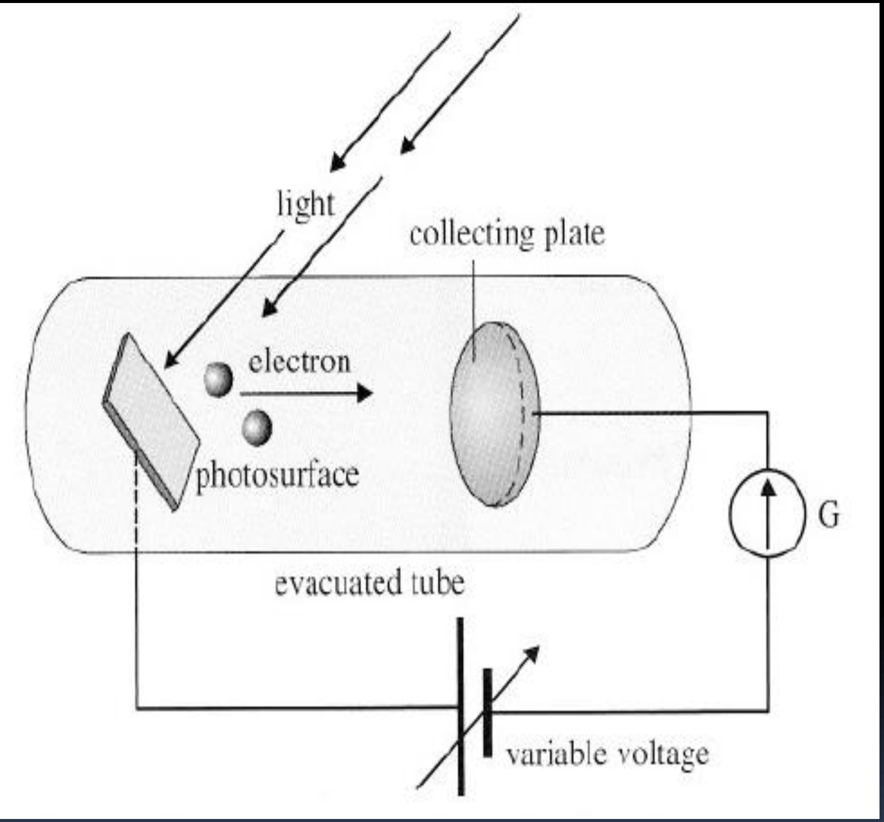
The Photoelectric Effect

- The stopping voltage is the same regardless of light intensity
- The intensity of the light has no effect on the maximum energy of the electrons
- Thus the increase in the current is due to more electrons being emitted



The Photoelectric Effect

- Miliken then varied the frequency / wavelength of the light
- *Surprise, Surprise*

