# PHYS 3313 – Section 001
# Lecture #12

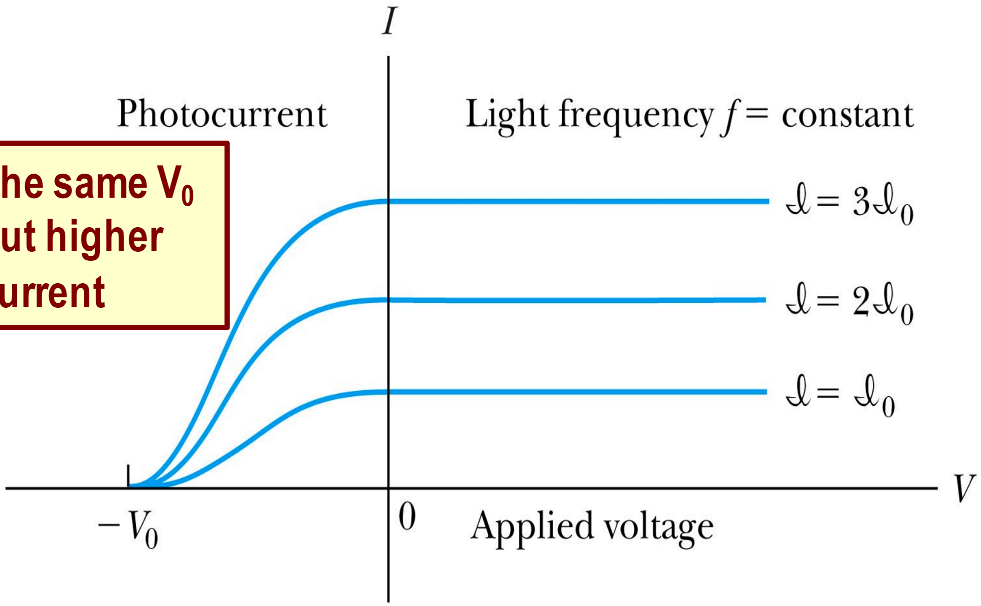
*Monday, Feb. 27, 2017*
*Dr. Jaehoon Yu*

- Photoelectric Effect
- Compton Effect
- Pair production/Pair annihilation
- Rutherford Scattering Experiment and Rutherford Atomic Model

