Photoelectric Effect
Photon Theory of Light
Photon Interactions

Summary

J. J. Thomson discovered that so-called cathode rays deflected by electric and magnetic fields; cathode rays came to be called electrons.

At the end of 19th century, only three problems were remained in physics: (1) black body radiation, (2) photoelectric effect, and (3) atomic spectra.

M. Plank: the atoms could only emit in small portion as they went from one energy level to the next.

\[ E = nhf \]

\[ n \text{ is a quantum number (discrete amount, } n = 1, 2, 3, \ldots) \]

\[ h \text{ is the Plank’s constant} \]

\[ f \text{ is the frequency of the oscillator (Hz or 1/s)} \]

Plank’s constant can be expressed in different units:

\[ h = 6.63 \times 10^{-34} \text{ J \cdot s (J/Hz)} \]

\[ h = 4.136 \times 10^{-15} \text{ eV \cdot s (eV/Hz)} \]

Einstein interprets electromagnetic quanta as photons; light is emitting in packets, or quanta, each with an energy:

\[ E = hf \]

Problem 2: Photoelectric Effect

In the late 1800’s Heinrich Hertz found that metals illuminated with light would release their electrons.

Electromagnetic waves give their energy to the electrons, and this allows them to escape from the surface of the metal.

This process is known as the “photoelectric effect”, it is a way of triggering of the electric current by light.

Heinrich Hertz
(1857-1894)

Photoelectric Effect: Stopping Voltage

If light of high enough frequency strikes a metal, electrons are emitted.

If the metal is connected to a battery, the electrons are attracted to the positively charged “collector” and a current flows.

We can measure the maximum kinetic energy of the electrons, \( KE_{\text{max}} \), via the “stopping voltage”, \( V_0 \).

How? Reverse the EMF and increase it until no current flows.

Stopping voltage, \( V_0 = \text{reverse voltage needed to stop all electrons from reaching the collector} \)

\[ KE_{\text{max}} = eV_0 \]
Einstein's Photon Theory vs. Wave Theory

Einstein suggested that, given the success of Planck’s theory, light must be emitted in small packets or “quanta” (particles).

These tiny packets, or quanta, are called photons, each of energy:

\[ E = hf \]

\( h \) is Planck’s constant 
\( f \) is frequency of light

Another Einstein’s bright idea how the energy and mass related to each other: (you need this equation for HW assignment)

\[ E = mc^2 \]

Wave theory:

1. If the light intensity is increased, the number of electrons emitted and their kinetic energy should be increased.
2. The frequency of the light should not affect the kinetic energy of emitted electrons. Only intensity should affect \( KE_{\text{max}} \).

Photon Theory of Light (#1)

- All photons have the same energy \( E = hf \) (if light is monochromatic).
- When a photon hits the metal it disappears; all its energy is transferred to the emitted \( e^- \) (electrons).
- Energy is needed to overcome the attractive forces that hold the electron in the metal.
- Work function, \( W_0 \) = minimum energy needed to get an electron out of the metal (typically a few eV).
- For photon energies below \( W_0 \), no electrons are emitted.
- For photon energies above \( W_0 \), the least tightly bound electrons will gain the most kinetic energy (\( KE_{\text{max}} \)).

\[ hf = KE_{\text{max}} + W_0 \]

Photon Theory of Light (#2)

- An increase in intensity of the light means more photons so more electrons will be emitted; since the energy of each photon is not changed, the maximum kinetic energy is not changed by an increase in intensity.
- If the frequency of the light is increased, the maximum kinetic energy of the electrons increases:

\[ KE_{\text{max}} = hf - W_0 \]

- If the frequency is less than the “cutoff” frequency, \( f_0 \), where \( hf_0 = W_0 \), no electrons will be emitted, no matter how great the intensity of the light.

Comparison of Photon and Wave Theories of Light

**Photon theory:**

1. If the light intensity is increased, the number of electrons emitted increases, but their \( KE_{\text{max}} \) is unchanged.
2. Below a “cutoff” frequency, \( f_0 \), no electrons are emitted, regardless of the intensity.
3. \( KE_{\text{max}} \) increases linearly with frequency.