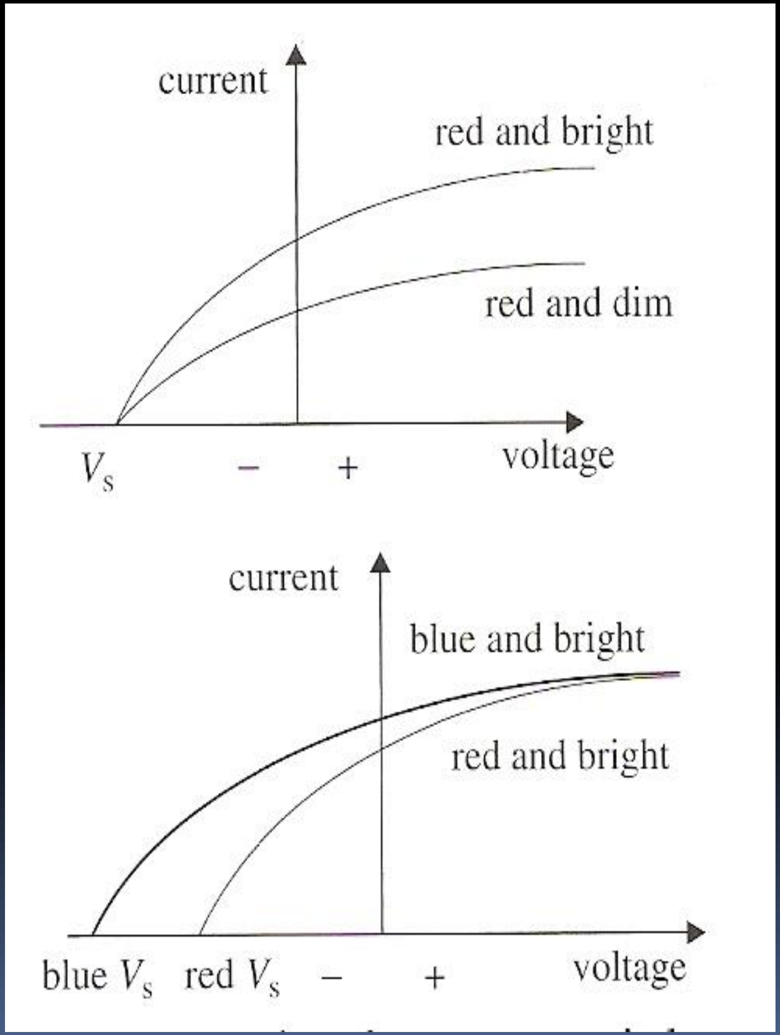


The Photoelectric Effect

- Stopping voltage does not depend on intensity

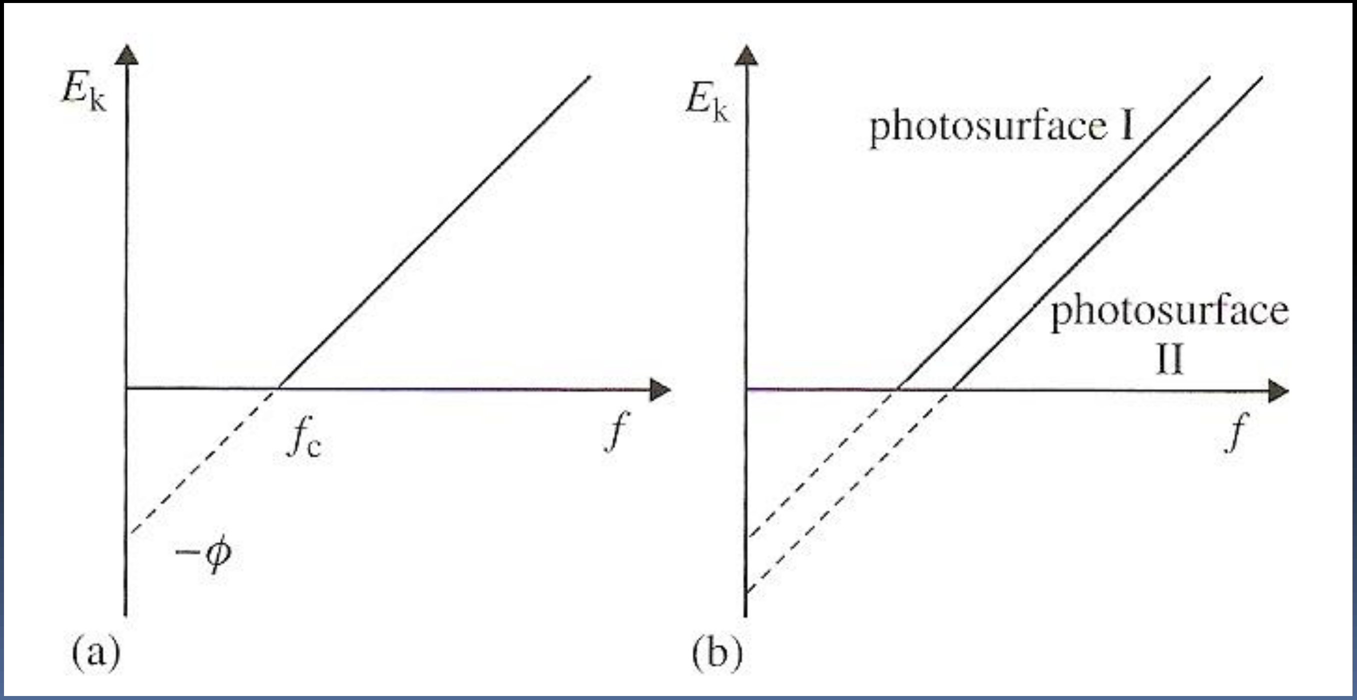
HOWEVER,

- Stopping voltage <u>does</u> depend on the <u>frequency</u> of the light source
- The larger the frequency, the larger the required stopping voltage



