Interaction Of Ionizing Radiation With Matter

Objectives: Interaction of Ionizing Radiation with Matter

Explain what Bremsstrahlung are and what causes their formation.

Explain the utility of Bremsstrahlung radiation in radiographic procedures

Describe the photoelectric effect and write the equation that explains the energy balance between the incoming photon, the exiting electron, and the binding energy.

Explain the dependence of Photoelectric effect upon atomic number of the absorber and the photon energy

Describe the process of Internal Conversion

Describe the Compton Effect and the type of collision involved regarding elasticity.

Identify Angle ϕ in the equation for Compton Effect

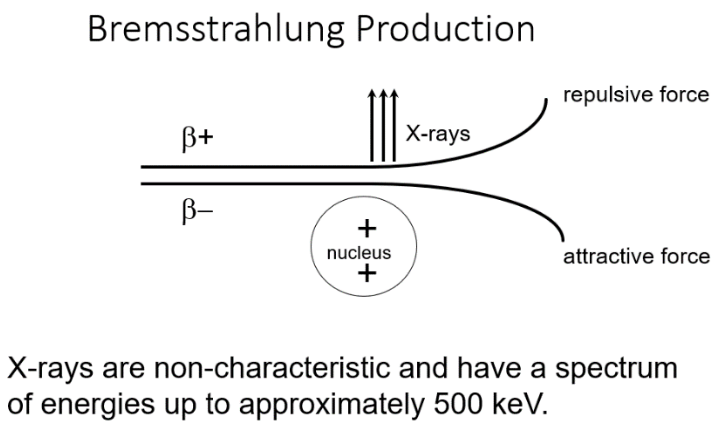
Explain the process of Pair Production, identify the pair, and explain how each of these two particles gives up their energy

Interaction of Ionizing Radiation with Matter

Bremsstrahlung

1. Production of Bremsstrahlung (the German word for "braking radiation") involves release of electromagnetic radiation in the form of X-rays by the deceleration that a fast-moving, charged particle undergoes when attracted to or repelled by another charged particle. The charged particles in this case are the electronegative beta particle (negatron) or the electropositive positron and the electropositive nucleus of an atom near which the beta particle passes.

2. Bremsstrahlung Production

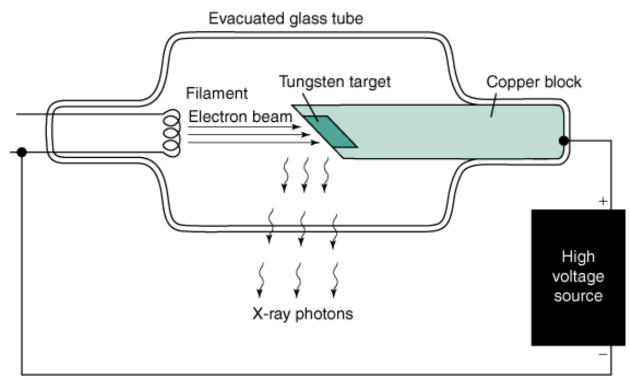


3. When a negative beta particle passes near the nucleus, its path of travel will be deflected in the direction of the nucleus due to the attractive forces of the two particles. This change of direction is accompanied by a deceleration of the beta particle.

4. This effect also takes place with positive electrons (positrons), but the forces involved are repulsive rather than attractive and the change of direction is away from the nucleus.

5. The X-rays produced have no discrete energy, but rather exhibit a broad spectrum of energies up to several hundred KeV.

6. In the practice of Radiology, an electron beam is aimed at a Tungsten target, chosen specifically for its high Z # and density, which enhance X-ray production. These X-rays are bremsstrahlung and are commonly used for many radiographic procedures. The diagram below illustrates the design of the X-ray tube.



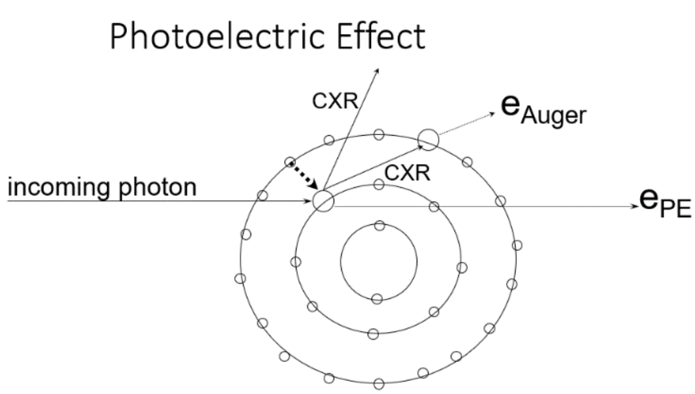
Source: Chen MYM, Pope TL, Ott DJ: *Basic Radiology, 2nd Edition*: http://www.accessmedicine.com

Photoelectric Effect

1. The Photoelectric Effect is especially important for gamma rays of low energy (<0.2 MeV). It involves the totally inelastic collision of a photon and an electron in which all of the energy of the photon is transferred to the electron.

