

PHYS 3313 – Section 001

Lecture #8

Monday, Sept. 23, 2013

Dr. Amir Farbin

- Discovery of Electron
- Determination of Electron Charge
- Line Spectra
- Blackbody Radiation
- Photoelectric Effect
- Compton Effect
- Pair production/Pair annihilation



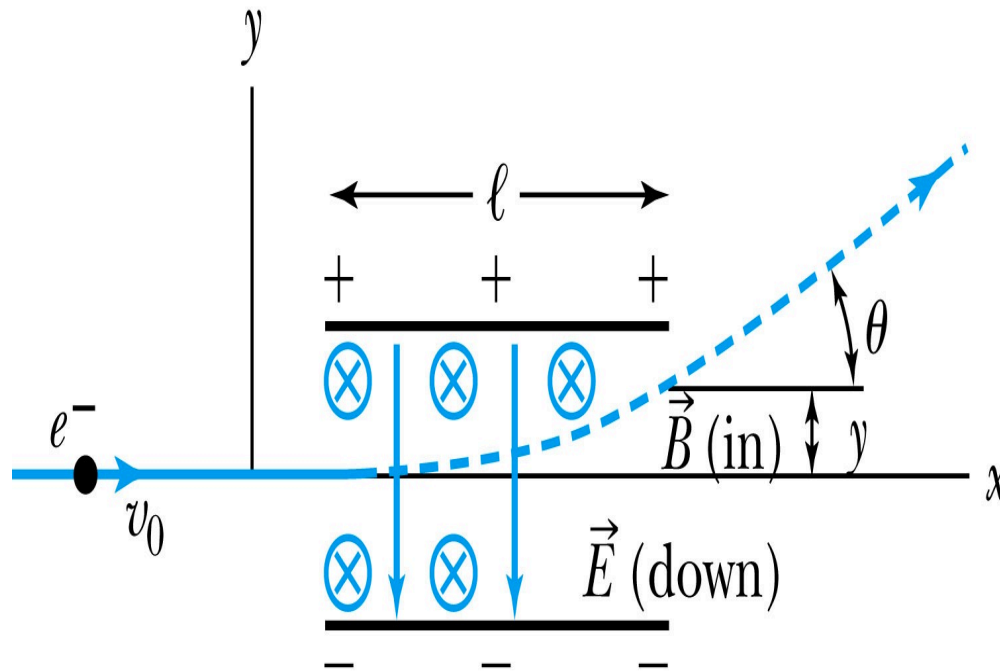
Announcements

- Reading assignments: CH3.9
- Homework #2
 - CH3 end of the chapter problems: 2, 19, 27, 36, 41, 47 and 57
 - Due Wednesday, Oct. 2
- Quiz #2 Monday, Sept. 30
 - Beginning of the class
 - Covers CH1.1 – what we finish Wednesday, Sept. 26



Thomson's Experiment

- Thomson measured the ratio of the electron's charge to mass by sending electrons through a region containing a magnetic field perpendicular to an electric field.



- Measure the deflection angle with only E!
- Turn on and adjust B field till no deflection!
- What do we know?
 - l , B, E and θ
- What do we not know?
 - v_0 , q and m

Calculation of q/m

- An electron moving through the electric field w/o magnetic field is accelerated by the force: $F_y = ma_y = qE$
- Electron angle of deflection: $\tan \theta = \frac{v_y}{v_x} = \frac{a_y t}{v_0} = \frac{qE l / v_0}{m v_0} = \frac{qE l}{m v_0^2}$
- Adjust the perpendicular magnetic field till it balances E and keeps electrons from deflecting in y-direction

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = 0$$

$$F_y = -qE + qv_x B = 0 \Rightarrow qE = qv_x B \Rightarrow v_x = \frac{E}{B} = v_0$$

- Charge to mass ratio:

$$\tan \theta = \frac{qE l}{m v_0^2} \Rightarrow \frac{q}{m} = \frac{v_0^2 \tan \theta}{El} = \frac{(E/B)^2 \tan \theta}{El} = \frac{E \tan \theta}{B^2 l}$$



Ex 3.1: Thomson's experiment

- In an experiment similar to Thomson's, we use deflecting plates 5.0cm in length with an electric field of $1.2 \times 10^4 \text{ V/m}$. Without the magnetic field, we find an angular deflection of 30° , and with a magnetic field of $8.8 \times 10^{-4} \text{ T}$ we find no deflection. What is the initial velocity of the electron and its q/m ?
- First v_0 using E and B , we obtain:

$$v_0 = v_x = \frac{E}{B} = \frac{1.2 \times 10^4}{8.8 \times 10^{-4}} = 1.4 \times 10^7 \text{ m/s}$$