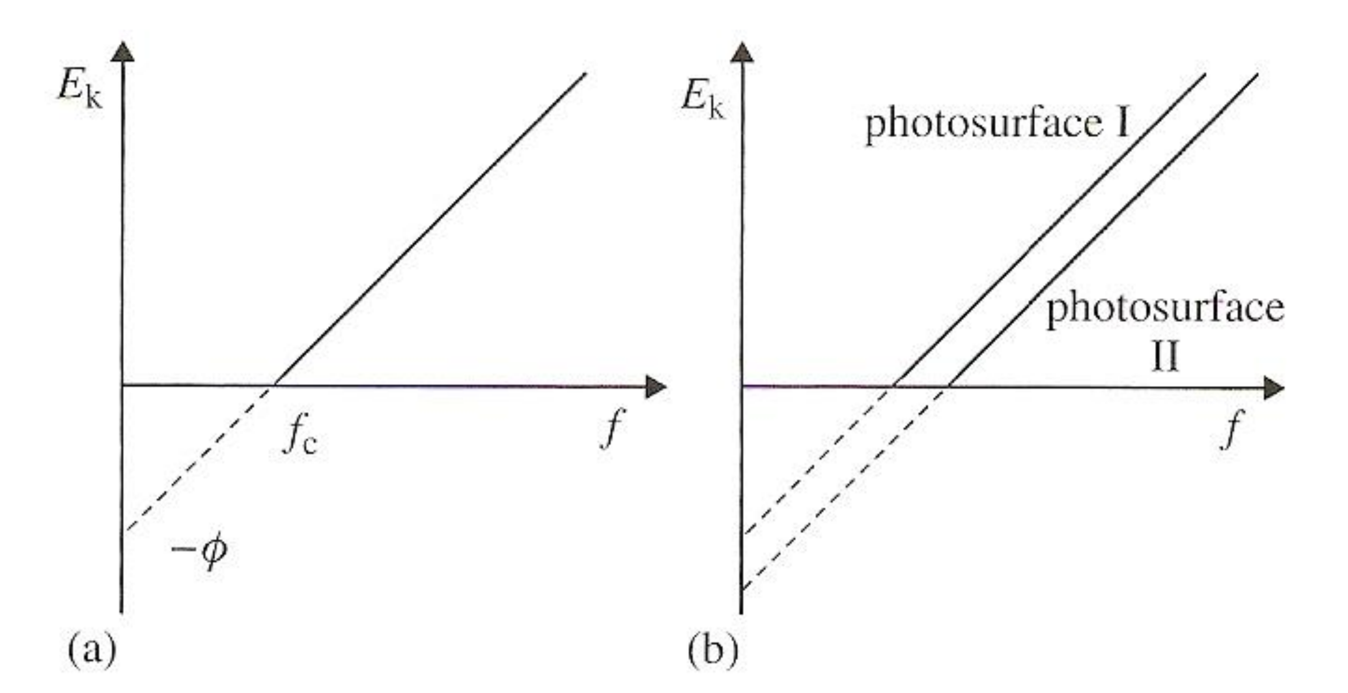
The Photoelectric Effect

- Another twist:
  - There does exist a critical or ***threshold frequency, f_c***, such that sources emitting light below the threshold frequency will cause no electrons to be emitted no matter how intense the light



The Photoelectric Effect

- The critical frequency was different for different photosurfaces (the surface the light was shown on)
- *Kinetic energy of the electrons is directly proportional to light frequency*



The Photoelectric Effect

- Four observations:
  - The intensity of the incident light does not affect the energy of the emitted electrons
  - The electron energy depends on the frequency of the incident light
  - There is a certain minimum frequency below which no electrons are emitted.
  - Electrons are emitted with no time delay, i.e. no "build-up" of energy
- *Is there a problem here?*

The Photoelectric Effect

- ***All four of these observations are in violation of the standard laws of physics***
  - A more intense beam of light ***should*** produce electrons with more energy
  - Classical electromagnetism gives no explanation for the relationship between frequency and electron energy
  - Classical electromagnetism gives no explanation for the reason for a minimum frequency to release electrons instantaneously
  - With a low intensity light beam, the electrons should have to wait to build up energy before being emitted
- ***So What's Up With That?***

The Photoelectric Effect

- Big Al to the Rescue
  - Einstein postulated that light, like any other form of electromagnetic radiation, consists of ***quanta*** which are 'packets of energy and momentum'
  - The energy of one such quantum is given by:

$$E = hf$$

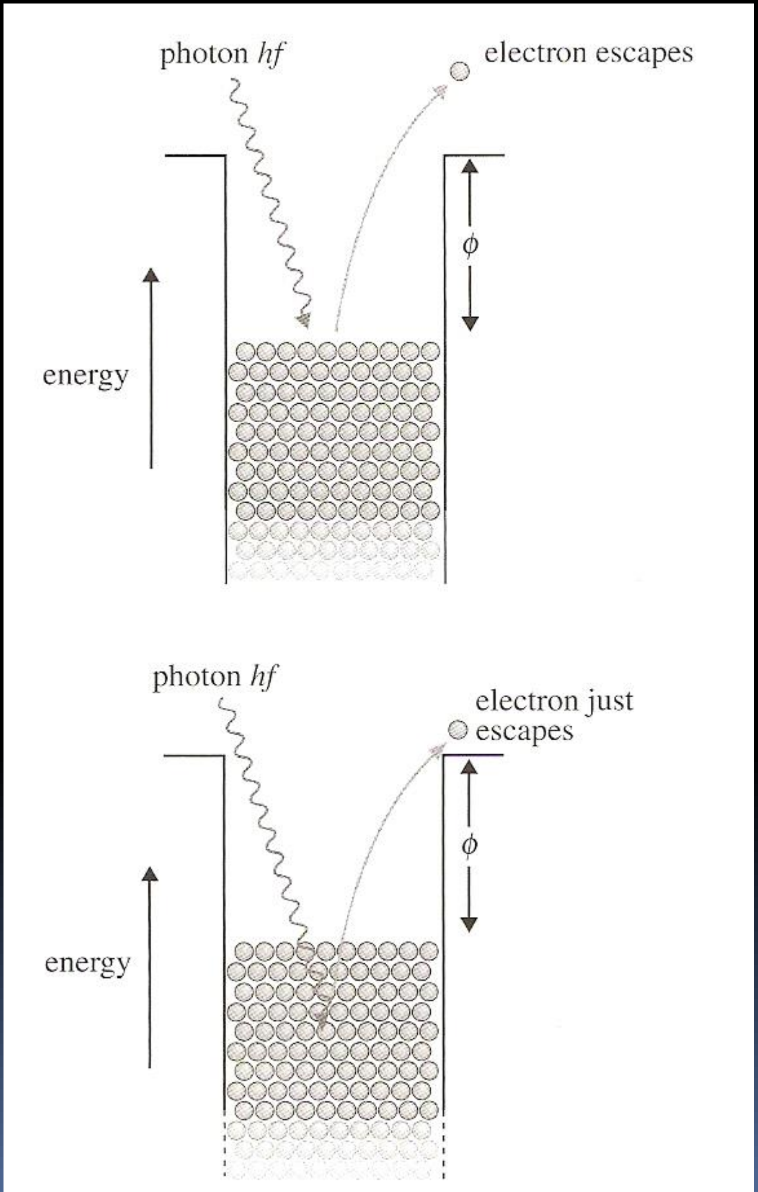
  - where f is the frequency of the electromagnetic radiation and $h = 6.63 \times 10^{-34}$ Js, a constant known as Planck's constant

