Radiation and Safety
Unit2: Interaction of Radiation with Matter

Dr Priya Hasan[1*]
Maulana Azad National Urdu University, Hyderabad 32

October 15, 2018

Abstract

Types of Radiation: Alpha, Beta, Gamma and Neutron and their sources, sealed and unsealed sources, Interaction of Photons - Photo-electric effect, Compton Scattering, Pair Production, Linear and Mass Attenuation Coefficients, Interaction of Charged Particles: Heavy charged particles Beth-Bloch Formula, Scaling laws, Mass Stopping Power, Range, Straggling, Channelling and Cherenkov radiation. Beta Particles- Collision and Radiation loss (Bremsstrahlung), Interaction of Neutrons- Collision, slowing down and Moderation.

1 Photoelectric Effect

The photoelectric effect is the observation that many metals emit electrons when light shines upon them. Electrons emitted in this manner can be called photoelectrons. (Fig 1)

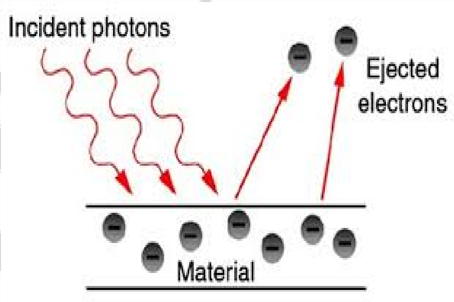

Figure 1: Photoelectric Effect

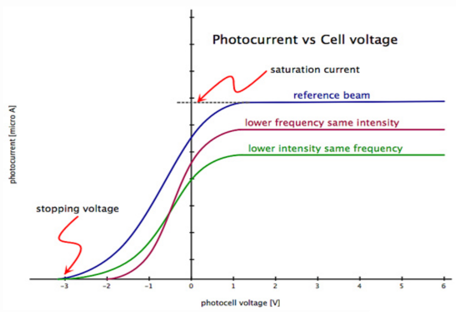

Figure 2: Stopping Potential vs frequency

According to classical electromagnetic theory, this effect can be attributed to the transfer of energy from the light to an electron in the metal. That means, the more intense the incident light the greater the energy with which the electrons should be ejected from the metal. That is, the average energy carried by an ejected (photoelectric) electron should increase with the intensity of the incident light.

It was found the energies of the emitted electrons to be independent of the intensity of the incident radiation.

Einstein (1905) successfully resolved this paradox by proposing that the incident light consisted of individual quanta, called photons, that interacted with the electrons in the metal like discrete particles, rather than as

*e-mail:priya.hasan@gmail.com, priyashasan@yahoo.com

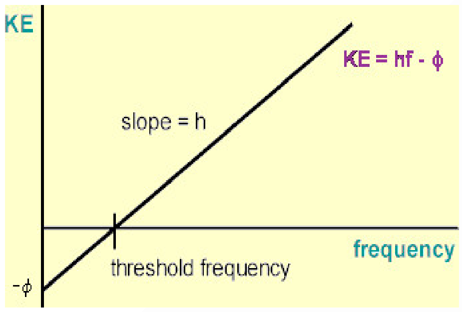

Figure 3: Intensity vs Voltage

continuous waves. For a given frequency of the incident radiation, each photon carried the energy $E = h\nu$, where h is Planck's constant and ν is the frequency. Increasing the intensity of the light corresponded, in Einstein's model, to increasing the number of incident photons per unit time (flux), while the energy of each photon remained the same (as long as the frequency of the radiation was held constant)(Fig 2).

Clearly, in Einstein's model, increasing the intensity of the incident radiation would cause greater numbers of electrons to be ejected, but each electron would carry the same average energy because each incident photon carried the same energy. The minimum energy required for the electron to be released is called the work function (WF) and the frequency that corresponds to that is called the threshold frequency $E = h\nu_{th}$.

$$E = h\nu = WF + 1/2mv^2$$

The potential required to stop the emission of photoelectrons is called the stopping potential. It can be measured for different frequencies (Fig 3).

The photoelectric effect is perhaps the most direct and convincing evidence of the existence of photons and the 'corpuscular' nature of light and electromagnetic radiation.

Albert Einstein received the Nobel prize in physics in 1921 for explaining the photoelectric effect and for his contributions to theoretical physics.