- q/m is then

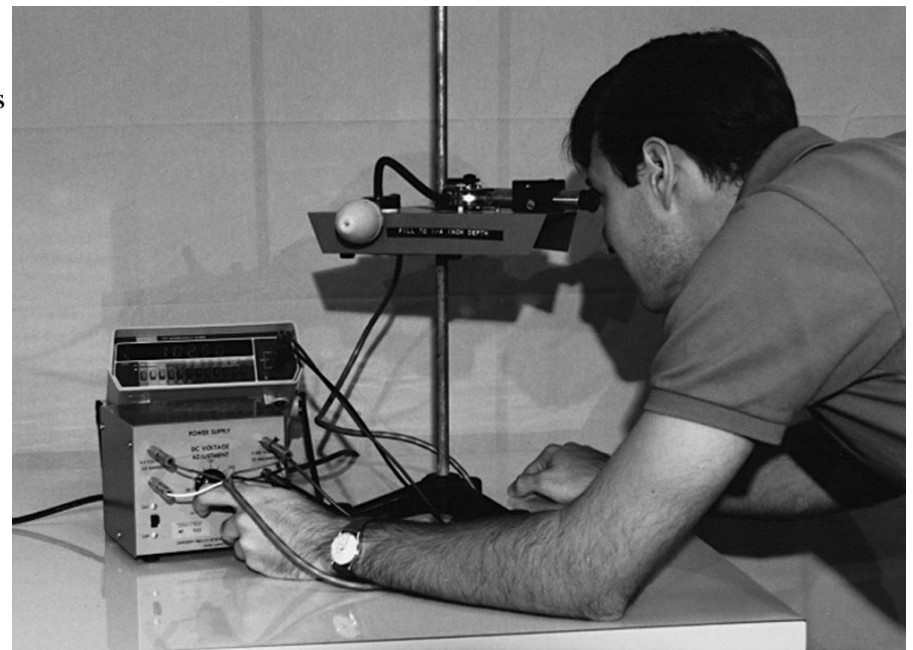
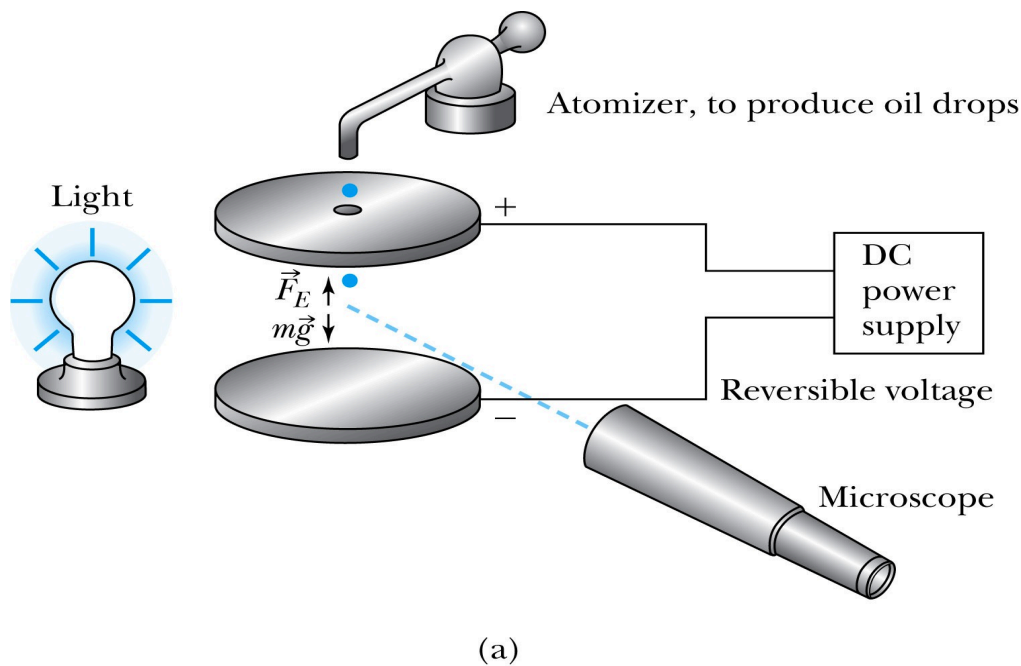
$$\frac{q}{m} = \frac{E \tan \theta}{B^2 l} = \frac{1.2 \times 10^4 \tan 30^\circ}{(8.8 \times 10^{-4})^2 \cdot 0.5} = 1.8 \times 10^{11} \text{ C/kg}$$

- What is the actual value of q/m using the known quantities?

$$\frac{q}{m} = \frac{1.6022 \times 10^{-19}}{9.1094 \times 10^{-31}} = 1.759 \times 10^{-11} \text{ C/kg}$$

Determination of Electron Charge

- Millikan (and Fletcher) in 1909 measured charge of electron, showed that free electric charge is in multiples of the basic charge of an electron



Calculation of the oil drop charge

- Used an electric field and gravity to suspend a charged oil drop

$$\vec{F}_E = q\vec{E} = -m\vec{g} \Rightarrow qV/d = mg$$

- So the magnitude of the charge on the oil drop

$$q = \frac{mgd}{V}$$

- Mass is determined from Stokes' relationship of the terminal velocity to the radius and density

$$m = \frac{4}{3}\pi r^3 \rho$$

- Thousands of experiments showed that there is a basic quantized electron charge