The Photoelectric Effect

- Big Al to the Rescue
  - These quanta of energy and momentum are photons, the particles of light
  - This implies light behaves in some cases as particles do, but the energy of the photons is dependent on the frequency of the light, not the intensity, implying wave properties
  - If a photon of frequency f is absorbed by an electron, the electron’s energy increases by hf

The Photoelectric Effect

- Big Al to the Rescue
  - If the energy required for the electron to break free of the nucleus and the photosurface is ϕ, then the electron will only be emitted if hf > ϕ



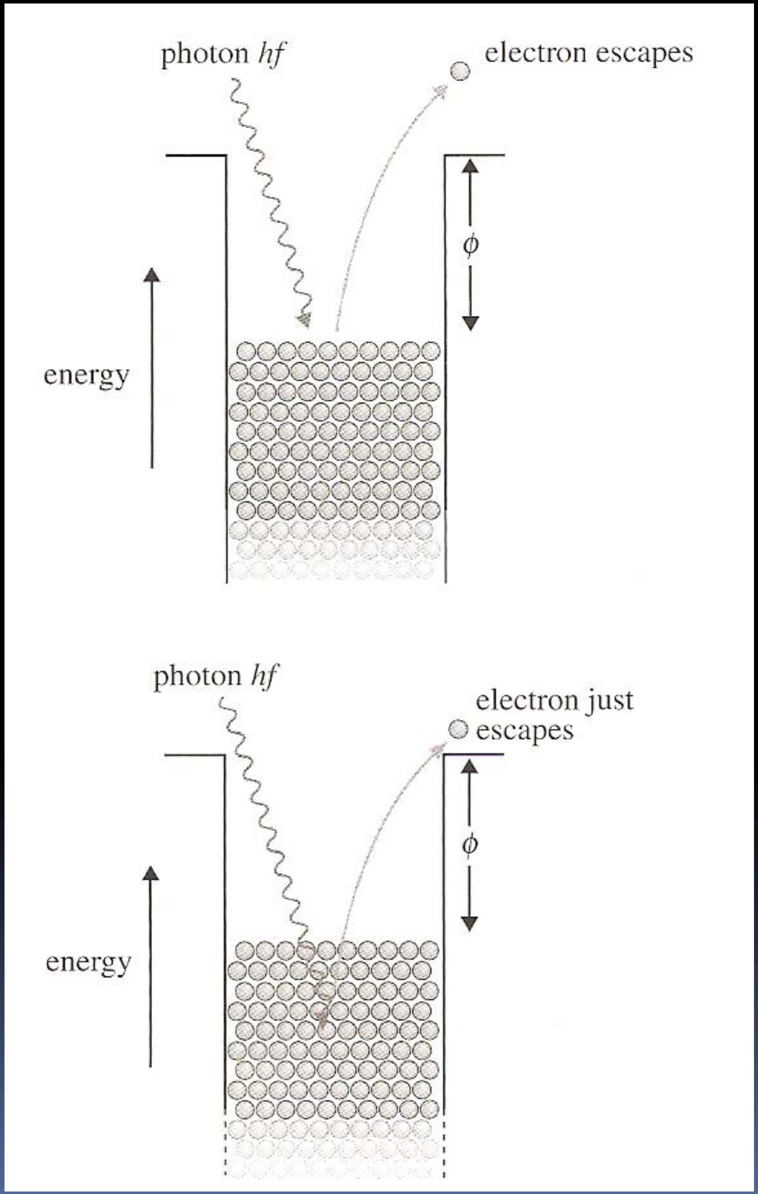
The Photoelectric Effect

- Big Al to the Rescue
  - The kinetic energy of the now free electron is:

    $$E_k = hf - \phi$$

    ϕ is called the ***work function***, the minimum amount of energy required to release an electron
- At the critical frequency:

