**Photons: particle-like properties of radiation**

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**- PHOTOELECTRIC EFFECT**

Experiments done by Heinrich Hertz (1887), Lenard (1900), Millikan (1914)

**Theoretical explanation:** Einstein (1905)

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**Photoelectric Simulation**

a) **Same \( \lambda, \nu \), different light intensities**

\[ \text{i}_{s,2} \quad \text{i}_{s,1} \]

\[ \text{I}_s(\lambda) \]

\[ \text{V} \]

- **When:** \( V \leq -V_o \) \( \Rightarrow \) no current
- \( V_o = \text{stopping potential} \)

\[ eV_o = \frac{1}{2} m \nu_{max}^2 \]

- \( V_o \) is the same for any intensity of the light beam. **Why?**

b) **Different \( \lambda, \nu \), same light intensity**

\[ \nu_2 > \nu_1 > \nu_t \]

\[ V \]

- **When:** \( V < \nu_t \) \( \Rightarrow \) no current

- \( V_o \) depends on \( \nu \), **Why?**
Einstein Explanation (1905): Light is formed by discrete packets of energy, the energy of each packet is determined by the frequency $\nu$.

\[ h \nu = \text{quanta of light energy (photon)} \]

\[ e V_0 = \frac{1}{2} m V_{\text{max}}^2 = h \nu - w_0 \]

\[ \text{work} = \text{minimum energy lost in crossing the surface and getting into free space} \]

When: \[ \frac{1}{2} m V_{\text{max}}^2 = 0 \Rightarrow h \nu = w_0 \]
COMPTON EXPERIMENT (1923):

Diagram of the Compton experiment setup:

- X-ray source
- Incident beam
- Scattered beam
- Scattering
- Lead collimating slits
- Crystal
- Detector

Graph showing intensity vs. wavelength ($\lambda$ in Å) for scattering angles $\theta = 0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$.
From special relativity: \( E^2 = m^2 c^4 + p^2 c^2 \) (particles, \( \gamma \) photons)

**photons**: \( m = 0 \)  \( \Rightarrow \ E^2 = p^2 c^2 \  \Rightarrow \ E = pc 

before collision: \( |\vec{p}_i| = \frac{E_i}{c} = \frac{h \nu_i}{c} = \frac{h}{\lambda_i} \),

after collision: \( |\vec{p}_f| = \frac{E_f}{c} = \frac{h \nu_f}{c} = \frac{h}{\lambda_f} \)

**electrons**: \( m_e \)  \( \Rightarrow \ E_{e}^2 = m_e^2 c^4 + p_e^2 c^4 

before collision: \( E_{e,o} = m_e^2 c^4 + \frac{1}{2} m c^4 = m_e^2 c^4 

after collision: \( E_{e,f} = m_e^2 c^4 + p_e^2 c^4 

Conservation of momentum: \( \vec{p}_i = \vec{p}_z + \vec{p}_e \  \Rightarrow \ \vec{p}_e = \vec{p}_i - \vec{p}_z - 2 \vec{p}_i \frac{p_z}{p_z} \cos \theta \) (1)

Conservation of energy: \( E_i + E_{e,o} = E_f + E_{e,f} \) (2)
We can write (2) as:
\[ \rho_1 c + m_e c^2 = \rho_2 c + (m_e c^2 + \rho_e c^2)^{1/2} \]

\[ \left( \rho_1 - \rho_2 \right) c + m_e c^2 = m_e c^2 + \rho_e c^2 \]

\[ p_e = -\frac{p_1^2 + p_2^2 - 2p_1p_2}{p_1^2 + (p_1 - p_2)^2} \]

Then:
\[ \left( \rho_1 - \rho_2 \right) m_e c = p_1p_2 \left( 1 - \cos \theta \right) \]

\[ \left( \frac{1}{p_2} - \frac{1}{p_1} \right) m_e c = 1 - \cos \theta \]

\[ \frac{\lambda_2 - \lambda_1}{\lambda_1} = \frac{1}{m_e c} \left( 1 - \cos \theta \right) \Rightarrow \frac{\Delta \lambda}{\lambda_1} = \frac{h}{m_e c} \left( 1 - \cos \theta \right) \]

**Remarks:**
* \( \frac{h}{m_e c} = \lambda_c = 0.00243 \text{ nm} \) (Compton wavelength)

* \( \lambda_2 - \lambda_1 = \Delta \lambda \) is independent of the wavelength

* Typically observed with x-rays and \( \gamma \) rays
Remarks:

* Light/matter interaction (absorption + emission) seems to require the particle nature of radiation (photon)

* Interference & diffraction strongly indicate the wave nature of radiation

* $E = h \nu \quad \text{and} \quad p = \frac{h}{\lambda}$

* Wave-particle duality of electromagnetic radiation