$$q = 1.602 \times 10^{-19} \text{ C}$$

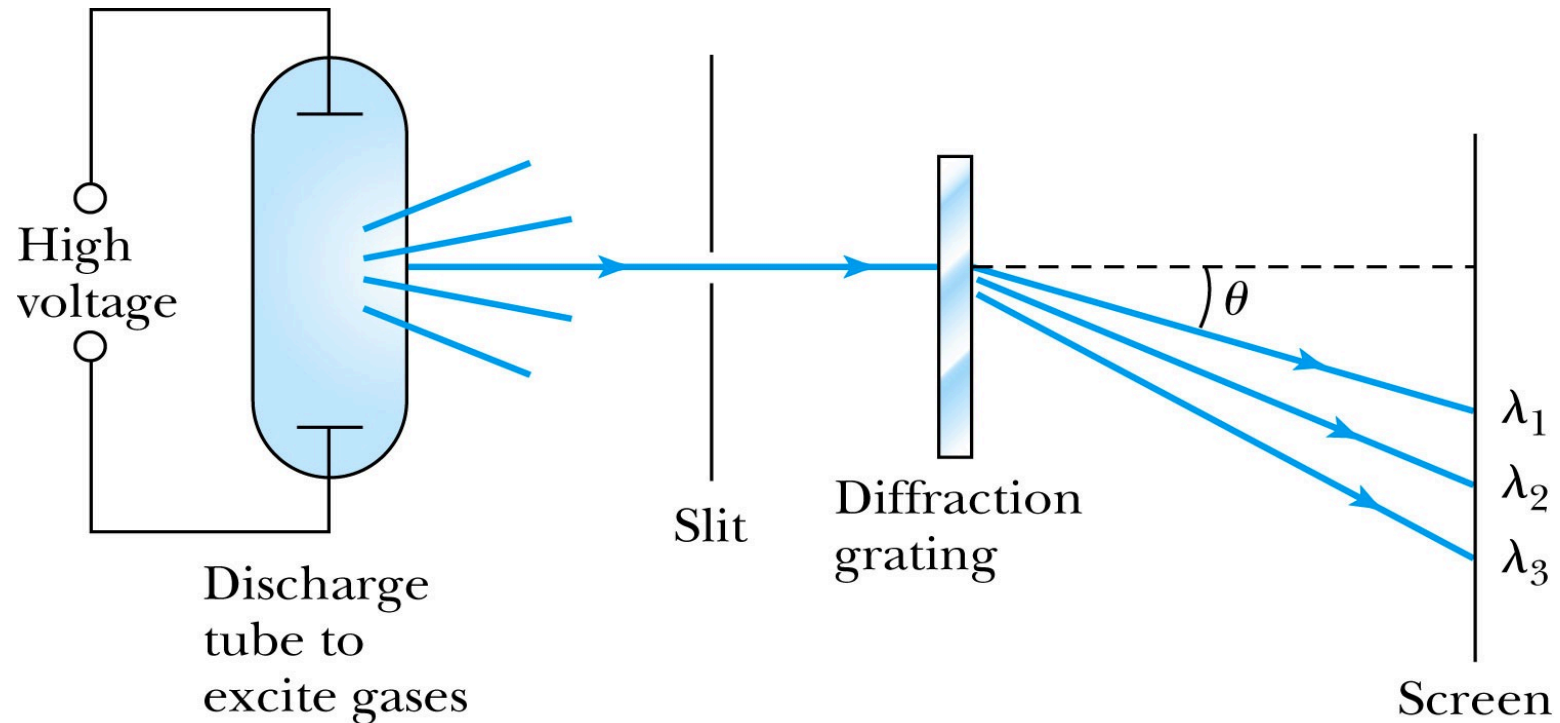
Line Spectra

- Chemical elements produce unique wavelengths of light when burned or excited in an electrical discharge.
- Collimated light is passed through a diffraction grating with thousands of ruling lines per centimeter.
 - The diffracted light is separated at an angle θ according to its wavelength λ by the equation:

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

where d is the distance between rulings and n is an integer called the order number

Optical Spectrometer

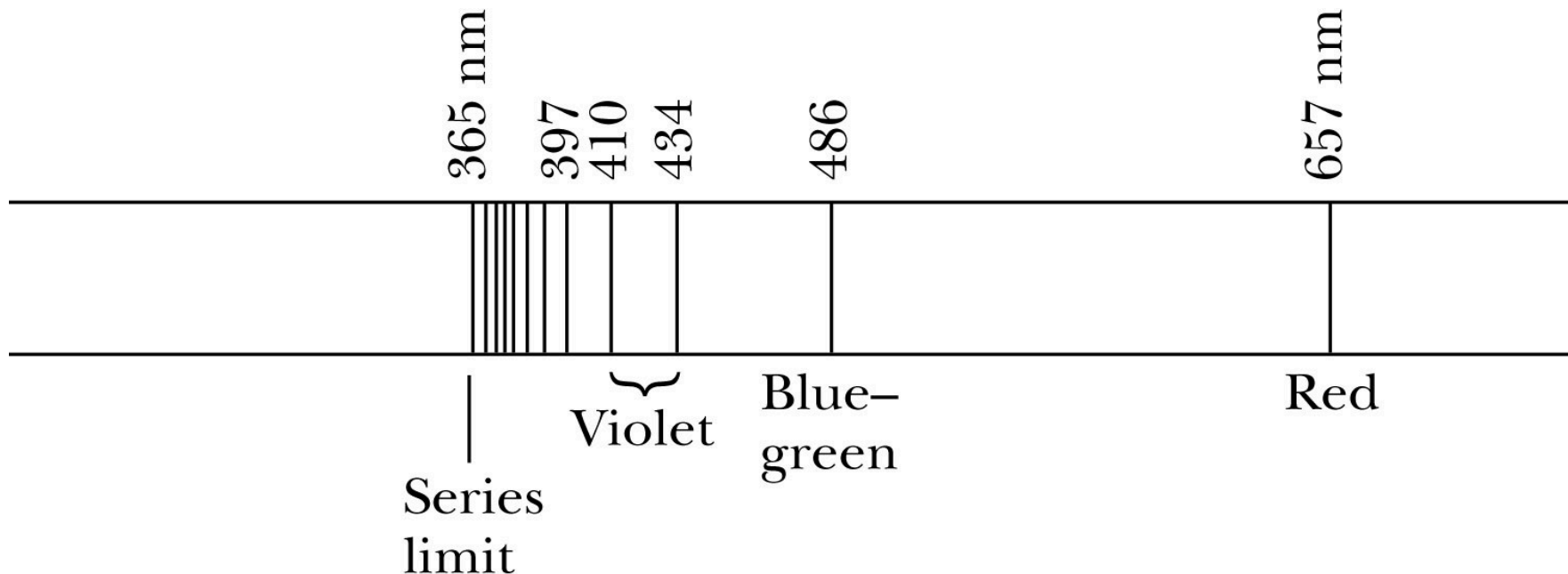


- Diffraction creates a *line spectrum* pattern of light bands and dark areas on the screen.
- Chemical elements and the composition of materials can be identified through the wavelengths of these line spectra

Balmer Series

- In 1885, Johann Balmer found an empirical formula for wavelength of the visible hydrogen line spectra in nm:

$$\lambda = 364.56 \frac{k^2}{k^2 - 4} \text{ nm} \quad (\text{where } k = 3, 4, 5 \dots \text{ and } k > 2)$$



