Being near an unshielded source of gamma radiation for a short period of time is very dangerous!

Probability of interaction \(\sim\) proportional to the “cross section” of a specific interaction type

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/radact.html
Interaction of Radiation with Matter

• Compton effect  (Lecture13)
• Photoelectric effect

Textbook: Chapter 2.2, 2.3, 2.5
Compton experiments confirmed the corpuscular (particle-like) nature of radiation.
The Compton Effect

Compton experiments confirmed the corpuscular (particle-like) nature of radiation:

\[ \Delta \lambda (\theta) = \lambda' - \lambda > 0 \]

is the Compton shift

\[ \Delta \lambda = \lambda' - \lambda \equiv \lambda_c (1 - \cos \theta) \]

\[ \lambda_c = \frac{h}{m_0 c} = 2.43 \times 10^{-12} m \]

Compton wavelength

\[ hc = 1.240 \ [eV \ \mu m] \]

\[ m_0 c^2 = 0.511 \ [MeV] \]

Reminder

Figure 2-5  Compton’s experimental arrangement. Monochromatic x rays of wavelength \( \lambda \) fall on a graphite scatterer. The distribution of intensity with wavelength is measured for x rays scattered at any scattering angle \( \theta \).
Reminder

The Compton Effect

\[ \Delta \lambda = \lambda' - \lambda \equiv \lambda_c (1 - \cos \theta) \]

\[ \lambda_c = \frac{h}{m_0 c} = 2.43 \times 10^{-12} m \]

Figure 2-8  Compton's result \( \Delta \lambda = (h/m_0 c)(1 - \cos \theta) \).
Compton’s experimental results

2 peaks:
- elastic (Rayleigh), intensity strongly depends on angle (prevails in the forward direction)
- inelastic (Compton scattering)

Figure 2-6: Compton’s experimental results. The solid vertical line on the left corresponds to the wavelength $\lambda$, that on the right to $\lambda'$. Results are shown for four different angles of scattering $\theta$. Note that the Compton shift, $\Delta \lambda = \lambda' - \lambda$, for $\theta = 90^\circ$, agrees well with the theoretical prediction $h/m_0c = 0.0243 \text{ Å}$. 
The Compton Effect

\[ \lambda' = \lambda + \frac{h}{m_0 c} (1 - \cos \theta) \]

\[ h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2} (1 - \cos \theta)} \]

\[ \lambda = \frac{c}{\nu} \]

Example 1: Low incident photon energies

Photon: \( h\nu \ll m_0 c^2 \Rightarrow \lambda \gg \frac{h}{m_0 c} \Rightarrow \lambda' \approx \lambda \)

Scattering without (significant) photon energy loss: photon has the same energy, but changes momentum direction

Scattered electron:

\[ E' \approx m_0 c^2 \]

\[ p' \approx \frac{h\nu}{c} \sqrt{2(1 - \cos \theta)} \]

Check at home
The Compton Effect

\[ \lambda' = \lambda + \frac{h}{m_0 c} (1 - \cos \theta) \]

\[ h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2} (1 - \cos \theta)} \]

\[ \lambda = \frac{c}{\nu} \]

Example 2: **High incident photon energies**

Photon: \( h\nu \gg m_0 c^2 \Rightarrow h\nu' \approx \frac{m_0 c^2}{1 - \cos \theta}, \theta \neq 0 \Rightarrow h\nu' \rightarrow 0 \)

The photon transfers almost all energy to the electron

Scattered electron: \( E' \approx h\nu + m_0 c^2 \)

If one neglects the electron mass: elastic collision of two particles of ~ equal (zero) masses
Photoelectric Effect

- the ejection of electrons from the surface by the action of light;

Expectations from the light wave theory:
- Should electron max kinetic energy depend on light intensity? Yes or No?
- Should photoelectric effect occur for any frequency of the light? Yes or No?
Photoelectric Effect
- the ejection of electrons from the surface by the action of light;

Expectations from the light wave theory:
- electron max kinetic energy should depend on light intensity
- photoelectric effect should occur for any frequency of the light

→ Experiment proves otherwise …
Photoelectric Effect
- The ejection of electrons from the surface by the action of light; electrons can be detected as current if they are attracted to B.