  $$hf_c = \phi, \text{ and } E_k = 0$$

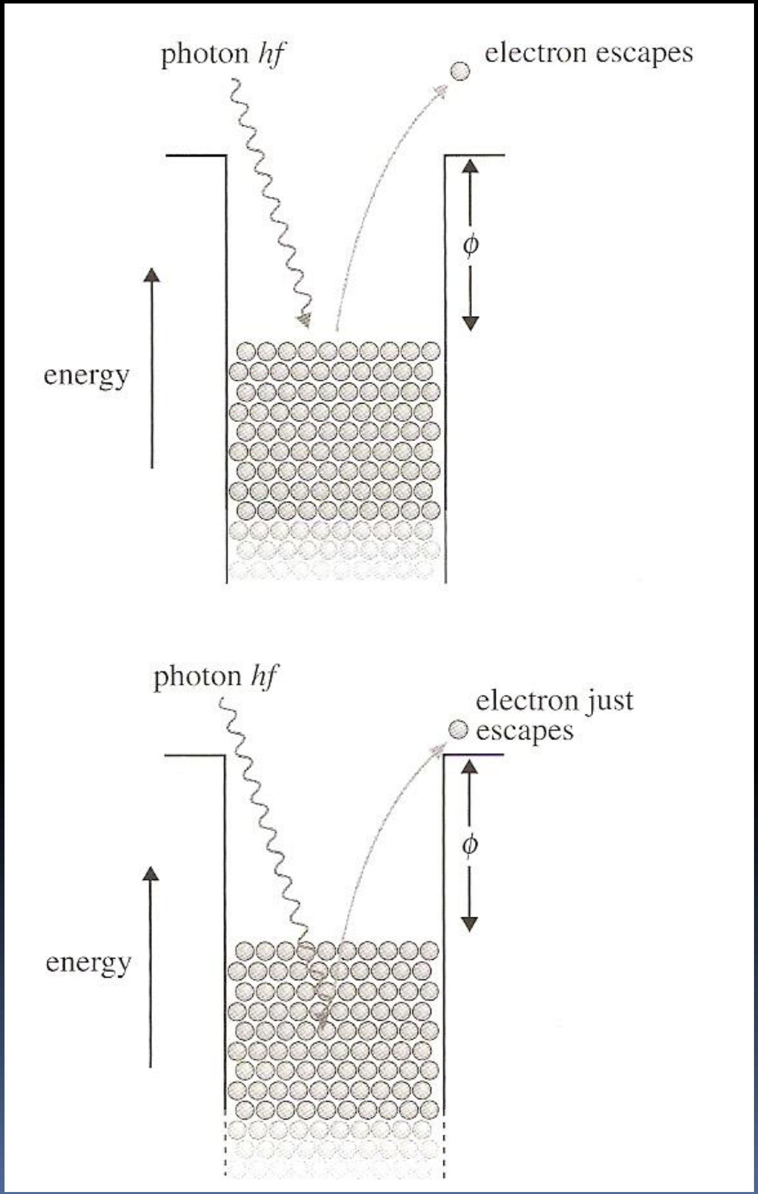


The Photoelectric Effect

- Big Al to the Rescue
  - It's kind of like the problem with the spring constant
  - You had to apply a certain amount of force to get the spring to move
  - After that, extension was proportional to force applied:

$$F = kx$$

$$E = kx^2$$



The Photoelectric Effect

- To summarize:

$$eV_s = E_k$$

$$E_k = hf - \phi$$

$$eV_s = hf - \phi$$

$$V_s = (h/e)\,f - \phi/e$$

  - The graph of the stopping voltage versus frequency yields a straight line with slope *h/e* and an x-intercept representing the work function

MATTER WAVES

Or, Waves Matter Too

DeBroglie's Wavelength Hypothesis

- He defined wavelength for a particle with momentum *p*:
- Assigns wave-like properties to what was considered a particle
- Referred to as the ***duality of matter*** – a particle that does the wave!