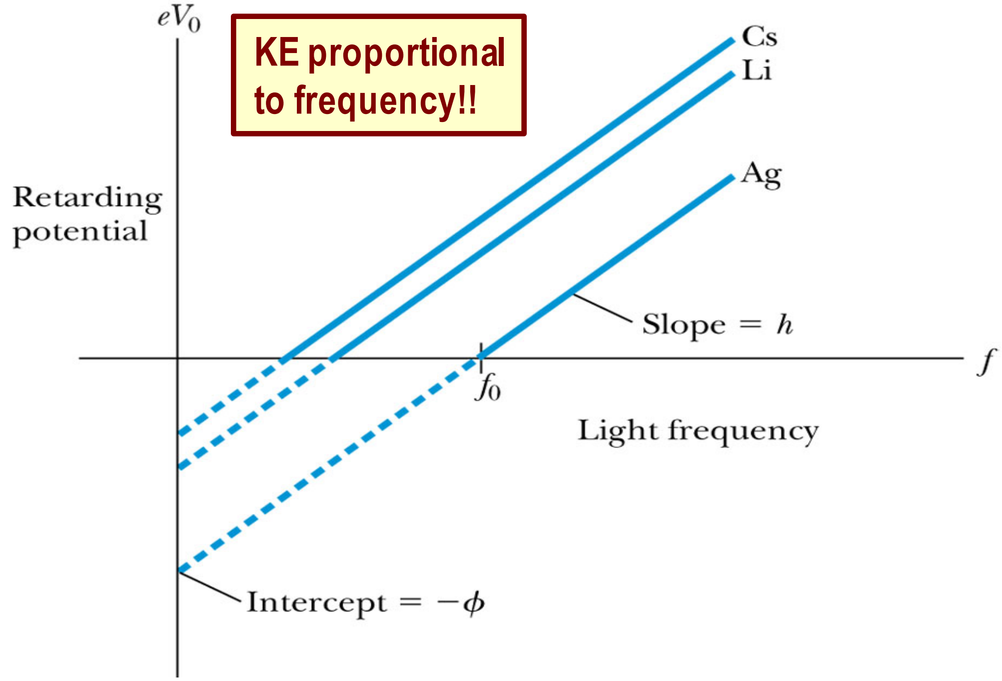
# Announcements

- Midterm Exam
  - In class Wednesday, March. 8
  - Covers from CH1.1 through what we learn March 6 plus the math refresher in the appendices
  - Mid-term exam constitutes 20% of the total
  - **Please do NOT miss the exam! You will get an F if you miss it.**
  - BYOF: You may bring a one 8.5x11.5 sheet (front and back) of handwritten formulae and values of constants for the exam
  - No derivations, word definitions or solutions of any problems!
    - Eg., Lorentz velocity transformation NOT allowed!
  - No additional formulae or values of constants will be provided!
- Quiz 2 results
  - Class Average: 34.5/60
  - Equivalent to : 57.5/100
    - Previous result: 20.8/100
  - Class top score: 60/60