2. In the Photoelectric Effect, an electron is ejected from its orbital with kinetic energy equal to the energy of the gamma ray which struck it, less the binding energy holding the electron in its orbital.

3. Diagram of the Photoelectric Effect



Auger electrons are ejected by the secondary process rather than the primary process

4. Equation for the Photoelectric Effect

$$E_{photoelectron} = E_{gamma\ ray} - BE_{electron}$$

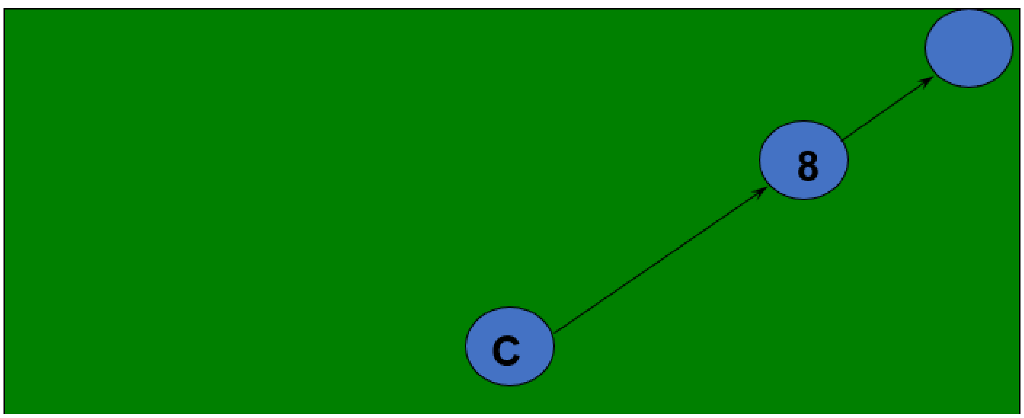
Mathematically, $\frac{1}{2} mv^2 = h\nu - \phi$ where

$\frac{1}{2} mv^2$ = KE of ejected electron

$h\nu$ = energy of the incident photon; and

ϕ = the BE holding electron in its orbital

5. Pool Table Analogy to Photoelectric Effect: a mechanical example analogous to a quantum mechanical example



Just as the gamma ray in a photoelectric effect undergoes a totally inelastic collision with an electron and transfers all is energy to the electron, on the pool table the cue ball collides with the 8 ball and transfers 100% of its energy in a completely inelastic collision. The cue ball stops instantly, and the 8 ball travels toward the corner pocket. The energy of the 8 ball = the energy of the cue ball that struck it minus the "binding energy" (inertia) holding the 8 ball on the table.

6. **Quiz question 1**: In which one of the following is the photoelectric effect most likely?
   a. Air (Z numbers 7 and 8)
   b. the patient (low Z numbers for C, H, O, N, Na, and other elements))
   c. NaI crystal (Z numbers 11 and 53)
   d. Pb collimator (Z number 82)

   Answer: Pb collimator. The Photoelectric Effect is most pronounced if the Z number of the absorbing material is high. Mathematically,

$$\text{Probability of PE} \;\alpha\; Z^3$$

Since it is a cubed relationship, the probability increases dramatically as a function of Z number.

7. **Quiz question 2**: For which one of the following isotopes is the Photoelectric Effect most likely to occur in a NaI(Tl) crystal?

   a. Tl-201 (71-80 keV)
   b. Co-57 (122 keV)
   c. Tc-99m (140 keV)
   d. I-123 (159 keV)
   e. In-111 (173 and 247 keV)

   Correct answer: Tl-201; $E\gamma$ = 71-80 keV. The Photoelectric Effect is most pronounced if the energy of the photon is low. Mathematically,

$$\text{Probability of PE} \;\alpha\; \frac{1}{E^3}$$

Again, since it is a cubed relationship, the probability increases dramatically as energy decreases.

8. If the two equations are combined into one, then

$$\textbf{Probability of Photoelectric Effect} = \frac{Z^3}{E^3}$$

9. **Quiz question 3**

   Based on the equation in paragraph 8 above, what happens to probability of Photoelectric Effect if

   a. Z is doubled and E is doubled?

   b. Z is doubled and E is halved?

   c. Z is halved and E is doubled?