Figure 2-1: An apparatus used to study the photoelectric effect. The potential difference $V$ can be varied continuously in magnitude, and also reversed in sign by the switching arrangement.
Photoelectric Effect
- the ejection of electrons from the surface by the action of light;

Expectations from the light wave theory:
- electron max kinetic energy should depend on light intensity
- photoelectric effect should occur for any frequency of the light

→ Experiment proves otherwise …
Experimental settings:
a) 100%, Red, (V=0, V>0, V<0)

b) 100%, UV, V=0
Experimental settings:

**c)** 100%, Red, V=7V

**d)** 100%, UV, V from 7V to -7V
Photoelectric Effect

Experimental observations:
- does not depend on light intensity
- depends on light frequency and electron emitter material
Below the cutoff frequency the photoelectric effect does not occur.
Einstein’s quantum theory of photoelectric effect

Einstein proposed that radiant energy is quantized into concentrated bundles (photons):

- Interference and diffraction phenomena involve large number of photons
- A single bundle of energy is localized in a small volume of space and it stays localized as it moves away from the source with speed $c$ and has energy: $E_\gamma = h\nu$
The Nobel Prize in Physics 1921

Albert Einstein

The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect".

Prize share: 1/1
Einstein’s quantum theory of photoelectric effect

In the photoelectric process one photon is absorbed by one electron in the photocathode. Electron’s kinetic energy:

\[ E_{\text{kin}} = h\nu - w \]

\( h\nu \) = energy of the absorbed incident photon
\( w \) = work required to remove the electron from the metal

\[ E_{\text{kin}}^{\text{max}} = h\nu - w_0 \]

\( w_0 \) = a characteristic energy of the metal, the work function
Expectations from the light wave theory:
- electron max kinetic energy should depend on light intensity
- photoelectric effect should occur for any frequency of the light

Einstein’s quantum theory:
- doubling the intensity increases the number of photons (and the photoelectric current), but has no effect on occurrence (or not) of the photoelectric effect
- **cutoff frequency above which the photoelectric effect occurs:**

\[ h\nu_0 \geq w_0 \implies E_{kin} \geq 0 \]
\[ \nu < \nu_0 \implies \text{no photoelectric effect} \]

\[ E_{kin}^{max} = eV_0 = h\nu - w_0 \Rightarrow V_0 = \frac{h\nu}{e} - \frac{w_0}{e} \]

Stopping potential \( V_0 \)
Below the cutoff frequency the photoelectric effect does not occur.

Exercise: Deduce the work function for sodium from Fig. 2-3.

\[ h = 6.62606957(29) \times 10^{-34} \left[ J \cdot s \right] \]
The photoelectric effect requires photons with energies from a few eV to over 1 MeV in high atomic number elements.
Planck Constant

Sodium

\[ w_0 = 2.28 \text{ eV} \]
\[ \sim 3.65 \times 10^{-19} \text{ J} \]

\[ V_0(\nu) = \frac{h}{e} \nu - \frac{w_0}{e} \]

From the line fit:
\[ \frac{h}{e} = 4.0 \times 10^{-15} [V \cdot s] \]
\[ e = 1.6 \times 10^{-19} C \]
\[ \Rightarrow h = 6.4 \times 10^{-34} [J \cdot s] \]

Millikan:
\[ h = (6.57 \pm 0.03) \times 10^{-34} [J \cdot s] \]

Modern data:
\[ h = 6.62606957(29) \times 10^{-34} [J \cdot s] \]

Good agreement with $h$ derived from Planck’s radiation formula

Millikan: $h = (6.57 \pm 0.03) \times 10^{-34} [J \cdot s]$  
Modern data: $h = 6.62606957(29) \times 10^{-34} [J \cdot s]$  

Photoelectric effect: applications
(1) a photomultiplier (PMT)

- useful for light detection of very weak signals, is a photo-emissive device in which the absorption of a photon results in the emission of an electron.
- these detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.

photomultiplier tube coupled to a scintillator.

https://en.wikipedia.org/wiki/Photomultiplier#Structure_and_operating_principles
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

IceCube detector
86 strings of DOMs, set 125 meters apart

DeepCore
DOMs are 17 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

Antarctic bedrock

1450 m

2450 m

50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

5160 PMT’s deployed in the ice (over 1 km³)

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

50 m

1450 m
IceCube Neutrino Detector

Animated: https://www.youtube.com/watch?v=aMnGWgoDaAA