2 Compton Effect

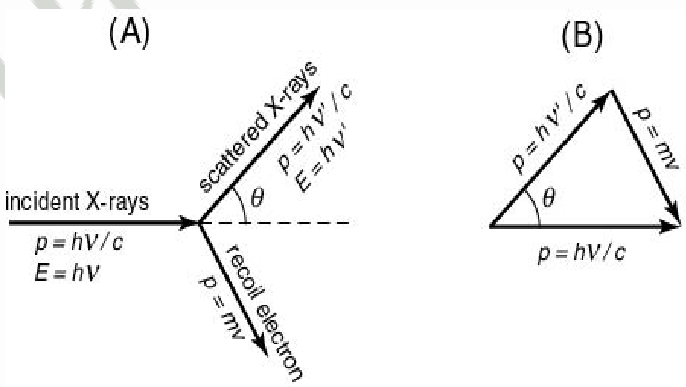

Figure 4: Compton Effect

When the monochromatic X rays are illuminated on a graphite (a kind of carbon crystal), the wavelength of the scattered X rays would be longer as the scattering angle becomes larger. This cannot be explained with the classical theory. In the classical theory consisting of Newtonian mechanics and Maxwellian electromagnetism, the incident X rays oscillate the charged particle (electron at present) and the oscillating charged particle radiates around the same frequency of electromagnetic waves (X rays). Accordingly, the frequency of the radiated (scattered) X rays must be the same as that of the incident X rays. Compton analyzed Compton scattering as follows. He explained that the incident X rays collide against the electron in the graphite as a 'particle' with the energy $h\nu$ and the momentum $h\nu/c$. Suppose that the energy and the momentum of the X rays scattered in the scattering angle θ are $h\nu^{'}$ and $h\nu^{'}/c$, respectively. The electron (the mass = m) recoils with a momentum mv. The energies and momenta in Compton scattering are shown in the following figure (A), and the relation of the momentum conservation is in the following figure (B).

The momentum conservation relation is written

$$m^2v^2 = \frac{h^2}{c^2}(\nu^2 + \nu^{'2} - 2\nu\nu^{'} cos\theta)$$

Since $\nu \approx \nu^{'}$, we have,

$$0 \approx (\nu - \nu^{'})^2 = \nu^2 + \nu^{'2} - 2\nu\nu^{'}$$

Inserting this into the above momentum conservation relation, we get

$$mv^2 = \frac{2h^2}{mc^2}\nu\nu^{'}(1 - cos\theta)$$

On the other hand, the energy conservation is written

$$mv^2 = 2h(\nu - \nu^{'})$$

Therefore, the difference between the the wavelength of the incident and scattered X rays becomes

$$\Delta\lambda = \lambda^{'} - \lambda = \frac{c}{\nu^{'}} - \frac{c}{\nu} = c \times \frac{\nu - \nu^{'}}{\nu\nu^{'}} = \frac{h}{mc}(1 - cos\theta)$$

Accordingly, the wavelength of the scattered X rays becomes longer as the scattering angle increases.

3 Pair Production

The high-energy photon that has energy h loses its entire energy when it collides with nucleus. Then, it makes pair of electron and positron and gives kinetic energy to each particle. These interactions have three kinds of

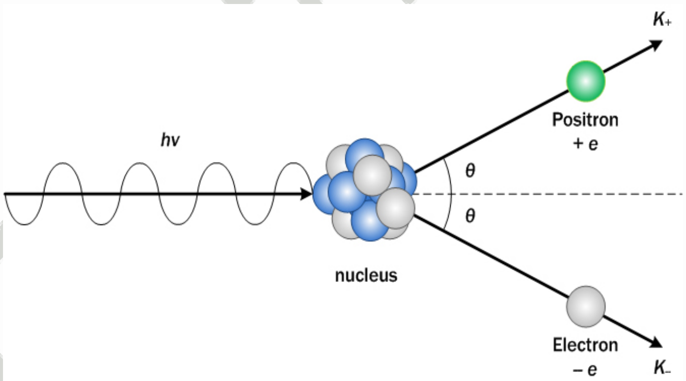

Figure 5: Pair Production

the law of conservation: total energy, momentum, and electric charge. After the collision, pair of electrons and positron occurs. In this collision, the positron, +e, as a particle, has the same properties which electron has, except its charge sign; the two particle, electron and positron has the opposite charge, and thus its magnetic momentum sign is also opposite. Having an opposite charge sign means that the sum of net charge of pairs is zero, which is actually equal to photon before the collision. Therefore, the conservation of electric charge will be conserved. Now, what counts is conservation of total energy and momentum. First of all, momentum in this process can be ignored because atomic nucleus is thousands of times more massive than pair of electron and positron, and thus, the photon momentum can be absorbed; thus, it is possible to anticipate that absorbing momentum occur without absorbing much energy. So, it is can be represented by an equation that shows the conservation of total energy only:

