Recap I

Key Ideas in Quantum Physics:
- Waves act as particles: particles act as waves
- Quantization: only certain values possible
- Uncertainty in quantities: probability distributions

Energies at small scales:
use \(1 \text{eV} = 1 \text{ electron volt} = 1.6 \cdot 10^{-19} \text{J}\)

Photons:
Electromagnetic radiation is composed of photons. Concentrated bundles of energy and momentum whose motion is described by an analysis that closely parallels the classical wave description in terms of "interfering amplitudes".

For light of frequency \(f\) and wavelength \(\lambda\):

\[
E_{\text{photon}} = hf \quad \text{and} \quad p_{\text{photon}} = \frac{hf}{\lambda} = \frac{\hbar}{\lambda}
\]

\(h = \text{Planck's constant} = 4.136 \cdot 10^{-15} \text{eV.s}\)

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Recap II

- **Evidence of Photons**: 2-slit experiment at low intensity

**Observations:**

- Classical intensity pattern is built up gradually
- Signals on screen arrive localized in position and time → photons!
- Both slits need to be open simultaneously to get classical interference pattern at high intensity
- *cannot* conclude that photon must have passed through one of the two slits
- *can* not predict when a given photon will arrive on the screen. Just can give *probabilities*!
- If one measures through which slit photons pass, interference pattern on screen disappears!
Today:

- Enter quantum mechanics:
  - The photoelectric effect
  - Compton scattering
  - X-ray production
Evidence for Photons (2): The Photoelectric Effect

Light energy is used to eject an electron ("photo electron") from the metal.

Q: How does the photoelectric effect depend on the frequency \( f \) and intensity \( I \) of the light?
Photoelectric effect: Experiment 1

Zink plate connected to electroscope

**Observations:**

- Effect **depends on the frequency of the light**. Only light of high enough frequency (here: ultraviolet light) produces the effect ⇒ **cutoff frequency**

- Effect is seen immediately after the metal is exposed to light.
An electron must overcome an electric potential energy barrier in order to go from $T$ to $C$:

$$\Delta U = q(V_C - V_T) = -e\Delta V_{CT} > 0$$

Electrons are ejected by the light from the target $T$ and hit the collector $C$.

$\Rightarrow T$ & $C$ charge up like a capacitor.

$\Rightarrow \Delta V_{CT}$ between $T$ and $C$. 

**Photoelectric effect: Experiment 2**

- **Target** ($T$)
- **Evacuated Glass Phototube**
- **Collector** ($C$)
- **Voltmeter**
- **Photoelectrons**
- **Light**
Observations:

(1) The T-C capacitor charges up to a final potential $\Delta V_{TC, \text{max}} = \Delta V_{\text{stop}} = \text{stopping potential}$

=> Electrons come off the metal with some maximum kinetic energy $K_{\text{max}} = e \Delta V_{\text{stop}}$

=> Charging stops once $\Delta V_{TC}$ reaches $\Delta V_{\text{stop}}$ since electrons no longer reach the collector.

(2) The stopping potential (therefore also $K_{\text{max}}$) is independent of light intensity.
(3) The stopping potential $V_{\text{stop}}$ depends on frequency $f$ of the light.

$$X_{\text{max}} = eV_{\text{stop}}$$

From data:

$$X_{\text{max}} = hf - hf_0$$

- Same for all metals
- For $f < f_0$ there is no photoemission!

(4) Photoemission occurs instantaneously ($< 10^{-9}$ s) even for very low intensities.
Photoelectric Effect: Quantum Picture

(Einstein 1905; 1921 Nobel Prize in Physics)

1. Energy of light of frequency $f$ is quantized

Energy of one photon:

$$E_{\text{photon}} = hf$$

Planck's constant

$\Rightarrow$ Visible light: $E_{ph} = 1.8 \text{ eV} \ldots 3.1 \text{ eV}$

2. In the photoelectric effect, one photon is completely absorbed by one electron

$\Rightarrow$ gives all of its energy to the electron
(3) It takes a certain **minimum energy** (work function \( \Phi \)) to remove an electron from the metal. 

\[ \Rightarrow \text{property of the metal} \]

\( \Rightarrow \) Examples:

- \( \Phi_{\text{cesium}} = 2.1 \text{ eV} \)
- \( \Phi_{\text{zinc}} = 4.3 \text{ eV} \)
- \( \Phi_{\text{gold}} = 5.1 \text{ eV} \)

(4) **Apply energy conservation**:

\[ E_{\text{photon}} = hf = K_{\text{max}} + \Phi \]

\[ K_{\text{max}} = eDV_{\text{stop}} \]

\[ \Phi = hf - \omega \]
=) This explains all observations:

- No time lag: one photon $\rightarrow$ one photoelectron

- $K_{\text{max}}$ (and therefore the stopping potential $U_{\text{stopping}}$) does not depend on intensity, since $E_{\text{photon}} \propto f$, but indep. of intensity.

- $K_{\text{max}}$ increase linearly with frequency $f$

- No photo emission, if $E_{\text{ph}} = hf < \Phi$ (i.e. $f < f_0$)
Evidence of Photons (3): The Compton Effect

Measure dynamics of individual x-ray photon in collision with a (almost) free electron.

Key Idea: Photons carry momentum and obey energy and momentum conservation laws!

Before collision:
- X-ray photon
- \( \lambda \)
- \( E_{\text{photon}} = hf = \frac{hc}{\lambda} \)
- \( P_{\text{photon}} = \frac{h}{\lambda} \)

After collision:
- Scattered photon
- \( E_{\text{photon}} = \frac{hc}{\lambda} \)
- Free electron, \( u \times v_0 \)
- \( P_{e^-}, i = 0 \) (kinetic energy)
- \( P_{e^-}, i = 0 \) (momentum)
Setup and Results:

- Incident photon interacts with carbon target
- Scattering angle $\phi$
- Detector

$\Delta \lambda = \text{Compton shift}$; depends on scattering angle $\phi$

At $\phi = 45^\circ$:
- $\Delta \lambda > 0$

At $\phi = 90^\circ$:
- Unshifted line from scattering with tightly bound electrons in target

At $\phi = 135^\circ$:
- Shifted line from scattering of photons with free electrons in carbon target