The Particle-Like Properties of Electromagnetic Waves

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1 Review of Electromagnetic Waves

- Reviewing the nature of light (or electromagnetic waves)
  - A plane wave
    * A plane wave traveling in the positive x direction:

$$\begin{cases} \vec{E} = \vec{E}_o \sin(kx - \omega t) \\ \vec{B} = \vec{B}_o \sin(kx - \omega t) \end{cases}$$

    * The direction of energy transport would be $\vec{E} \times \vec{B}$
    * $|\vec{E}|$ and $|\vec{B}|$ are constant at a given t
    * The power, P, of the wave:

$$P = \frac{E}{\Delta t} = \frac{1}{\mu_o c} E_o^2 A \sin^2(kx - \omega t)$$

    * Two important features:
      1. Intensity (average power per unit area) is proportional to E_o^2

$$P_{avg} = \int_0^T P(t)\, dt$$

      2. The intensity of the system fluctuates with time

$$\frac{P_{avg}}{A}$$

  - A spherical wave
    * Spreads out uniformly along the three axis

2 The Photoelectric Effect

- Experiment performed by Heinrich Hertz (1887)
- When a metal surface is illuminated, light electrons can be emitted from the surface
- The Experiment:
  - Connect emitter and collector to an external circuit
  - Apply a negative potential to the circuit collector
  - Increase the potential difference $((-V) - (+V))$ to be more negative
  - At some point, even the most energetic electrons do not have enough kinetic energy to reach the collector

– The maximum kinetic energy to reach the collector with the stopping voltage, V_s, is:

$$K_{max} = eV_s$$

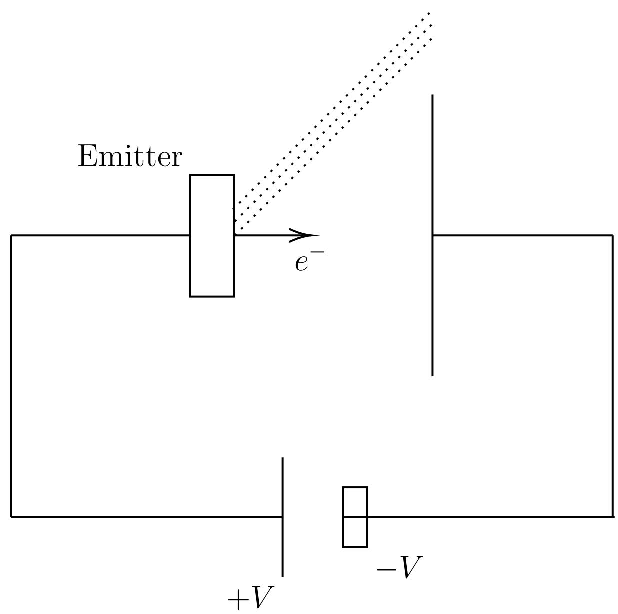

Figure 1: Set up of the Photoelectric Effect Experiment

– The classical picture: The energy of light with intensity I is absorbed by electrons, $E_{light} > E_{binding}$, e is released

– What does the classical wave theory predict?

1. The maximum kinetic energy of the electrons, K_{max}, is proportional to the intensity of light
2. The effect occurs for light with any frequency or wavelength
3. e^- are released after a finite Δt

- Experimental Results

1. For a fixed f or λ, K_{max} is independent of the intensity of light
2. The effect occurs only if $f > f_{\text{cutoff}}$
3. The first electrons are emitted almost instantaneously ($< 10^{-9}$[s])

– This means everything that classical wave theory predicted was essentially incorrect

- The Quantum Theory of the Photoelectric Effect
  - Developed by Albert Einstein (in 1905), based on Max Planck's idea explaining thermal radiation
  - Assumptions:
    - The energy of electromagnetic waves is not continuously distributed
    - The energy is concentrated in localized bands or "quanta"
    - This quanta is called "photon"
  - The energy of a photon is $\boxed{E = hf}$, where h is Planck's constant, and f is the frequency

$$\boxed{f = \frac{c}{\lambda} \Rightarrow E = \frac{hc}{\lambda}}$$

  - Photons travel at speed c, and are technically massless, so:

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

  - If $E = hf > \phi$, then photoelectrons are released; E is the photon energy, and ϕ is the work function
  - The kinetic energy of the electron is:

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

  - Evidently, the intensity is not relevant; a larger intensity would mean more photons in a unit area, which means more electrons released; this means there is more current.

- In 1915, Robert Millikan performed an experiment (won 1923 Nobel Prize)
  - Determined Planck's constant ($h = 6.57 \cdot 10^{-34}\,\mathrm{J\,s}$)
  - Fairly accurate, modern calculations found $h = 6.626 \cdot 10^{-34}\,\mathrm{J\,s}$