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

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

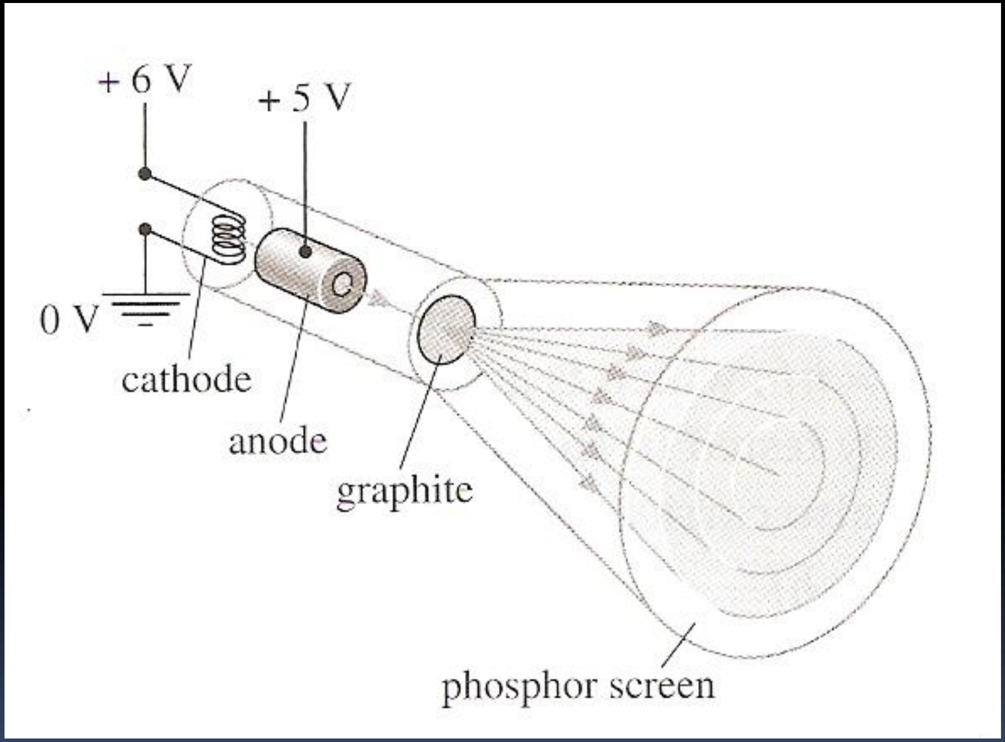
Electron as a Wave

- If we call something a wave, then it must exhibit wave-like properties – such as diffraction
  - A wave will only diffract around an object if its wavelength is comparable or bigger than the object
    - Electron at $v = 10^5$ m/s
    - Momentum $p = 9.1 \times 10^{-26}$ kg-m/s^2
    - Wavelength 7.2×10^{-9} m

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Electron as a Wave

- **Openings in some crystals are on the right order of magnitude ~ 10^{-8} m**



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- Momentum $p = 9.1 \times 10^{-26}$ kg-m/s²
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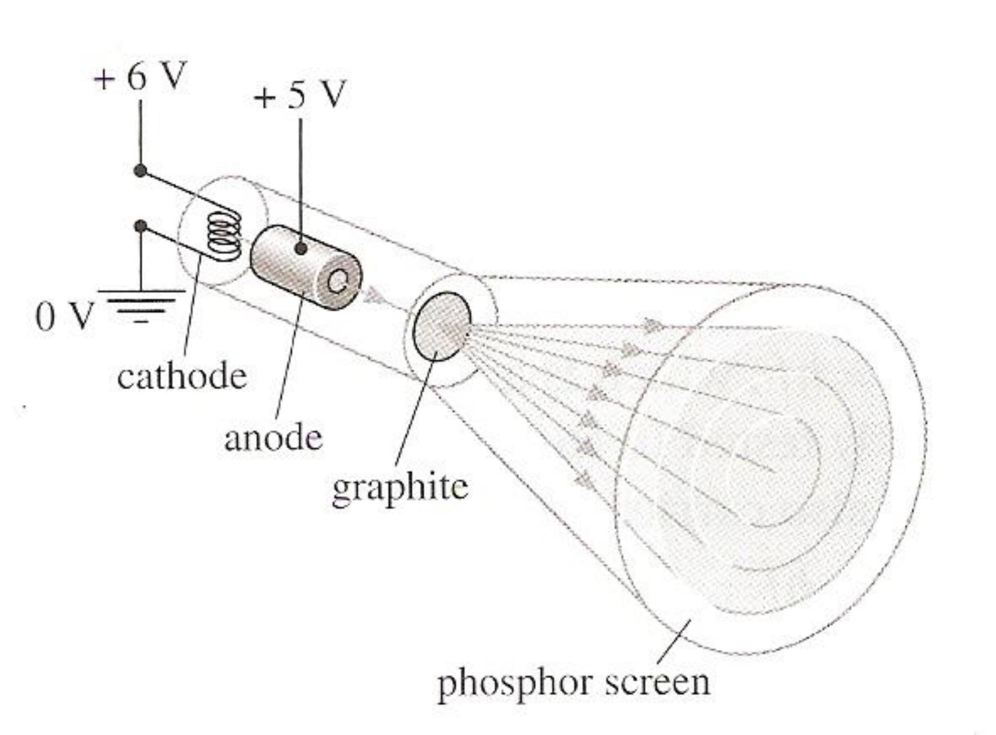
Electron as a Wave