Rydberg Equation

- Several more series of emission lines at infrared and ultraviolet wavelengths were discovered, the Balmer series equation was extended to the Rydberg equation:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n^2} - \frac{1}{k^2} \right) \quad R_H = 1.096776 \times 10^7 \text{ m}^{-1} \quad (n = 2)$$

Table 3.2 Hydrogen Series of Spectral Lines

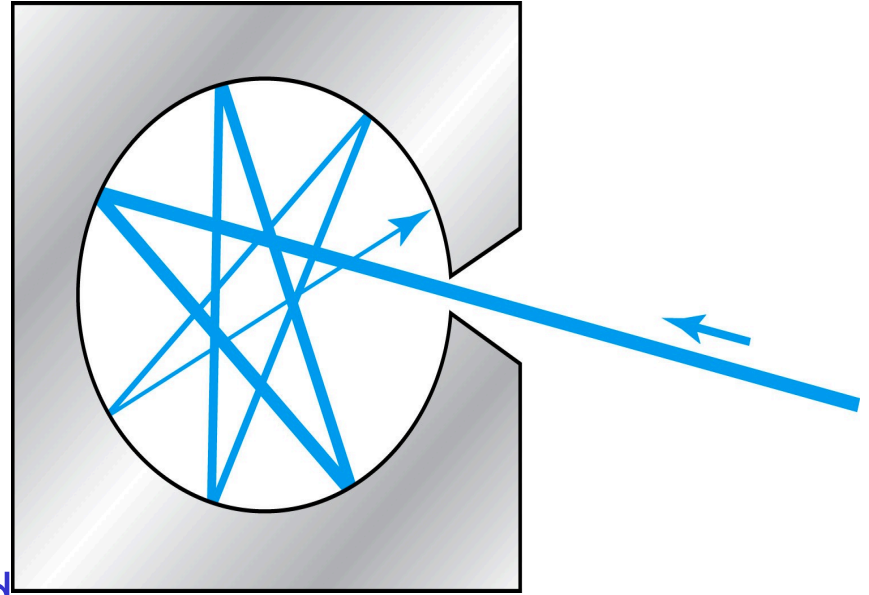
Discoverer (year)	Wavelength	n	k
Lyman (1916)	Ultraviolet	1	>1
Balmer (1885)	Visible, ultraviolet	2	>2
Paschen (1908)	Infrared	3	>3
Brackett (1922)	Infrared	4	>4
Pfund (1924)	Infrared	5	>5

Quantization

- Current theories predict that charges are quantized in units (**quarks**) of $\pm e/3$ and $\pm 2e/3$, but quarks are not directly observed experimentally.
- The charges of particles that have been directly observed are always quantized in units of $\pm e$.
- The measured atomic weights are not continuous—they have only discrete values, which are close to integral multiples of a unit mass.

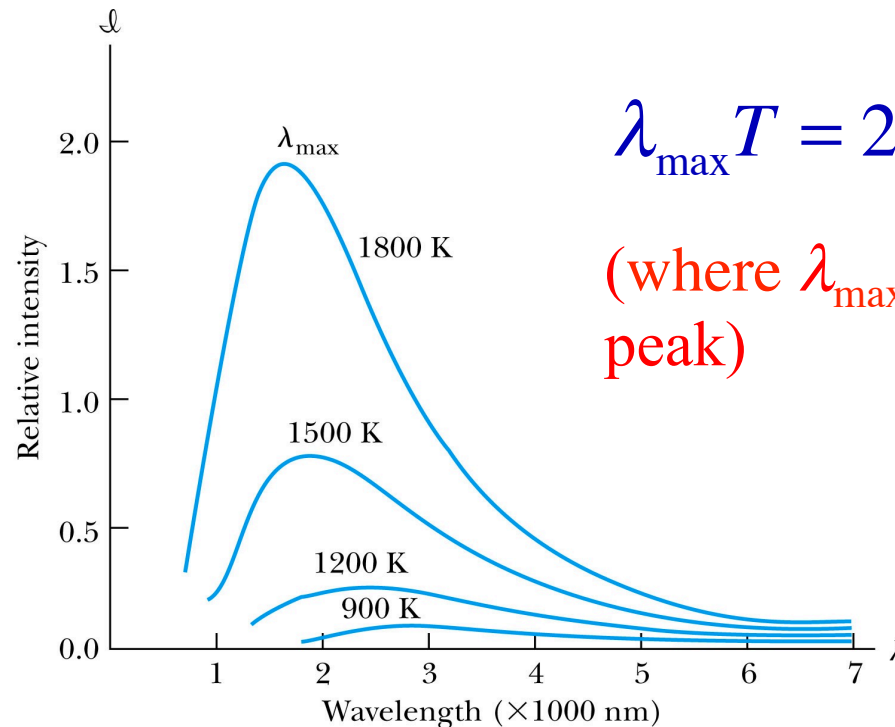
Blackbody Radiation

- When matter is heated, it emits radiation.
- A blackbody is an ideal object that has 100% absorption and 100% emission without a loss of energy
- A cavity in a material that only emits thermal radiation can be considered as a black-body. Incoming radiation is fully absorbed in the cavity.
- Blackbody radiation is theoretically interesting because
 - Radiation properties are independent of the particular material.
 - Properties of intensity versus wavelength at fixed temperatures can be studied



Wien's Displacement Law

- The intensity $\mathcal{I}(\lambda, T)$ is the total power radiated per unit area per unit wavelength at a given temperature.
- **Wien's displacement law:** The maximum of the distribution shifts to smaller wavelengths as the temperature increases.