$$h\nu = E_- + E_+ = (m_0c^2 + K_-) + (m_0c^2 + K_+) = K_- + K_+ + 2m_0c^2$$

Here, $E-$ and $E+$ represent total energy of the electron and positron, and K_- and K_+ represent the kinetic energy of the electron and positron. Both the two particles have the same amount of rest mass energy. In the kinetic energy, because of the Coulomb interaction between positively-charged nucleus and both the two particlesthe positron and electron, positron would be accelerated and electron would be decelerated; thus, the kinetic energy of positron is actually little larger than electrons.

The wavelength of $2m_0c^2$ is 0.012A. If the wavelength of photon is shorter than 0.012A, it has larger than threshold energy, and total photon energy convert into kinetic energy as well as rest mass energy. This wavelength, 0.012A, is in the range of high energy of γ-ray or X-ray.

4 Pair Annihilation

Pair Annihilation means the reverse process of pair production. In the pair annihilation, the electron and positron in the stationary state combine with each other and annihilate. Surely, the particles are disappeared and radiation energy will occur instead of two particles. For the momentum conservation, the most frequent process in pair annihilation is making two photons that have exactly opposite direction and the same amount of momentum. (Sometimes it produces three photons in the pair annihilation process.)

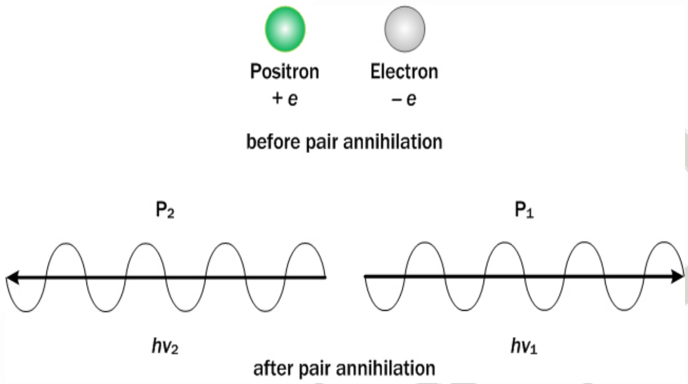

Figure 6: Pair Annihilation

5 Linear and Mass Attenuation Coefficients

Linear attenuation coefficent () is a constant that describes the the fraction of attenuated incident photons in a monoenergetic beam per unit thickness of a material. Its complement is the transmitted portion of the beam. It is expressed numerically in units of cm^{-1}.

The intensity of the beam at distance x (cm) within a material is calculated using the following equation:

$$I_x = I_0.e^{-\mu x}$$

Where I_x is the intensity at depth of x cm, I_0 is the original intensity, and μ is the linear attenuation coefficient.

Rearrange and take the log of both sides gives the equation for μ.

$$\mu = ln(I_o/I_x)/x$$

The mass attenuation coefficient is a normalisation of the linear attenuation coefficient per unit density of a material producing a value that is constant for a given element or compound The mass attenuation coefficient characterizes how easily it can be penetrated by a beam of light, sound, particles, or other energy or matter. In addition to visible light, mass attenuation coefficients can be defined for other electromagnetic radiation (such as X-rays), sound, or any other beam that attenuates. The SI unit of mass attenuation coefficient is the square metre per kilogram (m^2/kg).

The values of mass attenuation coefficients are dependent upon the absorption and scattering of the incident radiation caused by several different mechanisms such as

Rayleigh scattering (coherent scattering); Compton scattering (incoherent scattering); photoelectric absorption; pair production, electron-positron production in the fields of the nucleus and atomic electrons.

6 Charged Particle Interactions

Gamma-rays, x-rays, neutrons, and neutrinos all have no net charge - they are electrostatically neutral. In order to detect them they must interact with matter and produce an energetic charged particle. In the case of gamma and x-rays, a photo-electron is produced. In the case of neutrons, a proton is given kinetic energy in a collision.

Charged particles can be divided into two types: 1) electrons, including positrons and beta particles from radioactive decay, Auger electrons, and internal conversion electrons, and; 2) heavy charged particles such as the alpha particle, fission fragments, protons, deuterons, tritons, and mu and pi mesons.

The charged particles interact with matter primarily through the Coulomb force. Differences in the energy deposition trails between the two types of charged particles are due to the mass differences, i.e., the more easily altered trajectory of the electron.The heavy particles appear to continuously slow down, gradually losing their kinetic energy along an unaltered linear path.