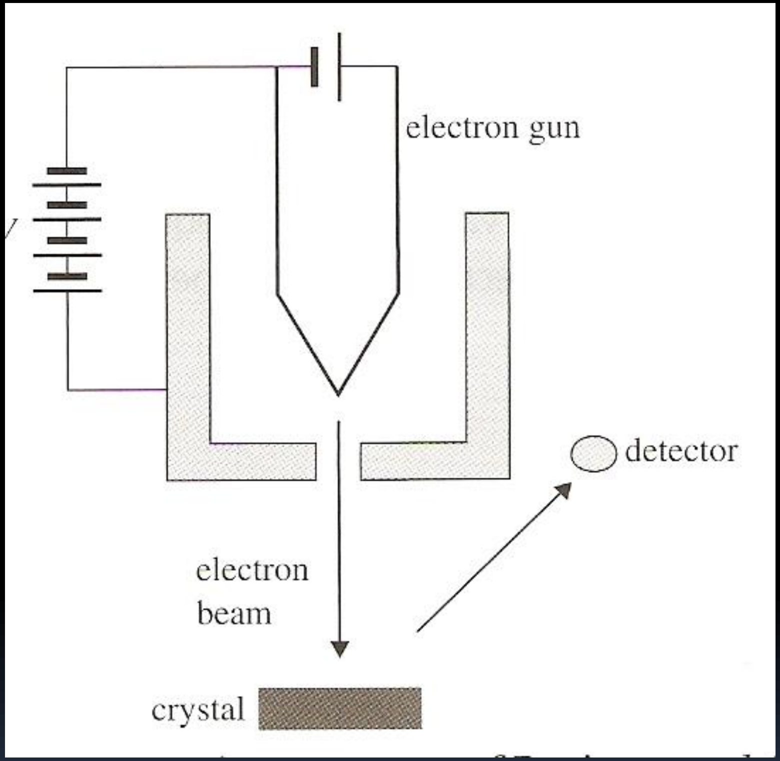
- Sir William Henry Bragg derived a relation between spacing of atoms in a crystal and wavelength of X-rays
- Bragg's formula allows us to determine wavelength from crystal spacing or vice versa



- Electron at $v = 10^5$ m/s
- Momentum $p = 9.1 \times 10^{-26}$ kg-m/s²
- Wavelength 7.2×10^{-9} m

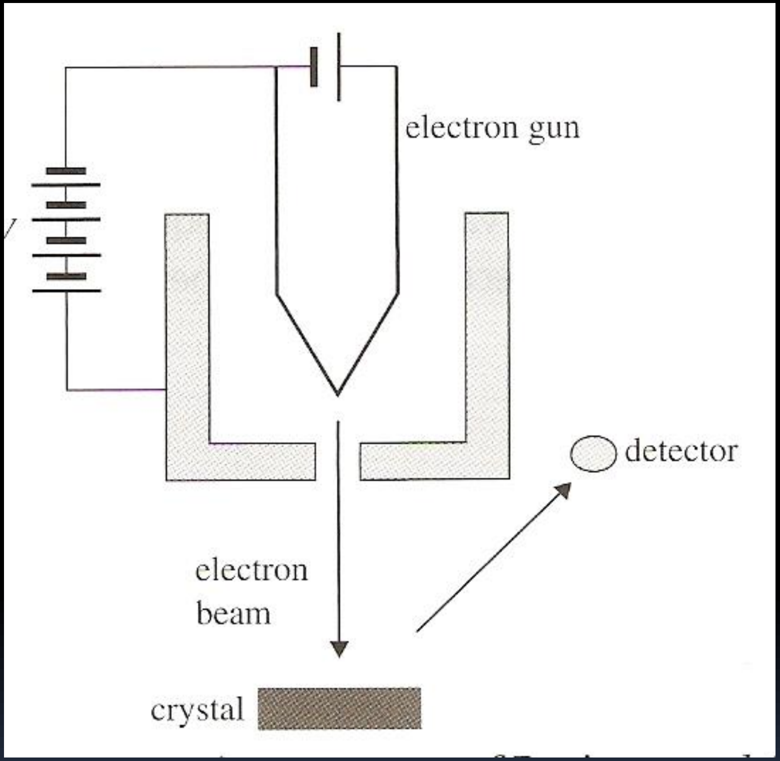
Electron as a Wave

- Davisson-Germer experiment directed electrons toward a nickel surface where a single crystal had been grown
- The electrons were scattered by the crystal similar to X-rays in previous experiments which confirmed the wave nature



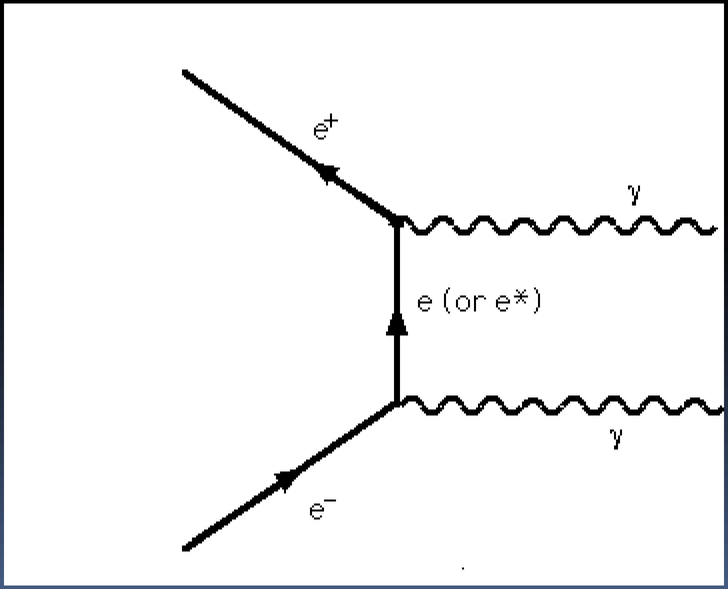
Electron as a Wave

- The Bragg formula was used to determine the wavelength which agreed with the de Broglie hypothesis
- Thus, the Davisson-Germer experiments confirmed the de Broglie wavelength hypothesis



Pair Annihilation and Pair Production

- Particle – Anti-Particle
  - For every particle, there is an anti-particle
  - Same mass, all other properties opposite
  - When a particle collides with it's anti-particle . . .