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

(where λ_{\max} = wavelength of the peak)

Stefan-Boltzmann Law

- The total power radiated increases with the temperature:

$$R(T) = \int_0^{\infty} \ell(\lambda, T) d\lambda = \varepsilon \sigma T^4$$

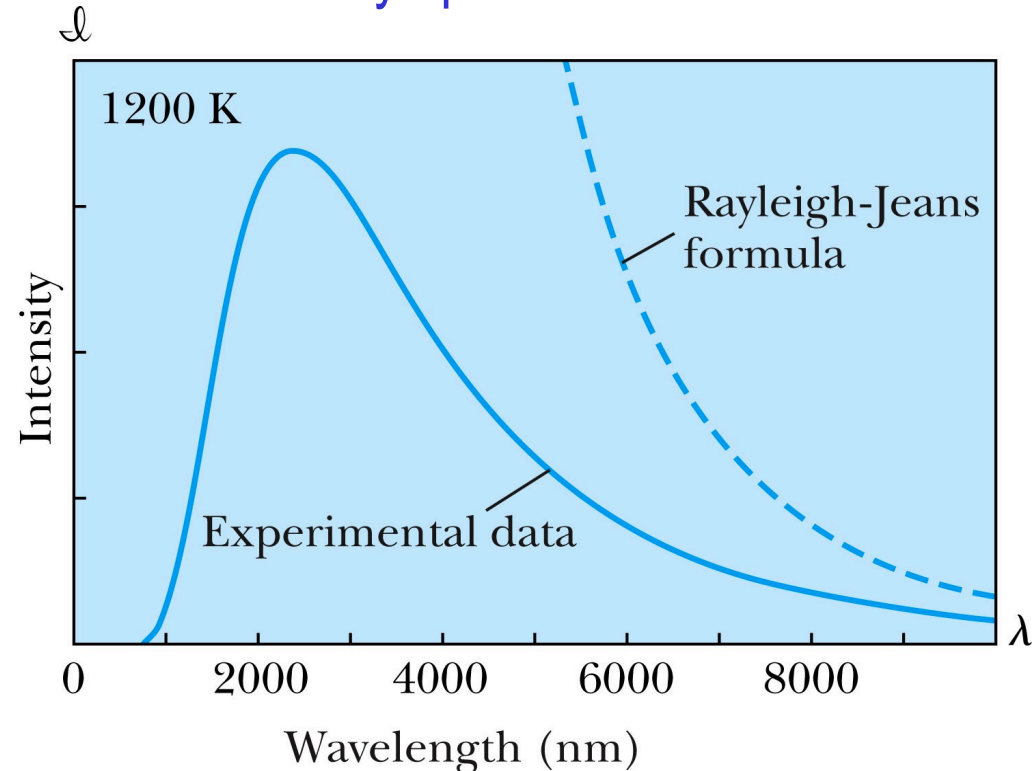
- This is known as the **Stefan-Boltzmann law**, with the constant σ experimentally measured to be $5.6705 \times 10^{-8} \text{ W} / (\text{m}^2 \cdot \text{K}^4)$.
- The **emissivity** ε ($\varepsilon = 1$ for an idealized blackbody) is the ratio of the emissive power of an object to that of an ideal blackbody and is always less than 1.



Rayleigh-Jeans Formula

- Lord Rayleigh used the classical theories of electromagnetism and thermodynamics to show that the blackbody spectral distribution should be

$$\ell(\lambda, T) = \frac{2\pi ckT}{\lambda^4}$$



- Worked reasonably at longer wavelengths
- it deviates badly at short wavelengths.
- ➔ “the ultraviolet catastrophe” a serious issue that couldn’t be explained

Planck's Radiation Law

- Planck assumed that the radiation in the cavity was emitted (and absorbed) by some sort of “oscillators” that were contained in the walls. He used Boltzman’s statistical methods to arrive at the following formula that fit the blackbody radiation data.

$$\ell(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad \text{Planck's radiation law}$$

- Planck made two modifications to the classical theory:
 - The oscillators (of electromagnetic origin) can only have certain discrete energies determined by $E_n = nhf$, where n is an integer, f is the frequency, and h is called Planck’s constant. $h = 6.6261 \times 10^{-34}$ J.s.
 - The oscillators can absorb or emit energy ONLY in discrete multiples of the fundamental quantum of energy** given by

$$\Delta E = hf = \frac{hc}{\lambda}$$

PHYS 3313-001, Fall 2013

Dr. Jaehoon Yu



Photoelectric Effect

Definition: Incident electromagnetic radiation shining on the material transfers energy to the electrons, allowing them to escape the surface of the metal. Ejected electrons are called photoelectrons

Other methods of electron emission:

- Thermionic emission: Application of heat allows electrons to gain enough energy to escape.
- Secondary emission: The electron gains enough energy by transfer from another high-speed particle that strikes the material from outside.
- Field emission: A strong external electric field pulls the electron out of the material.

