# PHYS 3313 – Section 001 Lecture #7

Wednesday, Sept. 19, 2012 Dr. **Jae**hoon **Yu** 

- 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, Sept. 26
- Quiz #2 Wednesday, Sept. 26
  - Beginning of the class
  - Covers CH1.1 what we finish Monday, Sept. 24
- Conference volunteer application
  - LCWS12 international conference : Oct. 21 26, 2012
  - Send e-mail to Dr. Jackson (cbjackson@uta.edu)
    - Subject must have: LCWS12 Volunteer Application
- Colloquium this week: Physics Faculty Expo II
  - Drs. Chen (bio-phys), Park (Astro), White (HEP), Mohanty(bio-phy), Fazleev (material) and Ngai (optics)



#### 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





#### 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  $\phi$  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 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 (photon) = energy after (electron)

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

where  $\phi$  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  $\phi$  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 a slope h, the same constant found by Planck.  $eV_0 = \frac{1}{2}mv_{\text{max}}^2 = hf - hf_0 = h(f - f_0)$
- From this, Einstein concluded that light is a particle with energy:

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$$E = hf = \frac{hc}{\lambda}$$
Retarding  
potential
Retarding  
potential
Retarding  
potential
Retarding  
potential
Retarding  
potential
Retarding  
Slope = h
f
Light frequency

### Ex 3.11: Photoelectric Effect

- Light of wavelength 400nm is incident upon lithium (=2.93eV).
   Calculate (a) the photon energy and (b) the stopping potential V<sub>0</sub>.
- Since the wavelength is known, we use plank's formula:

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

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

$$eV_0 = hf - \phi = E - \phi$$
$$V_0 = \frac{E - \phi}{e} = \frac{(3.10 - 2.93)eV}{e} = 0.17V$$



#### **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 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.

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- 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.



#### **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

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



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

$$\Delta \lambda = \lambda' + \lambda = \frac{h}{mc} (1 - \cos \theta)$$



#### Radioactive Source Run with Internal Trigger



#### **GEM Application Potential**

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:







#### A. Bressan et al, Nucl. Instr. and Meth. A 425(1999)254 F. Sauli, Nucl. Instr. and Meth.A 461(2001)47

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### 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<sup>+</sup>) 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.

·e

- Can only happen inside a material
- How much energy do you think is needed?



# 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 energy exchange

$$hf_{\rm max} = p_-c + p_+c$$

Recall that the total energy for a particle can be written as

$$E_{\pm}^{2} = p_{\pm}^{2}c^{2} + m^{2}c^{4}$$

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 Wednesday, Sept. 19, 2012 PHYS 3313-001, Fall 2012 19 Dr. Jaehoon Yu

#### 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, the nucleus absorbs some energy and momentum.

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

The photon energy required for pair production in the presence of matter is  $hf > 2m_ec^2 = 1.022$  MeV





(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:  $2m_ec^2 \approx hf_1 + hf_2$
- 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 positronium annihilation will move in opposite directions with an energy:

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

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Positronium, before decay (schematic only)



(b) After annihilation