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Pair Annihilation

Pair Annihilation and Pair Production

- Particle – Anti-Particle Collision
  - Electron and positron travelling in opposite directions at the same speed

$$E_T = 2\left(mc^2 + E_K\right)$$

  - Upon annihilation, 2 photons are emitted with the same energy, travelling in opposite directions at the same speed (conservation of energy and momentum)
  - Their wavelength will be

$$\lambda = \frac{hc}{mc^2} + E_K$$

Pair Annihilation and Pair Production

- Particle – Anti-Particle Collision

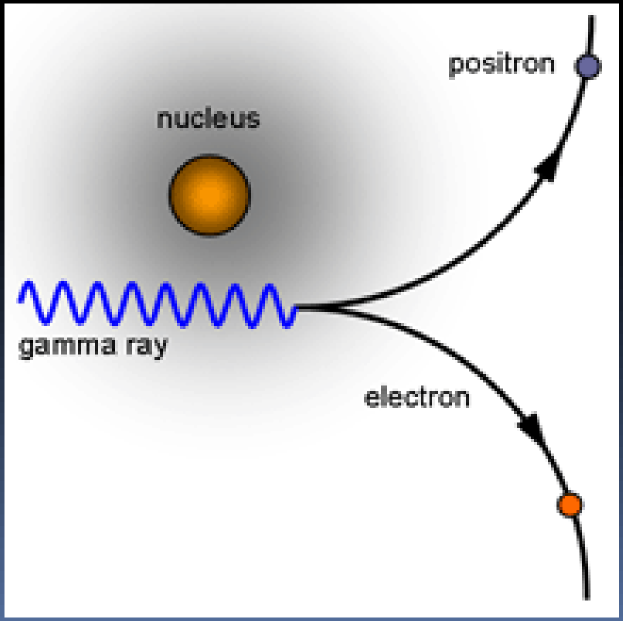
$$\lambda = \frac{hc}{mc^2} + E_K$$

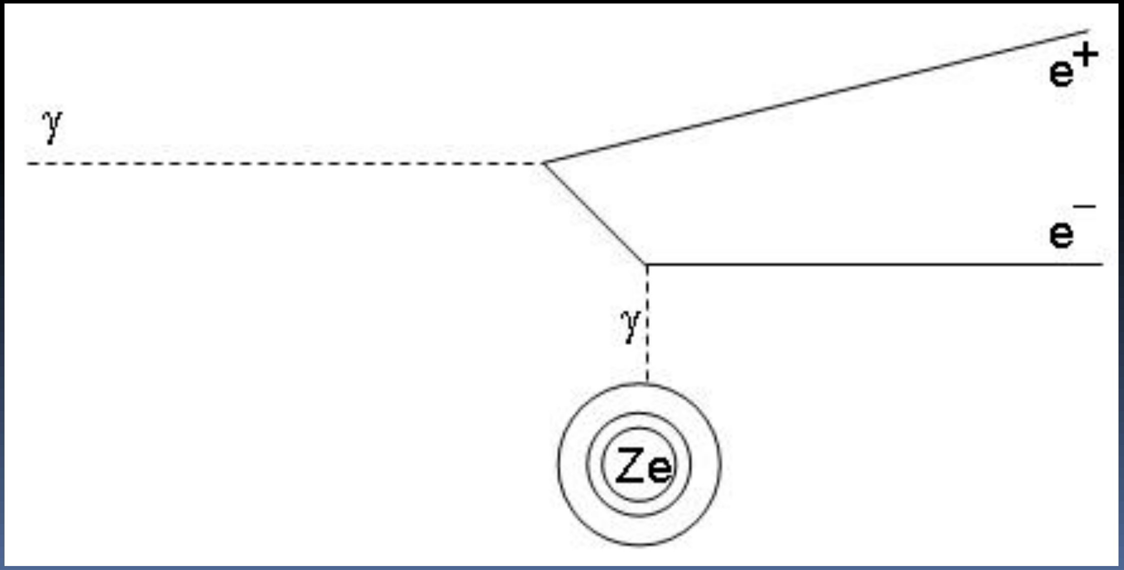
  - Assume the longest wavelength occurs when $E_K = 0$
  - Electron rest mass = mc^2 = 0.511 MeV (Data Guide), so

$$\lambda = \frac{1.24x10^{-6}}{0.511x10^{6}} = 2.4x10^{-12}\,m$$

Pair Annihilation and Pair Production

- Pair Production or Creation
  - A single photon cannot create a particle – anti-particle pair due to inability to conserve energy and momentum
  - However, it can interact with nucleus to do so
  - Energy is, in effect, converted into matter





Understandings:

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- The photoelectric effect
- Matter waves
- Pair production and pair annihilation
- Quantization of angular momentum in the Bohr model for hydrogen

Understandings:

- The wave function
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Guidance:

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QUESTIONS?

Homework

#1-16, odd and evens only