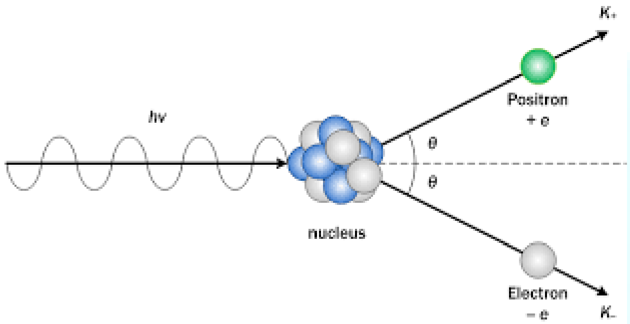
Particle properties of waves
Part-8
Pair Production & Pair Annihilation

Pair Production

- Dirac succeeded(1928) in extending quantum mechanics to the realm of relativistic phenomena. The new theory, called relativistic quantum mechanics, predicted the existence of a new particle, the positron.
- Positron, defined as the antiparticle of the electron, was predicted to have the same mass as the electron and an equal but opposite (positive) charge.
- Four years after its prediction by Dirac's relativistic quantum mechanics, the positron was discovered by Anderson in 1932 while studying the trails left by cosmic rays in a cloud chamber.
- In a collision a photon can give an electron all of its energy (the photoelectric effect) or only part (the Compton effect)
- It is also possible for a photon to materialize into an electron and a positron, which is a positively charged electron.
- In this process, called pair production, electromagnetic energy is converted into matter.
- When high-frequency electromagnetic radiation passes through a foil, individual photons of this radiation disappear by producing a pair of particles consisting of an electron, e^-, and a positron, e^+ :
- **i.e.** $\gamma \longrightarrow e^- + e^+$
- This process is called pair production.
- Due to charge, momentum, and energy conservation, pair production cannot occur in empty space.
- For this process to occur, the photon must interact with an external field such as the coulomb field of an atomic nucleus to absorb some of its momentum.

Minimum energy for Pair production

The rest energy mC^2 of an electron or a positron is 0.51 MeV, hence pair production requires a photon of energy of at least 1.02 MeV. Any additional photon energy becomes kinetic energy of the electron and positron. The corresponding maximum photon wavelength is 1.2 pm. Electromagnetic waves with such wavelengths are called gamma rays and are found in nature as one of the emission from radioactive nuclei and in cosmic rays.



Minimum Frequency and Wavelength

$$E_{min} = h\nu = 2m_eC^2 \text{ and } \lambda = {C}/{\nu} :$$

$$\nu = \frac{2m_eC^2}{h} = \frac{2\times9.1\times10^{-31}kg\times(3\times10^8 ms^{-1})^2}{6.63\times10^{-34}J\ s}$$

$$= 2.47\times10^{20}\ \text{Hz}$$

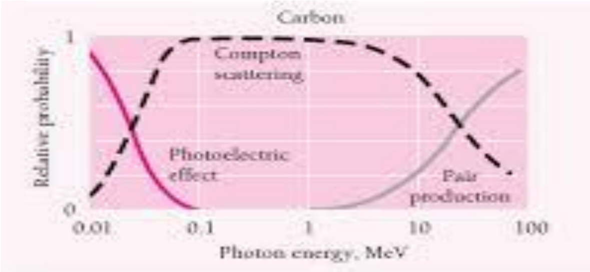
$$\lambda = \frac{C}{\nu} = \frac{3\times10^8 ms^{-1}}{2.47\times10^{20}Hz} = 1.2\times10^{-12}\text{m}$$

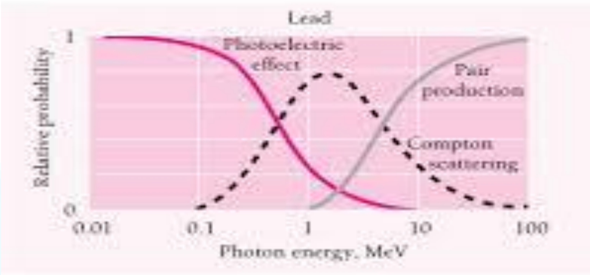
Pair Annihilation

The inverse of pair production occurs when a positron is near an electron and the two come together under the influence of their opposite electric charges. Both particles vanishes simultaneously, with the lost mass becoming energy in the form of two gamma-ray photons:

$$e^+ + e^- \rightarrow \gamma + \gamma$$

The total mass of the positron and electron is equivalent to 1.02 MeV, and each photon has an energy hν of 0.51 MeV plus half the kinetic energy of the particles relative to their centre of mass. The directions of the photons are such to conserve both energy and linear momentum, and no nucleus or other particle is needed for this pair annihilation to take





Photons And Gravity

KE= 0 E=hν

H

KE=mgh E= hν + $\frac{h\nu}{c^2}$ gH = hν′

Final photon energy = Initial photon energy + Increase in energy

$$h\nu' = h\nu + mgH$$

And so $$h\nu' = h\nu + \frac{h\nu}{c^2} gH$$

Photon energy after falling through a height H

$$\mathbf{h\nu' = h\nu\left(1 + \frac{gH}{C^2}\right)}$$

$$\mathbf{\nu' = \nu\left(1 + \frac{gH}{C^2}\right)}$$

- The increase in energy of a fallen photon was first observed in 1960 by pound and Rebka at Harvard. In their work H was 22.5 m. Find the change in frequency of a photon of red light whose original frequency is 7.3×10^{14}Hz when falls through 22.5m

Solution :

Given H = 22.5 m

$\nu = 7.3\times10^{14}$

$$\nu' = \nu\left(1 + \frac{gH}{C^2}\right)$$

$$\nu' - \nu = \left(\frac{gH}{C^2}\right)\nu$$

$$= \frac{9.8\, m/s^2 22.5m\times7.3\times10^{14}Hz}{(3\times10^8)2} = 1.8 \text{ Hz}$$

Gravitational Redshift

Einstein's theory of general relativity predicts that the wavelength of electromagnetic radiation will lengthen as it climbs out of a gravitational well. Photons must expend energy to escape, but at the same time must always travel at the speed of light, so this energy must be lost through a change of frequency rather than a change in speed. If the energy of the photon decreases, the frequency also decreases. This corresponds to an increase in the wavelength of the photon, or a shift to the red end of the electromagnetic spectrum – hence the name: gravitational redshift. This effect was confirmed in laboratory experiments conducted in the 1960s.

$$\mathbf{h\nu' = h\nu\left(1 - \frac{GM}{C^2R}\right)}$$

$$\mathbf{\nu' = \nu\left(1 - \frac{GM}{C^2R}\right)}$$

$$\frac{\nu}{\nu'} = \left(1 - \frac{GM}{C^2R}\right)$$