When a charged particle gives sufficient energy to an orbital electron such that the freed electron itself can cause secondary ionization, we say that a delta-ray has been produced. The majority of the energy loss of a heavy charged particle such as the alpha occurs via these delta-rays. We consider two types of interactions: collisional and radiative.

6.1 Collisonal

Inelastic collision with atomic electrons. This results in excitation or ionization. These processes ultimately end with the heating of the absorber (through atomic and molecular vibrations) unless the ions and electrons can be separated using an electric field as is done in radiation detectors.

6.2 Radiative

Inelastic collision with nucleus. A quantum of electromagnetic radiation is emitted (a photon). Energy loss is experienced by the particle. Important for electrons. Probability of nuclear excitation is negligible. This process is also known as RADIATIVE energy loss. The acceleration of electrons near a nucleus is known as beam braking or bremsstrahlung.

The stopping of charged particles in matter is by collisional and radiative processes which occur in frequencies dictated by their interaction cross sections (or probabilities). What we observe then is a statistical average of the 2 processes occurring as the particle slows down. Linear Stopping Power is given by

$$S = -dT/dx$$

where T is the charged particle kinetic energy, -dT is the energy increment lost in infinitesimal material thickness of dx. The units of stopping power are keV/micron. The higher the stopping power, the shorter the range into the material the particle can penetrate. The quantity S is also referred to as specific energy loss .

The stopping power S increases as the particle velocity is decreased. The classical depiction of the charged particle interaction with an electron is depicted in the following fig:

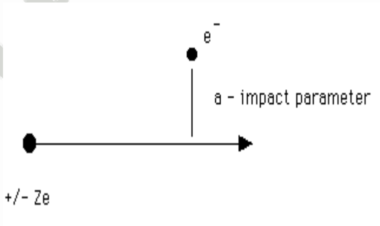

Figure 7: Charged particle interaction

Classically, a passing charged particle will impart kinetic energy to the electron given by the following formula:

$$T_e = \frac{Z^2 e^4}{8\pi\epsilon_0^2 a^2 m_0 v^2}$$

The faster the particle is, the less energy is given to the electron (the less time it has to spend imparting energy to the electron).

The Bethe-Bloch formula for electrons contains must take into account two facts: 1) that the electron has a much smaller mass than the heavy particles; and 2) that the electron is identical to the particles with which it is interacting, thus giving the possibility of the exchange of identity, i.e., the incoming particle has a probability of becoming the atomic electron with the atomic electron becoming the outgoing particle. Taking this into account, as well as relativity, gives us the Bethe-Bloch formula for electrons.

6.3 Bragg Curve

The plot of specifc energy loss (which can be related to specifc ionization) along the track of a charged particle is called a Bragg Curve. The Bragg curve is typical for heavy charged particles and describes energy loss of ionizing radiation during travel through matter. For this curve is typical the Bragg peak, which is the result of 1/v2 dependency of the stopping power.

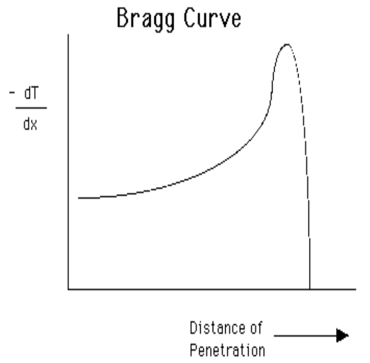

Figure 8: Bragg Curve

As the energy falls, the specific energy loss increases according to the Bethe-Bloch formula. As the energy falls below a threshold, however, an electron will attach to the alpha, dramatically lowering the specific energy loss.

The energy deposition of the electron increases more slowly with penetration depth due to the fact that its direction is changed so much more drastically.

Energy loss in a material is a statistical or stochastic process. Therefore, a spread of energies always results when an initially monoenergetic beam of particles encounters an absorber. Many particles lose the "average energy," although some will lose not so much and some will lose more than the average. This results in a finite width to the energy distribution curve known as "energy straggling." The straggling peak is approximately Gaussian shaped, with a width that increases with the ratio Z/A. In other words, at lower atomic numbers (where the Z/A ratio is higher) we have wider widths. This is due to the fact that there is less shielding of inner electrons in the lower Z elements - there is more stopping influence per electron.