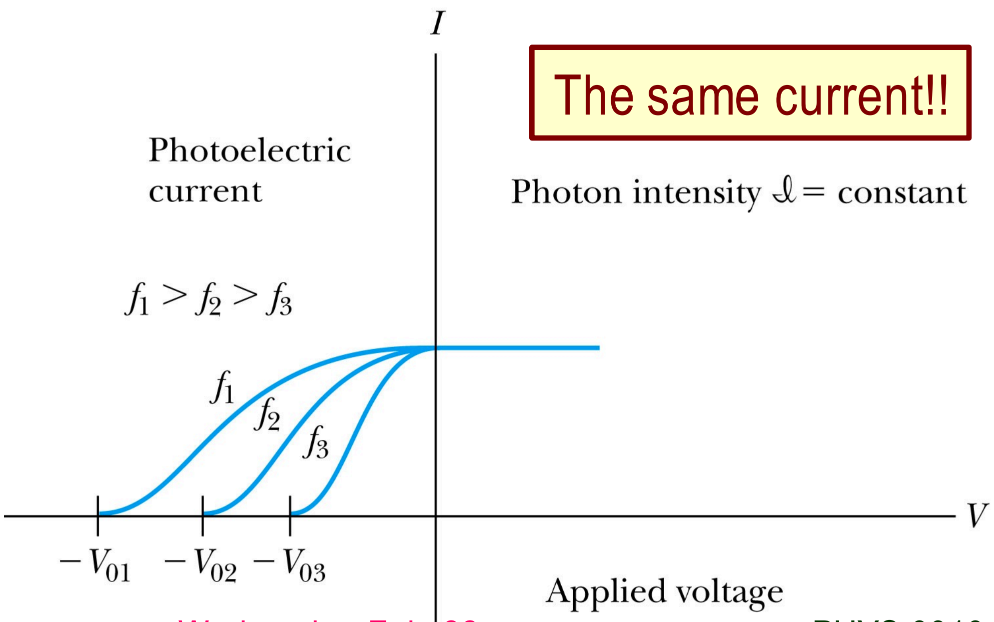
# Experimental Observations



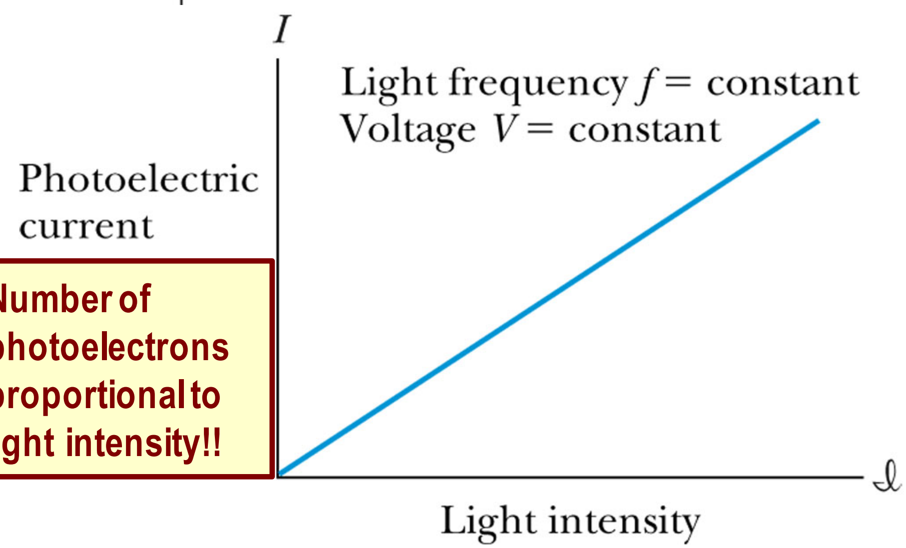

The same $V_0$ but higher current




KE proportional to frequency!!




The same current!!




Number of photoelectrons proportional to light intensity!!

# Summary of Experimental Observations

- Light intensity does not affect the KE of the photoelectrons
- The max KE of the photoelectrons for a given emitter material depends only on the frequency of the light
- The smaller the work function $\phi$ 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 the illumination of the photocathode, independent of the intensity of the light. ➔ Totally unexplained by classical physics

# Einstein's Theory of Photoelectric Effect

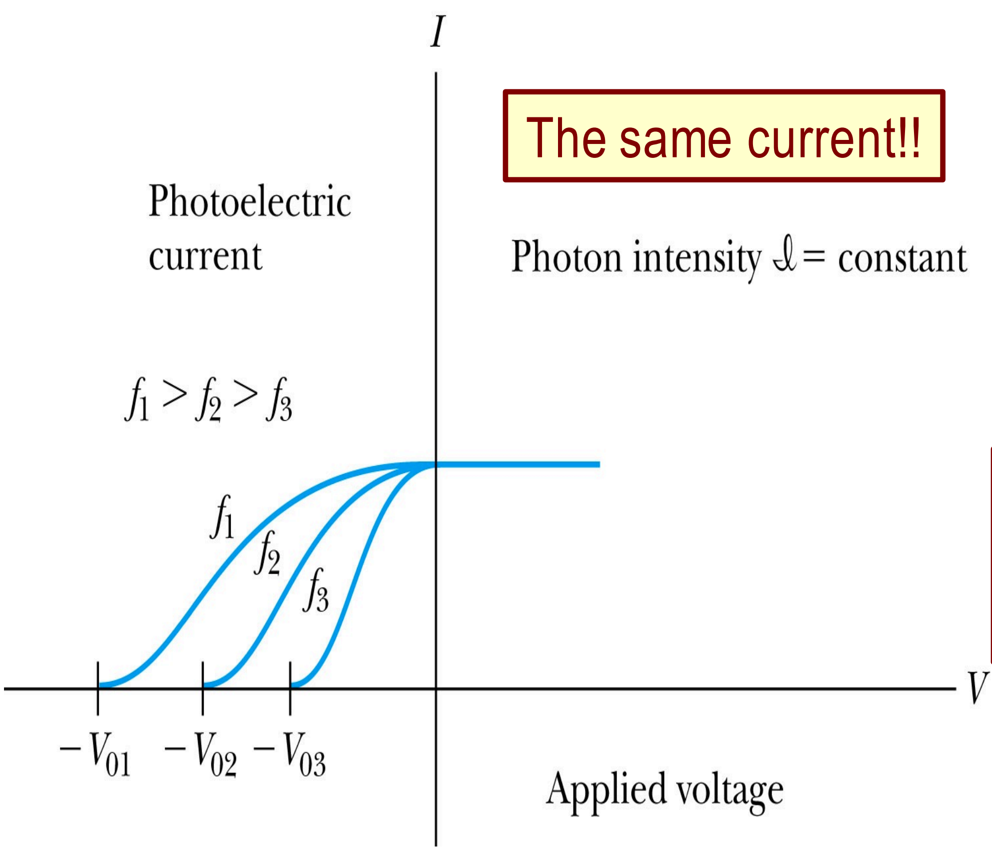
- Einstein suggested that the electromagnetic radiation of the light is quantized into particles called **photons**. Each photon has the energy quantum:

