Lecture 28

- Modern Physics
  - Quantum Physics
  - Compton scattering

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Chapter 27
If you want to know your progress so far, please send me an email request at

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Lightning Review

Last lecture:

1. Quantum physics
   ✓ Photoeffect

\[ E_n = n hf , \quad n = 1, 2, 3, ... \]

\[ KE = hf - \Phi \]

**Review Problem:** A xenon arc lamp is covered with an interference filter that only transmits light of 400- nm wavelength. When the transmitted light strikes a metal surface, a stream of electrons emerges from the metal. If the intensity of the light striking the surface is doubled,

1. more electrons are emitted in a given time interval.
2. the electrons that are emitted are more energetic.
3. both of the above.
4. neither of the above.
Molybdenum has a work function of 4.20 eV. Calculate the stopping potential if the incident light has a wavelength of 180 nm.
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**Given:**
- $\Phi = 4.40 \text{ eV}$
- $\lambda = 180 \text{ nm}$

**Find:**
- $V_s = ?$

Recall that $KE_{max} = hf - \Phi$. This can be used to obtain kinetic energy, which will be equal to electric potential energy

$$KE_{max} = e(\Delta V_s)$$

Thus,

$$\Delta V_s = \frac{hf}{e} - \frac{\Phi}{e} = \frac{hc}{e\lambda} - \frac{\Phi}{e}$$

Or numerically,

$$\Delta V_s = \left( \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{1.60 \times 10^{-19} \text{ C}} \right) \left( \frac{3.00 \times 10^8 \text{ m/s}}{180 \times 10^{-9} \text{ m}} \right) - \left( \frac{4.20 \text{ eV}}{1.60 \times 10^{-19} \text{ J/eV}} \right) \frac{1.60 \times 10^{-19} \text{ C}}{1.60 \times 10^{-19} \text{ C}} = 2.71 \text{ V}$$
27.4 X-Rays

- Electromagnetic radiation with short wavelengths
  - Wavelengths less than for ultraviolet
  - Wavelengths are typically about 0.1 nm
  - X-rays have the ability to penetrate most materials with relative ease

- Discovered and named by Roentgen in 1895
Production of X-rays

- X-rays are produced when high-speed electrons are suddenly slowed down
  - Can be caused by the electron striking a metal target

- A current in the filament causes electrons to be emitted

- These freed electrons are accelerated toward a dense metal target

- The target is held at a higher potential than the filament
Production of X-rays

- An electron passes near a target nucleus.
  - The electron is deflected from its path by its attraction to the nucleus.
    - This produces an acceleration.
- It will emit electromagnetic radiation when it is accelerated.

The maximum x-ray energy, and minimum wavelength results when the electron loses all its energy in a single collision, such that

\[ e\Delta V = h f_{\text{max}} = \frac{hc}{\lambda_{\text{min}}} \]

or therefore

\[ \lambda_{\text{min}} = \frac{hc}{e\Delta V} \]
Diffraction of X-rays by Crystals

For diffraction to occur, the spacing between the lines must be approximately equal to the wavelength of the radiation to be measured.

For X-rays, the regular array of atoms in a crystal can act as a three-dimensional grating for diffracting X-rays.
Schematic for X-ray Diffraction

- A continuous beam of X-rays is incident on the crystal.

- The diffracted radiation is very intense in certain directions.
  - These directions correspond to constructive interference from waves reflected from the layers of the crystal.

- The diffraction pattern is detected by photographic film.
The array of spots is called a *Laue* pattern.

The crystal structure is determined by analyzing the positions and intensities of the various spots.

This is for NaCl.
Bragg’s Law

The beam reflected from the lower surface travels farther than the one reflected from the upper surface.

If the path difference equals some integral multiple of the wavelength, constructive interference occurs.

Bragg’s Law gives the conditions for constructive interference.

\[ 2d \sin \theta = m \lambda, \quad m = 1, 2, 3 \ldots \]
Problem: X-ray diffraction

X-rays of wavelength 0.140 nm are reflected from a certain crystal, and the first-order maximum occurs at an angle of 14.4°. What value does this give for the interplanar spacing of this crystal?
27.4 The Compton Effect

- Compton directed a beam of x-rays toward a block of graphite.
- He found that the scattered x-rays had a slightly longer wavelength than the incident x-rays.
  - This means they also had less energy.
- The amount of energy reduction depended on the angle at which the x-rays were scattered.
- The change in wavelength is called the *Compton shift*.
Compton Scattering

- Compton assumed the photons acted like other particles in collisions
- Energy and momentum were conserved
- The shift in wavelength is

\[ \Delta \lambda = \lambda - \lambda_0 = \frac{h}{m_e c} (1 - \cos \theta) \]

Compton wavelength
Compton Scattering

The quantity $\frac{h}{m_e c}$ is called the *Compton wavelength*

- Compton wavelength = 0.00243 nm
- Very small compared to visible light

The Compton shift depends on the **scattering angle** and not on the **wavelength**

Experiments confirm the results of Compton scattering and strongly support the photon concept
Problem: Compton scattering

A beam of 0.68-nm photons undergoes Compton scattering from free electrons. What are the energy and momentum of the photons that emerge at a 45° angle with respect to the incident beam?
QUICK QUIZ 1

An x-ray photon is scattered by an electron. The frequency of the scattered photon relative to that of the incident photon (a) increases, (b) decreases, or (c) remains the same.

(b). Some energy is transferred to the electron in the scattering process. Therefore, the scattered photon must have less energy (and hence, lower frequency) than the incident photon.
QUICK QUIZ 2

A photon of energy $E_0$ strikes a free electron, with the scattered photon of energy $E$ moving in the direction opposite that of the incident photon. In this Compton effect interaction, the resulting kinetic energy of the electron is (a) $E_0$, (b) $E$, (c) $E_0 - E$, (d) $E_0 + E$, (e) none of the above.

(c). Conservation of energy requires the kinetic energy given to the electron be equal to the difference between the energy of the incident photon and that of the scattered photon.
27.8 Photons and Electromagnetic Waves

Light has a dual nature. It exhibits both wave and particle characteristics

- Applies to all electromagnetic radiation

The photoelectric effect and Compton scattering offer evidence for the particle nature of light

- When light and matter interact, light behaves as if it were composed of particles

Interference and diffraction offer evidence of the wave nature of light
28.9 Wave Properties of Particles

In 1924, Louis de Broglie postulated that because photons have wave and particle characteristics, perhaps all forms of matter have both properties.

Furthermore, the frequency and wavelength of matter waves can be determined.

The de Broglie wavelength of a particle is

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

The frequency of matter waves is

$$f = \frac{E}{h}$$
The Davisson-Germer Experiment

- They scattered low-energy electrons from a nickel target.
- They followed this with extensive diffraction measurements from various materials.
- The wavelength of the electrons calculated from the diffraction data agreed with the expected de Broglie wavelength.
- This confirmed the wave nature of electrons.
- Other experimenters have confirmed the wave nature of other particles.
A non-relativistic electron and a non-relativistic proton are moving and have the same de Broglie wavelength. Which of the following are also the same for the two particles: (a) speed, (b) kinetic energy, (c) momentum, (d) frequency?

(c). Two particles with the same de Broglie wavelength will have the same momentum $p = mv$. If the electron and proton have the same momentum, they cannot have the same speed because of the difference in their masses. For the same reason, remembering that $KE = p^2/2m$, they cannot have the same kinetic energy. Because the kinetic energy is the only type of energy an isolated particle can have, and we have argued that the particles have different energies, Equation 27.15 tells us that the particles do not have the same frequency.
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