Physics - 2

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Energy, Mass, and Momentum of a Photon

- Now there is experimental proof for the particle nature of light from photo electric effect.
- The energy of a single photon particle is $E = hf$
- The momentum of a particle of mass m, when moving very close to the speed of light is:

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Energy, Mass, and Momentum of a Photon

- But, for photon $v = c$, then the denominator becomes zero. To avoid this we conclude that the mass of photon must be zero.
- This means a photon can never be it rest, at always moves with the speed of light.
- So, it total energy is always kinetic energy.
- This means

$$KE = E = hf$$

Energy, Mass, and Momentum of a Photon

- Then what will be the momentum of photons?
- Since photon is a relativistic particle and it's mass is zero, we can find it's momentum from the relativistic(particles moving, having mass m, moving close to the speed of light) equation of energy. Which is

$$E^2 = p^2c^2 + m^2c^4$$

- Since $m = 0$ for photons, then

$$p = \frac{E}{c}$$

- or

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

- is the momentum of photon

Example: Momentum of a Photon

What will be the momentum of blue color 500 *nm* photon?

- Since:

$$p = \frac{h}{\lambda}$$

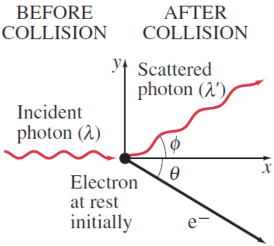
$$p = \frac{6.63 \times 10^{-34}}{500 \times 10^{-9}} = 1.3 \times 10^{-27} kg.m/s$$

Compton Effect

- **Compton Effect** (named after its discoverer) is another experimental proof in the support of particle theory of light.
- Compton aimed short wavelengths of light (which are x-rays) on various materials. He measured the scattered light at various angles.
- He found that the scattered light had slightly longer wavelength compared to the incident light. Which means smaller frequency and smaller energy.
- Compton concluded that incident light consists of photons; in collisions with (nearly) free electrons, a photon transfers part of its energy and momentum to the electron, so the scattered photon has lower energy (longer wavelength).

Compton Effect

- Compton used the conservation of momentum and energy to derive the following equation for the wavelength of the scattered photons.



$$\lambda' = \lambda + \frac{h}{m_e c}(1 - cos\phi)$$

- we can see that the wavelength (λ') of the scattered photons depend on the angle ϕ

Compton Effect

- The experimental measurement that Compton did were consistent with this formula.
- Hence the Compton effect adds to the firm experimental foundation for the photon theory of light.

Example: X-ray scattering

X-rays of wavelength 0.140nm are scattered from a very thin slice of carbon. What will be the wavelengths of X-rays scattered at (a) 0^o, (b) 90^o, (c) 180^o?

Example: X-ray scattering

- Since the wavelength of the scattered x-rays is:

$$\lambda^{'} = \lambda + \frac{h}{m_e c}(1 - cos\phi)$$

- (a) For $\phi = 0^o$, it will become

$$\lambda^{'} = \lambda = 0.142\ nm$$

- Since for $\phi = 0^o$, the x-rays photons are just passing the material without any collision. So, there wavelength is exactly the same as before collision.

Example: X-ray scattering

- (b) For $\phi = 90^o$

$$\lambda^{'} = \lambda + \frac{h}{m_e c}$$

- putting values

$$\lambda^{'} = 0.140\ nm + \frac{6.63 \times 10^{-34}}{(9.11 \times 10^{-31})(3 \times 10^8)} = 0.142\ nm$$

- We can see that the wavelength of the x-rays, scattered at an angle 90^o have increased. This means frequency and energy have decreased.

- (c) For $\phi = 180^o$, the equation become.

$$\lambda^{'} = \lambda + \frac{2h}{m_e c}$$

- Putting values and simplifying we get

$$\lambda^{'} = 0.145\ nm$$

- The maximum shift occur for backward scattering.

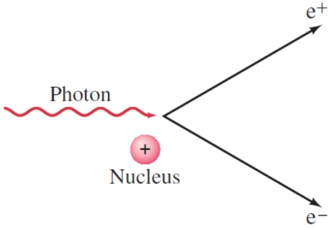
Photon Interactions

Photon interact with atoms and electrons(when passing through matter) in four ways:

1. **Photoelectric Effect:** A photon knock electrons out of an atom and disappear itself.
2. **Bohr Model:** Collide with an electron, electron will go to higher energy state and photons disappear.
3. **Compton Effect:** Scattered from an electron, lose some energy in the process which change its wavelength.
4. **Pair production:** Photons create matter.

Pair Production

- A single high-energy photon passing near a nucleus can convert into an electron–positron(anti electron) pair. The nucleus is needed to take up recoil so energy–momentum are conserved.



- Since the rest mass energy of an electron and proton is $E = m_e c^2$, the photons energy must be greater than $2m_e c^2$.
- This process is called **pair production**.

Example: Pair Production

(a) What is the minimum energy of a photon that can produce an electron–positron pair? (b) What is this photon's wavelength?

Example: Pair Production

- (a) Since we already saw that the minimum energy needed is $2m_ec^2$. So energy of the photon should be

$$E = 2m_ec^2 = 2(9.1 \times 10^{-31})(3 \times 10^8)^2$$

$$E = 1.64 \times 10^{-13} J$$

$$\boxed{E = 1.02\ MeV}$$

Example: Pair Production

- (b) The wavelength of the photon is

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(1.64 \times 10^{-13})}$$

$$\boxed{\lambda = 1.2 \times 10^{-12}\ m}$$

- This is very short wavelength. This is in the range of very short x-rays or gamma rays of electromagnetic radiation.