$$E = hf$$

- where *f* is the frequency of the light and *h* is Planck's constant.
- The photon travels at the speed of light in vacuum, and its wavelength is given by

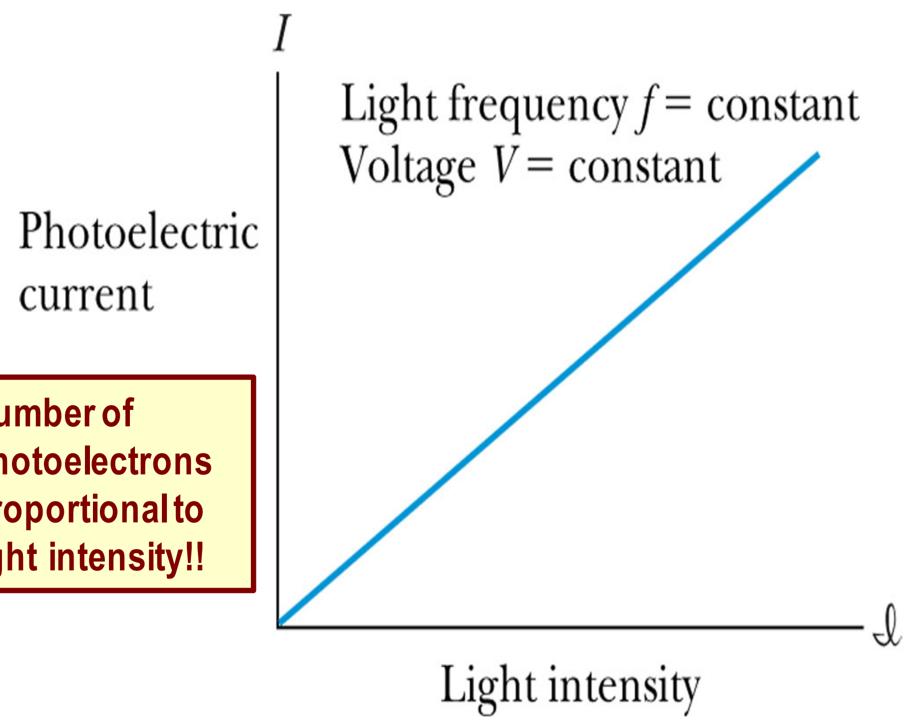
$$\lambda f = c$$

# Experimental Observations




The same current!!

Number of photoelectrons proportional to light intensity!!



# Einstein's Theory

- Conservation of energy yields:

$$\text{Energy Before(photon)=Energy After (electron)}$$

$$hf = \phi + KE(photoelectron)$$

where $\phi$ is the work function of the metal

The photon energy can then be written

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

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

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

# Quantum Interpretation

- KE of the electron depends only on the light frequency and the work function $\phi$ of the material not the light intensity at all

