Photons

Representation of a Photon

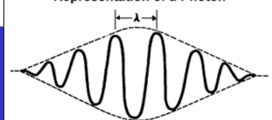


Figure 2

- **Quantum theory** describes light as a particle called a **photon**
- According to **quantum theory**, a **photon** has an **energy** given by

E = hf = hc/λ h = 6.6x10^{-34} [J s] Planck's constant, after the scientist Max Planck.

- The energy of the light is proportional to the frequency (inversely proportional to the wavelength) ! The higher the frequency (lower wavelength) the higher the energy of the photon.
- 10 photons have an energy equal to ten times a single photon.
- **Quantum theory describes experiments to astonishing precision**,

Photoelectric Effect - **Example**

- Most metals have a work function on the order of several electron volts. Copper has a work function of 4.5 eV.
- Therefore, the cut-off frequency for light ejecting electrons from copper is:

hf_{cutoff} = 4.5 eV, or

f_{cutoff} = 4.5 x (1.6 x 10^{-19} C) x (1 V) / 6.63 x 10^{-34} J-sec
 = 1.09 x 10^{15} Hz

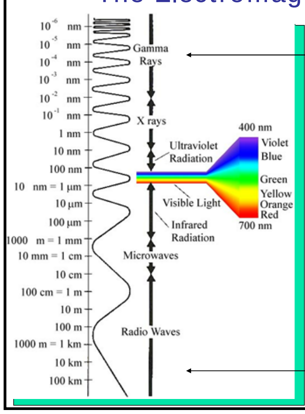
- or λ_{cutoff} = c/ f_{cutoff} , or

λ_{cutoff} = (3 x 10^{8} m/s) / (1.09 x 10^{15} cycles/sec)
 = 276 nm (in the UV range)

- Any frequency lower than the cut-off (or any wavelength greater than the cut-off value) will NOT eject electrons from the metal.
- From Einstein's equation:

hf = W + e*V_{stop} , we can see that the straight line of the V_{stop} vs f graph should have a slope of (h/e) .

The Electromagnetic Spectrum



Shortest wavelengths (Most energetic photons)

E = hf = hc/λ

h = 6.6x10^{-34} [J*sec] (Planck's constant)

Longest wavelengths (Least energetic photons)

Momentum

In physics, there's another quantity which we hold just as sacred as energy, and this is momentum.

For an object with mass, momentum is given by:

$\vec{p} = m\vec{v}$ The units are: [kg] [m/s] == [kg m/s]

The reason it is important in physics, is, because like Energy:
TOTAL MOMENTUM IS ALWAYS CONSERVED

Do photons carry momentum ?

DeBroglie's proposed that the a photon not only carries energy, but also carries momentum.

But, p = mv, and photon's have m=0, so how can it be that the momentum is not zero??

DeBroglie postulated that photons carry momentum, and their momentum is:

$$p = E / c$$

If we substitute: E = hc/λ into this equation, we get:

$$p = h / \lambda$$

Momentum carried by a photon with wavelength λ

DeBroglie's Relation

DeBroglie relation

p = h / λ   Photons carry momentum !!!   → **λ = h / p**

E = hc / λ   Photons also carry energy !!!

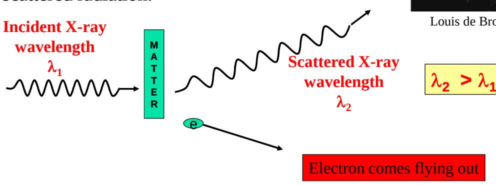
Both **energy & momentum are inversely proportional to the wavelength !!!**

➔ The highest energy photons are those which have small wavelength (that's why gamma rays are so dangerous)

The Compton Effect

In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.

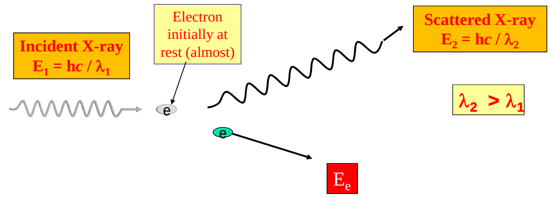
Louis de Broglie



Problem: According to the wave picture of light, the incident X-ray should give up some of its energy to the electron, and emerge with a lower energy (*i.e.*, the amplitude is lower), but should have $\lambda_2=\lambda_1$.

It was found that the scattered X-ray did not have the same wavelength ?

Quantum Picture to the Rescue

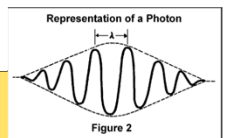


Compton found that if you treat the photons as if they were particles of zero mass, with energy $E=hc/\lambda$ and momentum $p=h/\lambda$

➔ The collision behaves just as if it were 2 billiard balls colliding !

Photon behaves like a particle with energy & momentum as given above!

Summary of Photons



- Photons can be treated as "*packets of light*" which behave as a particle.

- To describe interactions of light with matter, one generally has to appeal to the particle (quantum) description of light.

- A single photon has an energy given by

  $E = hc/\lambda$,

  where
  - h = Planck's constant = 6.6×10^{-34} [J s] and,
  - c = speed of light = 3×10^{8} [m/s]
  - λ = wavelength of the light (in [m])

- Photons also carry momentum. The momentum is related to the energy by: $p = E / c = h/\lambda$

So is light a wave or a particle ?

On macroscopic scales, we can treat a large number of photons as a wave.

When dealing with subatomic phenomenon, we are often dealing with a single photon, or a few. In this case, you cannot use the wave description of light. It doesn't work !