**Wave theory:**

1. The number of emitted electrons and \( KE_{\text{max}} \) both increase with intensity.
2. There is no “cutoff” frequency.
3. \( KE_{\text{max}} \) is independent of frequency.
A metal surface is struck with light of $\lambda = 400\ nm$, releasing a stream of electrons. The 400 nm light is replaced by $\lambda = 300\ nm$ light of the same intensity. What happened?

1) **more** electrons are emitted in a given time interval
2) **less** electrons are emitted in a given time interval
3) emitted electrons **are more** energetic
4) emitted electrons **are less** energetic

**KE$\text{max}$** increases linearly with frequency.

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An electron is emitted from a sodium surface whose work function is $W_0=2.28\ eV$ when illuminated by light with $\lambda = 410\ nm$ (blue).

1. Photon energy:

\[
E = hf = \frac{hc}{\lambda} = \frac{(4.14\times10^{-15}\ eV \cdot s)(3\times10^8 m/s)}{410\times10^{-9} m} = 3.03\ eV
\]

2. Maximum kinetic energy of emitted electron:

\[
KE = hf - W_0 = 3.03\ eV - 2.28\ eV = 0.75\ eV
\]

3. Speed of emitted electron:

\[
v_{max} = \sqrt{\frac{2KE_{max}}{m}} = \sqrt{\frac{2(0.75\ eV)}{9.1\times10^{-3} kg}} = 5.1\times10^3 m/s
\]

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An electron is emitted from a sodium surface whose work function is $W_0=2.28\ eV$ when illuminated by light with $\lambda = 700\ nm$ (red).

1. Photon energy:

\[
E = hf = \frac{hc}{\lambda} = \frac{(4.14\times10^{-15}\ eV \cdot s)(3\times10^8 m/s)}{700\times10^{-9} m} = 1.77\ eV
\]

Since this photon energy is less than the work function, no electrons are emitted from a sodium surface.

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What is the longest wavelength of light that will emit electrons from a metal whose work function is $3.10\ eV$?

\[
hf = KE_{\text{max}} + W_0\quad KE_{\text{max}} = 0\quad hf = 0 + W_0 = W_0\quad h\frac{c}{\lambda} = W_0
\]

\[
\lambda = \frac{hc}{W_0} = \frac{(4.14\times10^{-15}\ eV \cdot s)(3\times10^8 m/s)}{3.1\ eV} = 4\times10^{-7} m = 400\ nm
\]
**Photon Interactions**

Photons passing through matter can result in four types of interactions:

1. **Photoelectric effect**: photon is completely absorbed and an electron is emitted.

2. **Atomic excitation**: photon is totally absorbed and an electron is promoted to a higher energy level in atom.

3. **Compton effect**: photon scatters from an electron and loses energy.

4. **Pair production**: photon creates matter, e.g. an electron-positron pair.

A positron has the same mass as an electron but the opposite charge: $+e$.

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**Process 4: Electron-Positron Pair Production**

In pair production, energy, $E$, charge, $q$, and momentum, $p$, are conserved.

**Energy conservation**: Photon disappears; its energy is converted into the rest mass of the particles (electron and positron).

Any excess energy is converted into kinetic energy of the particles.

**Charge conservation**: If an electron is created, we also create a positron (same mass but opposite charge).

**Momentum conservation**: Pair production must take place near a heavy object, e.g. a nucleus, which carries away the momentum of the photon.

**Example 4: Pair Production**

What is the minimum energy of a photon and photon’s wavelength that can produce an electron-positron pair?

**1. Photon energy**:

$$E = mc^2 = (2)(9.1 \times 10^{-31} \text{ kg})(3 \times 10^8 \text{ m/s})^2 = 1.64 \times 10^{-13} \text{ J} = 1.02 \text{ MeV}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} \quad 1 \text{ MeV} = 10^6 \text{ eV} = 1.6 \times 10^{-13} \text{ J}$$

**2. Photon wavelength**:

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

$$\lambda = \frac{(6.63 \times 10^{-34} \text{ J} \cdot \text{s})(3 \times 10^8 \text{ m/s})}{1.64 \times 10^{-13} \text{ J}} = 1.2 \times 10^{-12} \text{ m}$$

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**Quantum Hypothesis**

What does it mean for something to be “quantized”:

1) it can have only certain discrete value

2) in can have any value in certain region

3) it can have values only between certain limits

4) none of the above