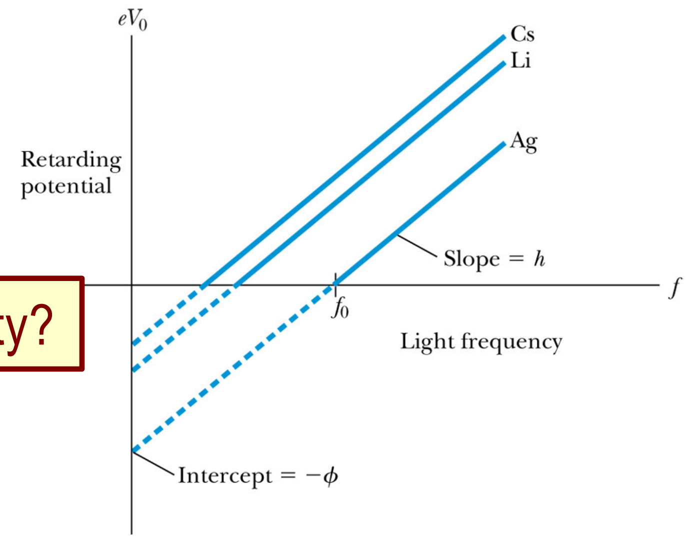
$$\frac{1}{2}mv_{max}^2 = eV_0 = hf - \phi$$

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

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

- 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 ($\phi$=2.93eV). Calculate (a) the photon energy (eV) and (b) the stopping potential $V_0$.

- Since the wavelength is known, we use plank's formula:

$$E = hf = \frac{hc}{\lambda} = \frac{\left(1.626\times10^{-34}\,J\cdot s\right)\left(3\times10^{8}\,m/s\right)}{400\times10^{-9}\,m} = 3.10eV$$

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

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

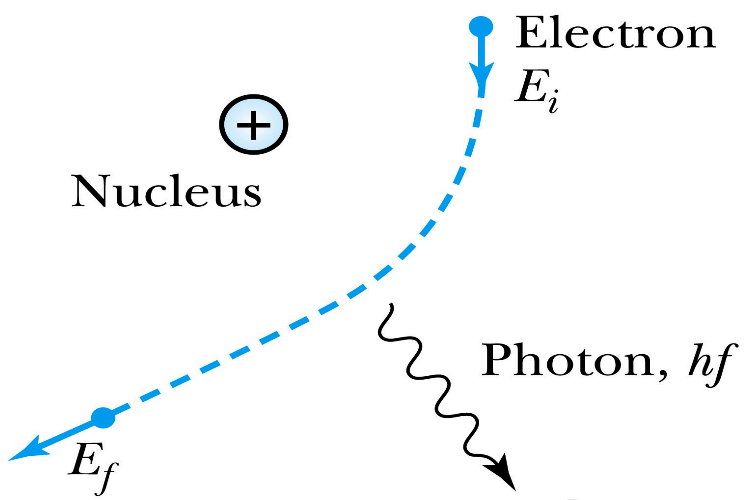
$$V_0 = \frac{E-\phi}{e} = \frac{\left(3.10-2.93\right)eV}{e} = 0.17V$$

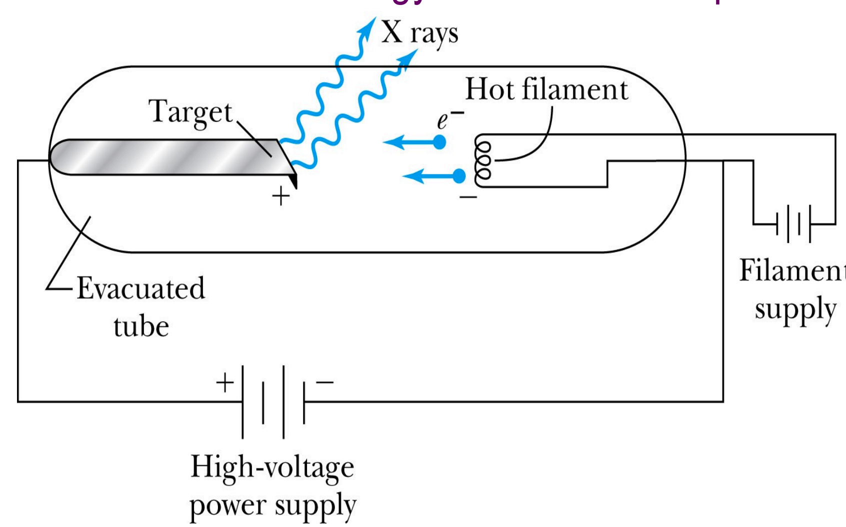
# X-Ray Production

- **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

$$E_f = E_i - hf$$

- 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
  - X-ray wavelengths range 0.01 – 10nm. What is the minimum energy of an electron to produce X-ray?