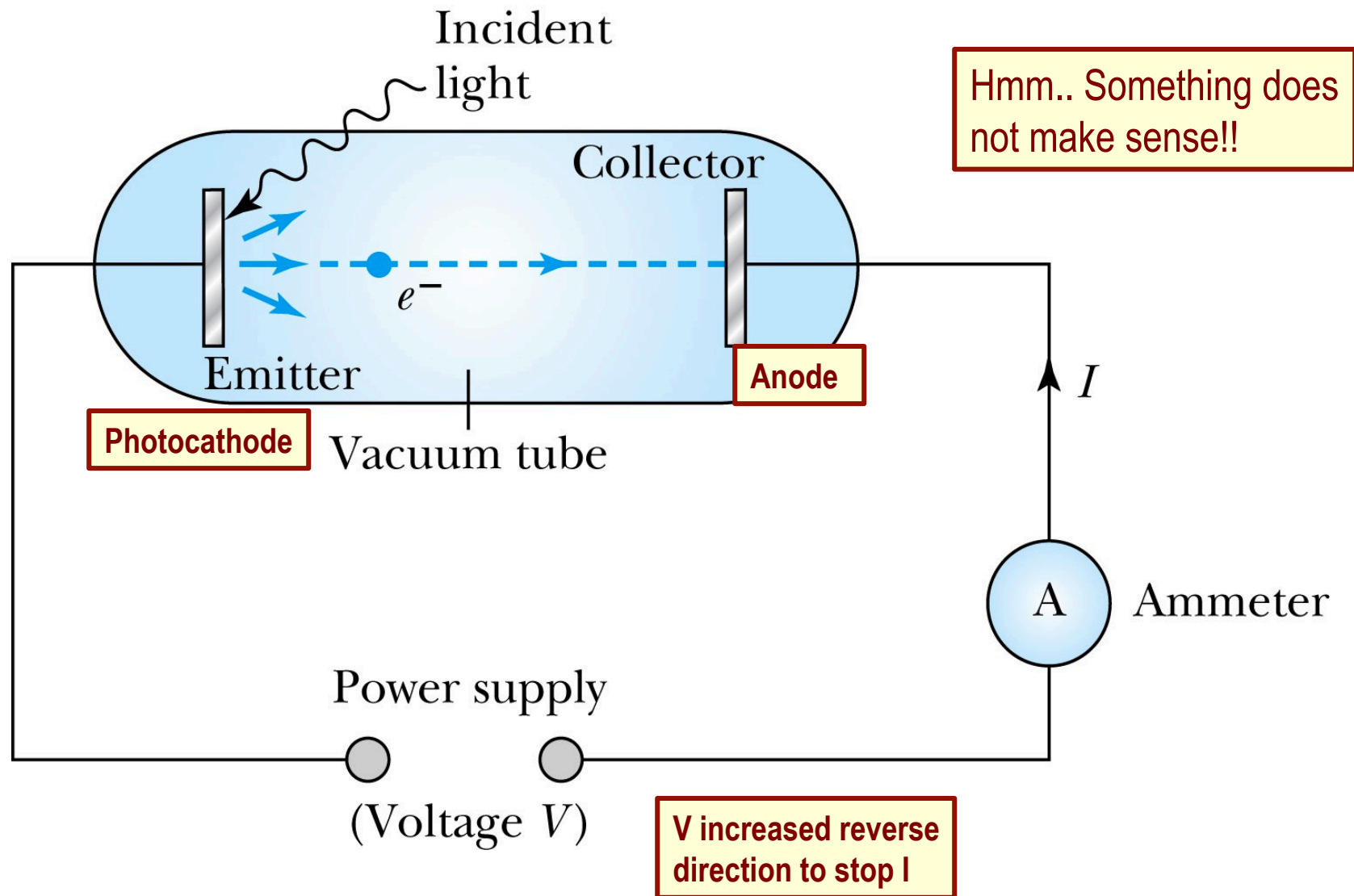


Classical Interpretation of Photoelectric Effect

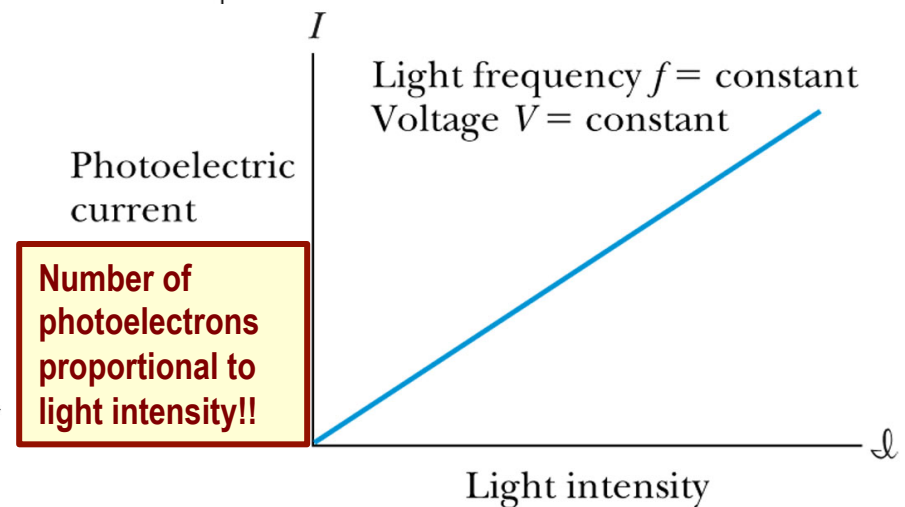
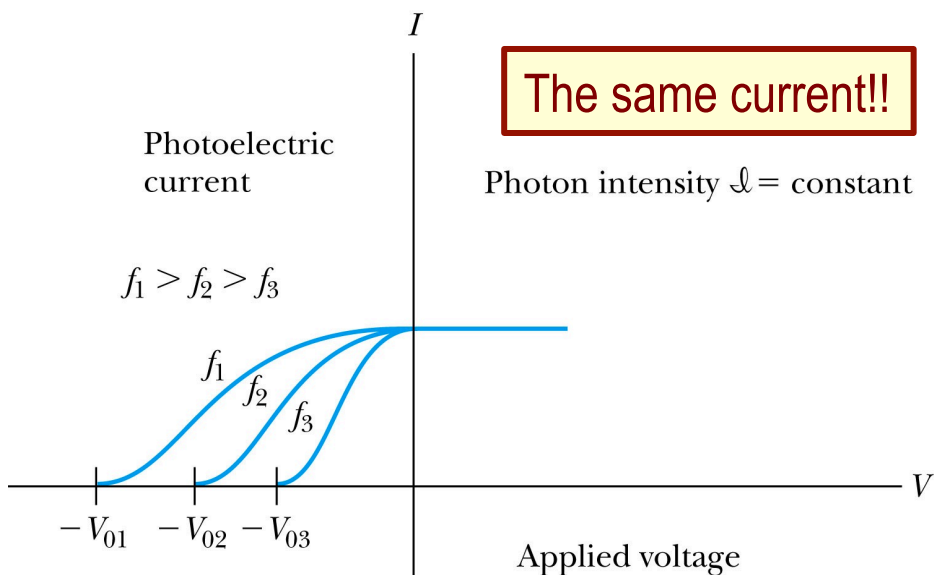
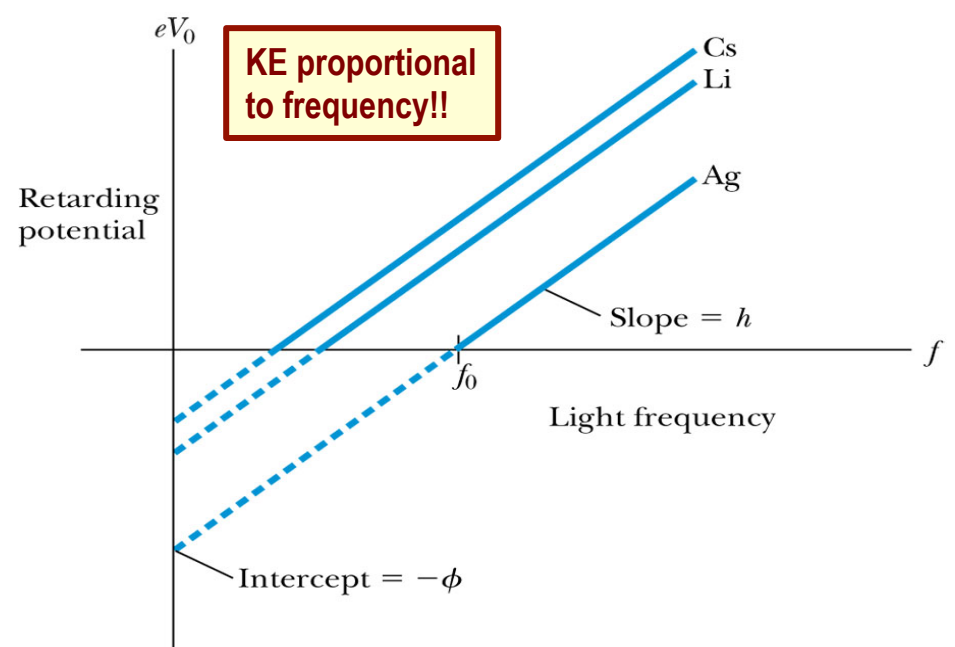
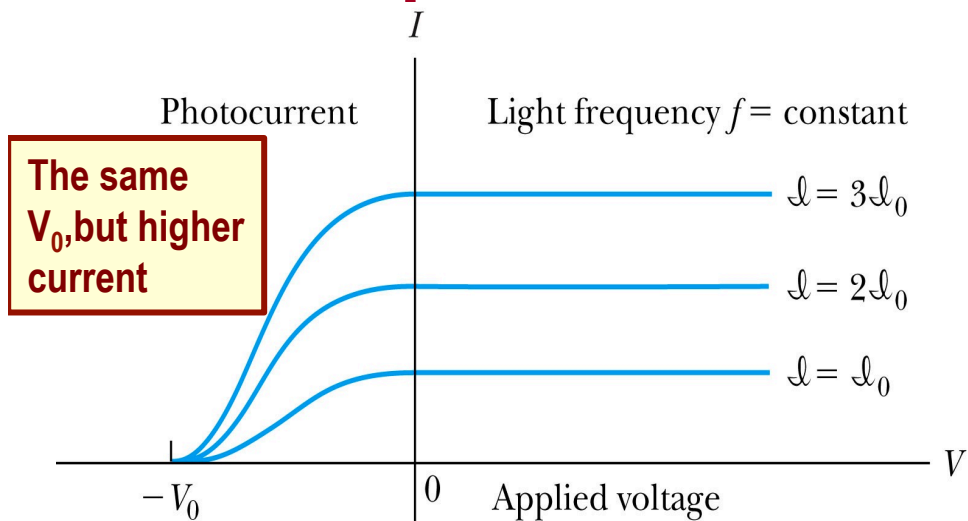
- Classical theory allows EM radiation to eject photoelectrons from matter
- Classical theory predicts the energy of the photoelectrons increase proportion to the radiation intensity
- Thus, KE of the photoelectrons must be proportional to the intensity of light not the current
- Time for an experiment!



Photoelectric Effect Experimental Setup



Experimental Observations



Summary of Experimental Observations

- Light intensity does not affect the KE of the photoelectrons
- The max KE of the photoelectrons, for a given emitting material, depends only on the frequency of the light
- The smaller the work function ϕ of the emitter material, the smaller is the threshold frequency of the light that can eject photoelectrons.
- When the photoelectrons are produced, their number is proportional to the intensity of light.
- The photoelectrons are emitted almost instantly following illumination of the photocathode, independent of the intensity of the light. → Totally unexplained by classical physics

Einstein's Theory of Photoelectric Effect

- Einstein suggested that the electromagnetic radiation field is quantized into particles called **photons**. Each photon has the energy quantum:

$$E = hf$$

where f is the frequency of the light and h is Planck's constant.