6.4 Linear and Mass Attenuation Coeficient

The mass attenuation coeficient is μ/ρ, where μ is the linear attenuation coefficient and ρ is the absorber density. The mass stopping power is:

$$(1/\rho) * (dT/dx)$$

in units of keV/(gm/cm^2)

Bremsstrahlung or braking radiation is any radiation produced due to the deceleration (negative acceleration) of a charged particle, which includes synchrotron radiation (i.e. photon emission by a relativistic particle), cyclotron radiation (i.e. photon emission by a non-relativistic particle), and the emission of electrons and positrons during beta decay. Bremsstrahlung emitted from plasma is sometimes referred to as free/free radiation. This refers to the fact that the radiation in this case is created by charged particles that are free; i.e., not part of an ion, atom or molecule, both before and after the deflection (acceleration) that caused the emission.

The total stopping power for electrons can be given as a combination of the collisional and radiative types of interactions:

$$[dT/dx]_{total} = [dT/dx]_{collision} + [dT/dx]_{radiative}$$

(for heavy particles we only consider orbital electron interactions (an atomic process) since the probability of nuclear interaction resulting in energy loss is much smaller.)

The fraction of energy lost to radiation is inversely proportional to the charged particle's mass. Bremsstrahlung will therefore be very low for heavy charged particles (compared to electrons). Even at 100 MeV, for example, heavy particles dissipate most of their energy through the collisional process.

6.5 Range

In passing through matter, charged particles ionize and thus lose energy in many steps, until their energy is (almost) zero. The distance to this point is called the range of the particle. The range depends on the type of particle, on its initial energy and on the material through which it passes.

For example, if the ionising particle passing through the material is a positive ion like an alpha particle or proton, it will collide with atomic electrons in the material via Coulombic interaction. Since the mass of the proton or alpha particle is much greater than that of the electron, there will be no significant deviation from the radiation's incident path and very little kinetic energy will be lost in each collision. As such, it will take many successive collisions for such heavy ionising radiation to come to a halt within the stopping medium or material. Maximum energy loss will take place in a head-on collision with an electron.

Since large angle scattering is rare for positive ions, a range may be well defined for that radiation, depending on its energy and charge, as well as the ionisation energy of the stopping medium. Since the nature of such interactions is statistical, the number of collisions required to bring a radiation particle to rest within the medium will vary slightly with each particle (i.e., some may travel further and undergo fewer collisions than others). Hence, there will be a small variation in the range, known as straggling.

The energy loss per unit distance (and hence, the density of ionization), or stopping power also depends on the type and energy of the particle and on the material. Usually, the energy loss per unit distance increases while the particle slows down. The curve describing this fact is called the Bragg curve. Shortly before the end, the energy loss passes through a maximum, the Bragg Peak, and then drops to zero (see the figures in Bragg Peak and in stopping power). This fact is of great practical importance for radiation therapy.

The range of alpha particles in ambient air amounts to only several centimeters; this type of radiation can therefore be stopped by a sheet of paper. Although beta particles scatter much more than alpha particles, a range can still be defined; it frequently amounts to several hundred centimeters of air.

The mean range can be calculated by integrating the inverse stopping power over energy. The mean range is the range at which the number of particles detected is one-half the original value.

Factors which affect range R:

Energy: Range is approximately linear with energy since the Bethe-Bloch equation for stopping power is inversely proportional to E.

Mass: for the same kinetic energy, the electron is much faster than the alpha due to its smaller mass, and therefore the electron has less time to spend near orbital electrons. This reduces the effect of Coulomb interactions (hence stopping power) and increases range.

Charge: the more charge, the more stopping power and the lower range. Range is inversely proportional to the square of the charge of the charged particle.

For example, a tritium particle with z=1 will have 1/4 the stopping power of a He-3 particle with z=2.

Density: The stopping power increases with increasing density. The range is inversely proportional to the density of the absorbing medium.

6.6 POSITRONS

Positrons behave nearly the same as electrons as they lose their energy, they are simply deflected in the opposite direction. As far as imaging is concerned, the 511 keV annihilation photons resulting from positrons come from the point at which the positron as slowed enough to engage in a prolonged encounter with an electron, i.e. it forms the unstable "positronium". This places an isotope-dependent limit on spatial resolution in PET imaging, since each positron emitter has a different E(max) for positrons and hence a different range. The other consideration is the center-of-mass momentum of the positronium, which contributes to non-opposition of the annihilation photons in the laboratory frame of reference.

6.7 CHERENKOV EFFECT

Cherenkov radiation is an electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. When the charged particle has a velocity greater than c/n (the speed of light in the medium), n is the index of refraction of the medium, a "shock wave" of photons is generated in the blue light range, analogous to the sonic boom of a jet flying faster than the speed of sound.