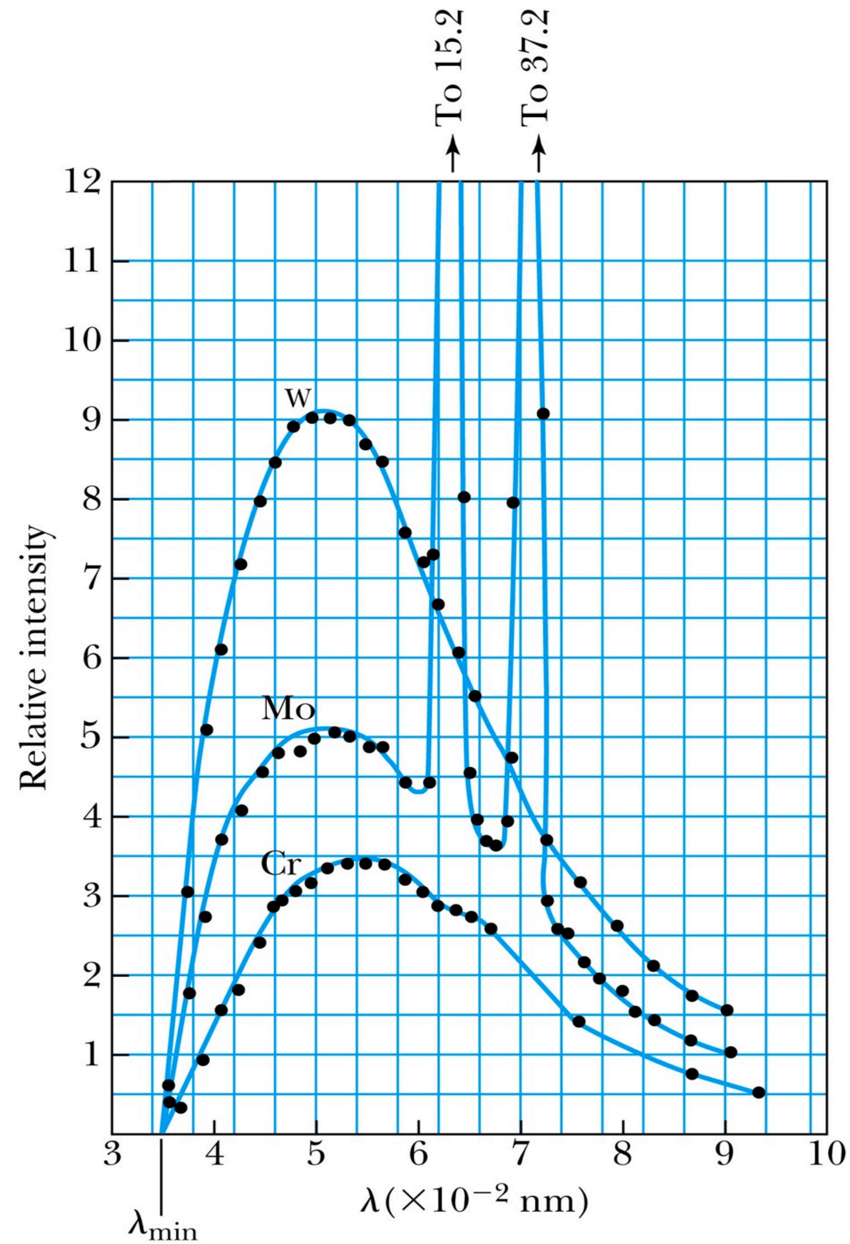



# Inverse Photoelectric Effect.

- Conservation of energy requires that the electron KE equals 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.

