The Photoelectric Effect: Experimental Evidence for the Particle Nature of Light

Objective

To demonstrate that light exhibits particle-like behavior by using a simple electroscope and ultraviolet light to reproduce the essential findings of the photoelectric effect, as explained by Albert Einstein in 1905.

Background

Classically, light was understood as a continuous electromagnetic wave. Wave theory predicted that increasing light intensity should increase the energy delivered to a surface, regardless of color (frequency). However, this prediction fails to explain observed phenomena such as the photoelectric effect.

In 1905, Albert Einstein proposed that light consists of discrete packets of energy called *quanta* or *photons*. He wrote:

> "Energy of light is not distributed continuously over wavefronts, but rather consists of energy quanta of magnitude $E = hf$, where h is Planck's constant and f is the frequency of light."
> – Einstein, *Annalen der Physik*, 1905

This model explained why electrons are only emitted from a material when the incoming light has a frequency above a certain threshold, regardless of intensity.

Einstein's Predictions

Einstein's photon theory made the following predictions, in direct contrast with classical wave theory:

(a) Electrons are ejected only if the light frequency f exceeds a material-specific threshold f_0.

(b) The kinetic energy of emitted electrons increases linearly with frequency, $K_{\max} = hf - \phi$, where ϕ is the work function.

(c) There is no time delay in electron emission, even at low light intensities.

(d) Increasing intensity at sub-threshold frequencies produces no emission.

Materials (DIY Setup)

- Aluminum foil
- Clear plastic or glass cup/jar
- Thin strips of foil (electroscope leaves)
- Plastic comb or rod
- Wool cloth or sweater
- UV flashlight (365–395 nm, ideally with visible-blocking filter)
- Glass from picture frame (UV-blocking)
- Optional: visible LED flashlight (for comparison)

Procedure

1. Construct an electroscope: tape a vertical strip of foil inside a clear container and attach two thin foil strips at the bottom to act as leaves.
2. Charge the electroscope negatively by rubbing a plastic comb with wool and touching it to the top foil.
3. Observe that the leaves repel due to electrostatic force.
4. Shine a visible flashlight on the top of the foil: no change should occur.
5. Shine the UV flashlight on the foil: leaves should collapse as photoelectrons escape.
6. Insert a pane of glass between the UV light and the foil: emission stops, proving UV is necessary.

Extended Theory

1. The Work Function and Photon Energy

The **work function** ϕ is the minimum energy needed to remove an electron from a material's surface. It is typically expressed in electronvolts (eV).

- Zinc: $\phi \approx 4.3$ eV

- Aluminum: $\phi \approx 4.1$ eV

The energy of a photon is:

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

Where:

- $h = 6.626 \times 10^{-34}$ J·s
- $c = 3.00 \times 10^{8}$ m/s
- λ is the wavelength (in meters)

In electronvolts:

$$E(\text{eV}) = \frac{1240}{\lambda\ (\text{nm})}$$

Examples:

- $\lambda = 400$ nm: $E \approx 3.1$ eV
- $\lambda = 300$ nm: $E \approx 4.13$ eV
- $\lambda = 250$ nm: $E \approx 4.96$ eV

Thus, only UV light below 300 nm consistently exceeds the work function for common metals.

2. Einstein's Evidence for $E = hf$

Einstein proposed:

$$K_{\text{max}} = hf - \phi$$

Where:

- K_{max} is the kinetic energy of emitted electrons,
- hf is photon energy,
- ϕ is the work function.

This explained:

- Threshold frequency behavior
- Linear relationship of K_{max} with frequency
- No delay in emission
- Intensity has no effect below threshold frequency

Robert Millikan confirmed this experimentally in 1916, measuring K_{max} vs. f and validating Einstein's model.

3. Electrostatics of the Foil Electroscope

The repulsion between foil leaves is due to stored negative charge:

$$Q = CV$$

Where:

- Q is the charge,
- C is capacitance (typically 1–10 pF),
- V is voltage (often 100 V from comb charging)

$$Q \approx 10^{-11}\ \mathrm{C} \Rightarrow \sim 6 \times 10^7 \text{ electrons}$$

If each UV photon ejects one electron, then:

- Millions of photons must strike per second to significantly discharge the foil
- Visible photons (e.g., $\lambda > 400$ nm, $E < 3.1$ eV) cannot eject any electrons

Conclusion

This experiment shows that:

- Bright visible light cannot eject electrons
- Dim UV light can, immediately and efficiently
- UV-blocking glass stops emission

These observations support Einstein's photon theory and refute classical wave explanations.

Historical Context

Einstein's 1905 paper, *"Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt"*, proposed the revolutionary idea of light quanta. For this, he received the 1921 Nobel Prize in Physics:

> *"For his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect."*

References

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- Feynman, R. (1963). *The Feynman Lectures on Physics, Vol. 1, Chapter 37*
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