- The photon travels at the speed of light in a vacuum, and its wavelength is given by

$$\lambda f = c$$

Einstein's Theory

- Conservation of energy yields:

Energy Before(photo)=Energy After (electron)

$$hf = \phi + KE(photo - electron)$$

where ϕ is the work function of the metal

The energy can then be written

$$hf = \phi + \frac{1}{2}mv_{\max}^2$$

- The retarding potentials measured the KE of the most energetic photoelectrons.

$$eV_0 = \frac{1}{2}mv_{\max}^2$$

Quantum Interpretation

- KE of the electron depend only on the light frequency and the work function ϕ of the material not the light intensity at all

$$\frac{1}{2}mv_{\max}^2 = eV_0 = hf - \phi$$

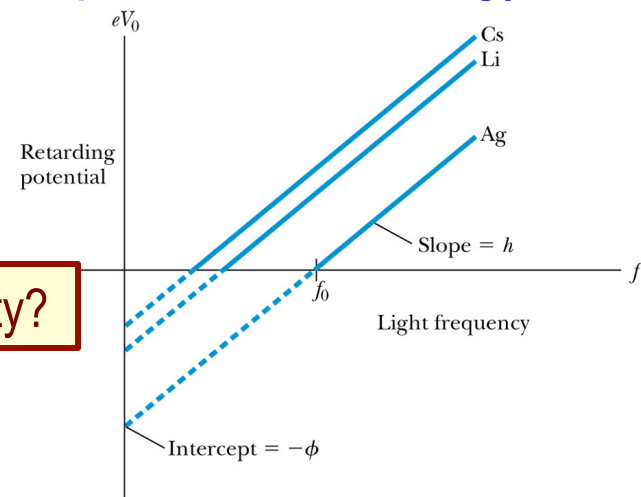
- Einstein in 1905 predicted that the stopping potential was linearly proportional to the light frequency, with a slope h , the same constant found by Planck.

$$eV_0 = \frac{1}{2}mv_{\max}^2 = hf - hf_0 = h(f - f_0)$$

- From this, Einstein concluded that light is a particle with energy:

$$E = hf = \frac{hc}{\lambda}$$

Was he already thinking about particle/wave duality?



Ex 3.11: Photoelectric Effect

- Light of wavelength 400nm is incident upon lithium ($\phi=2.93\text{eV}$). Calculate (a) the photon energy and (b) the stopping potential V_0 .
- Since the wavelength is known, we use plank's formula:

$$E = hf = \frac{hc}{\lambda} = \frac{(1.626 \times 10^{-34} \text{ J} \cdot \text{s})(3 \times 10^8 \text{ m/s})}{400 \times 10^{-9} \text{ m}} = 3.10 \text{ eV}$$

- The stopping potential can be obtained using Einstein's formula for photoelectron energy

$$eV_0 = hf - \phi = E - \phi$$

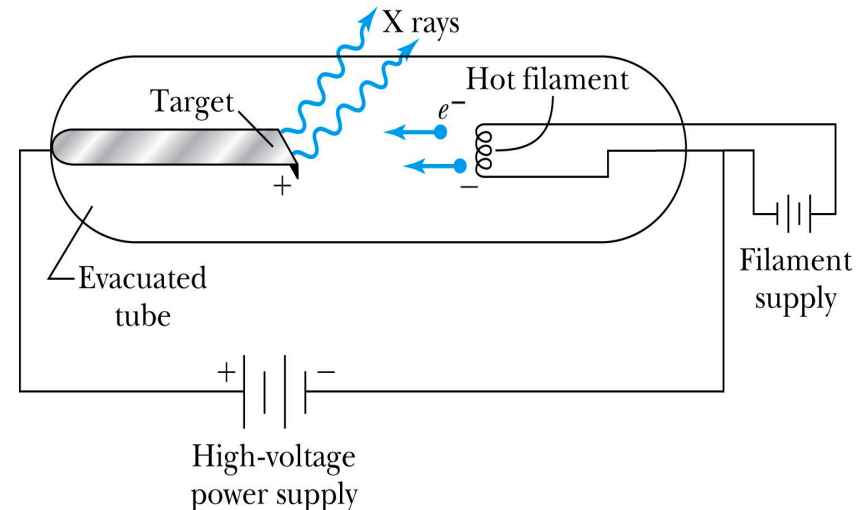
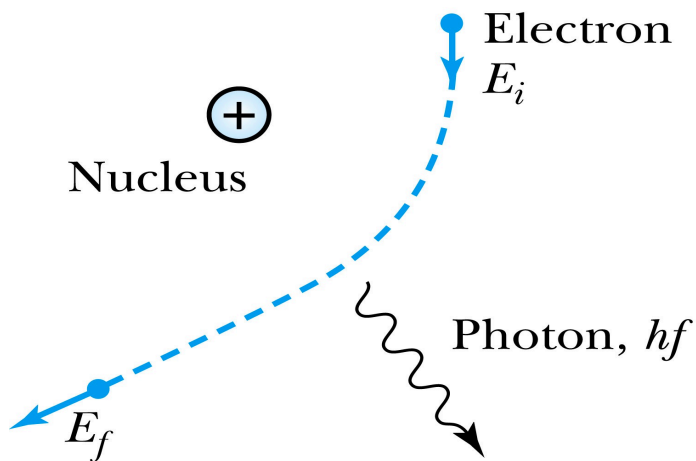
$$V_0 = \frac{E - \phi}{e} = \frac{(3.10 - 2.93) \text{ eV}}{e} = 0.17 \text{ V}$$

X-Ray Production

- **Bremsstrahlung** (German word for braking radiation): Radiation of a photon from an energetic electron passing through matter due to an acceleration
- Since linear momentum must be conserved, the nucleus absorbs very little energy, and it is ignored. The final energy of the electron is determined from the conservation of energy to be

$$E_f = E_i - hf$$

- An electron that loses a large amount of energy will produce an X-ray photon.
 - Current passing through a filament produces copious numbers of electrons by thermionic emission.
 - These electrons are focused by the cathode structure into a beam and are accelerated by potential differences of thousands of volts until they impinge on a metal anode surface, producing x rays by bremsstrahlung as they stop in the anode material



Inverse Photoelectric Effect.

- Conservation of energy requires that the electron KE equal the maximum photon energy

- Work function neglected since it's small compared to the potential energy of the electron.

- This is the **Duane-Hunt limit**

- The photon wavelength depends only on the accelerating voltage
- The same for all targets.

$$eV_0 = hf_{\max} = \frac{hc}{\lambda_{\min}}$$
$$\lambda_{\min} = \frac{hc}{eV_0} = \frac{1.24 \times 10^{-6} \text{ V} \cdot \text{m}}{V_0}$$