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

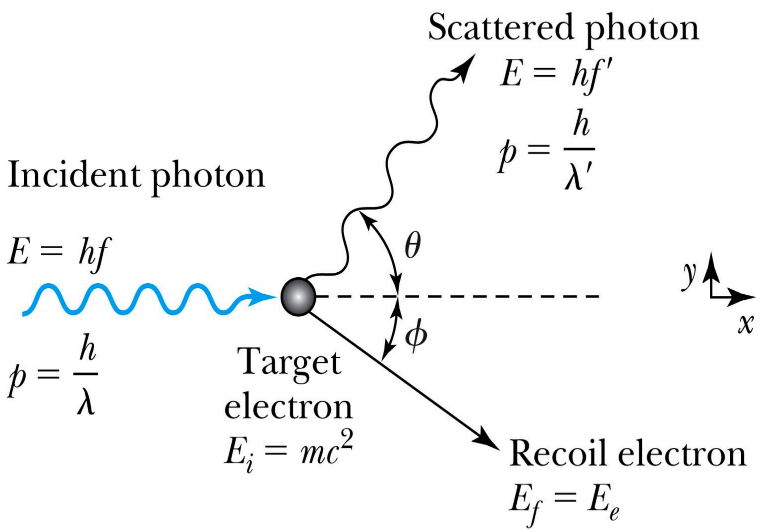
$$\lambda_{min} = \frac{hc}{eV_0} = \frac{1.24\times 10^{-6} V\cdot m}{V_0}$$



# Compton Effect

- When a photon enters matter, it is likely to interact with one of the atomic electrons.
- The photon is scattered from only one electron
- The laws of conservation of energy and momentum apply as in any elastic collision between two particles. The momentum of a particle moving at the speed of light is

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




- The electron energy can be written as

$$E_e^2 = \left(m_e c^2\right)^2 + p_e^2 c^2$$

- Change of the scattered photon wavelength is known as the **Compton effect**:

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

# Pair Production and Annihilation

- If a photon can create an electron, it must also create a positive charge to balance charge conservation.
- In 1932, C. D. Anderson observed a positively charged electron ($e^+$) in cosmic radiation. This particle, called a positron, had been predicted to exist several years earlier by P. A. M. Dirac.
- A photon's energy can be converted entirely into an electron and a positron in a process called **pair production**.
  - Can only happen inside a material
  - How much energy do you think is needed?

$$\gamma \rightarrow e^- + e^+$$

# Pair Production in Empty Space?

- Energy conservation for pair production in empty space

$$hf = E_+ + E_- + K.E.$$

- Momentum conservation yields

$$hf = p_- c\cos\theta + p_+ c\cos\theta$$

- Thus max momentum exchange $hf_{\max} = p_- c + p_+ c$
- Recall that the total energy for a particle can be written as

$$E_\pm^2 = p_\pm^2 c^2 + m_e^2 c^4$$

However this yields a contradiction: $hf > p_- c + p_+ c$

and hence the conversion of energy in empty space is impossible and thus pair production cannot happen in empty space

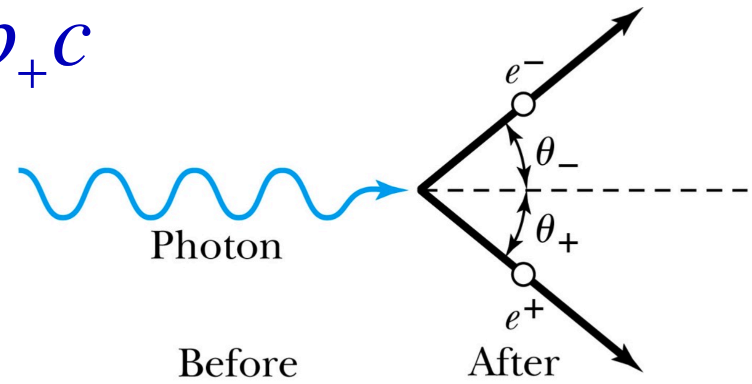
# Pair Production in Matter

- Since the relations $hf_{\max} = p_{-}c + p_{+}c$ and $hf > p_{-}c + p_{+}c$ contradict each other, a photon can not produce an electron and a positron in empty space.
- In the presence of matter, however, the nucleus absorbs some energy and momentum.

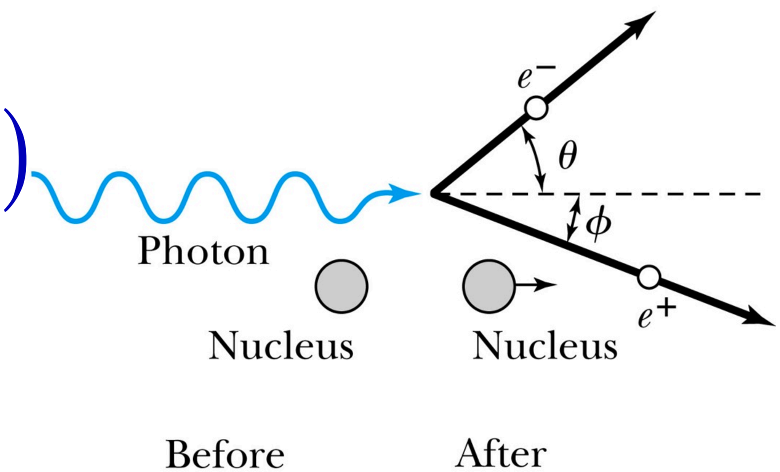
$$hf = E_{-} + E_{+} + K.E.(\text{nucleus})$$

- The photon energy required for pair production in the presence of matter is

$$hf > 2m_e c^2$$



(a) Free space (**cannot occur**)



(b) Beside nucleus

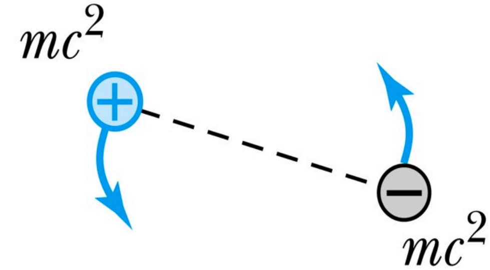
# Pair Annihilation

- A positron going through matter will likely **annihilate** with an electron.
- A positron is drawn to an electron and form an atom-like configuration called **positronium**.
- Pair annihilation in empty space will produce two photons to conserve momentum. Annihilation near a nucleus can result in a single photon.
- Conservation of energy: $2m_e c^2 \approx hf_1 + hf_2$
- Conservation of momentum: $0 = \frac{hf_1}{c} - \frac{hf_2}{c}$
- The two photons will be almost identical, so that

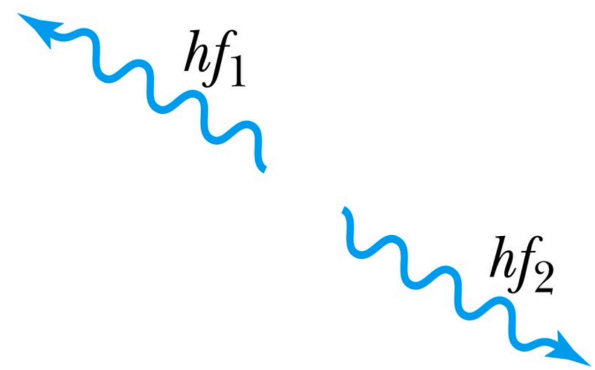
$$f_1 = f_2 = f$$

- The two photons from a positronium annihilation will move in the opposite directions with an energy of:

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




(a) Positronium, before decay (schematic only)




(b) After annihilation