   Answer:

   a. Z $\rightarrow$ 2Z and E $\rightarrow$ 2E, probability is unchanged

   b. Z $\rightarrow$ 2Z and E $\rightarrow$ ½ E, probability $\uparrow$ by 64

   c. Z $\rightarrow$ ½ Z and E $\rightarrow$ 2E, probability $\downarrow$ by 64

Internal Conversion

1. Internal Conversion is most similar diagrammatically to Photoelectric Effect. The only difference in the diagram is the source of energy. In Photoelectric Effect, the source is a photon from any other nucleus. In Internal Conversion, the source of energy is the nucleus of the atom itself.

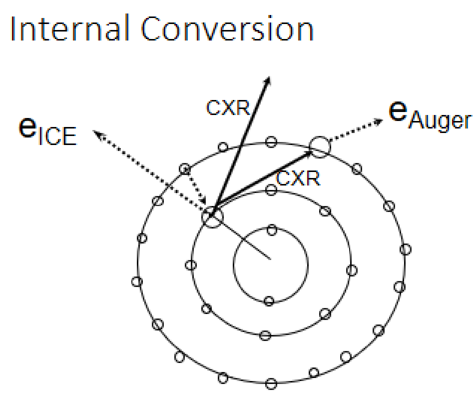
2. IC involves the totally inelastic transfer of excitation energy of the nucleus to an electron. As in PE, the electron is ejected from its orbital.

3. The equation for IC is

$$E_{ICE} = E_{excitation} - BE_{electron}$$

   In other words, the excess nuclear energy is internally converted within one atom into the kinetic energy of the ejected electron.

4. The diagram for Internal Conversion is shown below:

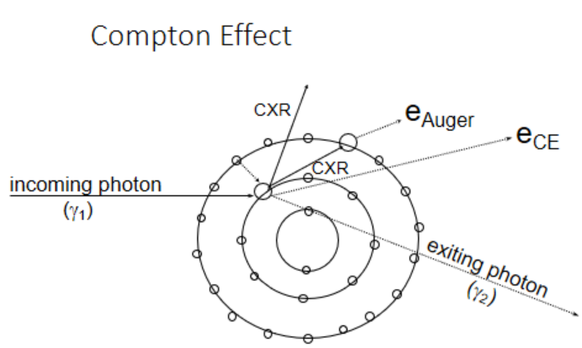


5. As is the case whenever an electron is ejected from an outer orbital, regardless of what caused the ejection, characteristic X-rays and Auger electrons will be produced. From a diagnostic standpoint, Auger electrons are useless and increase the internal radiation dose to the patient. The same can be said of the X-rays, unless their energy is in the imageable range of ~ 70-400 keV, in which case they may be used for imaging.

Compton Effect

1. The Compton effect (Compton scattering) is especially important for gamma rays of medium energy (0.5-1.0 MeV). It involves the partially elastic collision of a photon and an electron in which a part of the energy of the photon is imparted to the electron. The photon emerges from the collision in a new direction and with reduced energy.

2. Diagram for Compton Effect



As is evident from the diagram above, the incoming photon transfers part of its energy to the electron (a partially elastic collision) and the electron is ejected. The gamma ray, now lower in energy due to the collision, is deflected at an angle away from the ejected electron. This angle of deflection is referred to as angle ϕ in the equation below:

3. Formula for Compton Effect

$$\Delta \lambda = \frac{h}{mc} \cdot (1 - \cos \phi) \quad \text{where}$$

$\Delta \lambda$ = change in wavelength of 2 γ photons

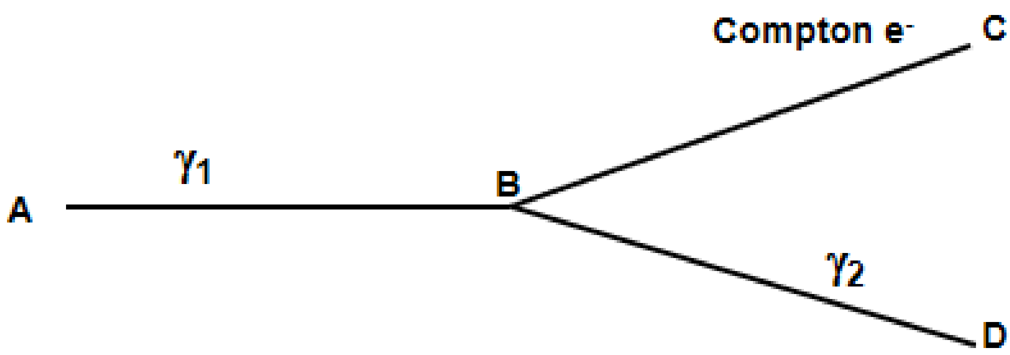
h = Planck's Constant

m = mass of an electron

c = velocity of light

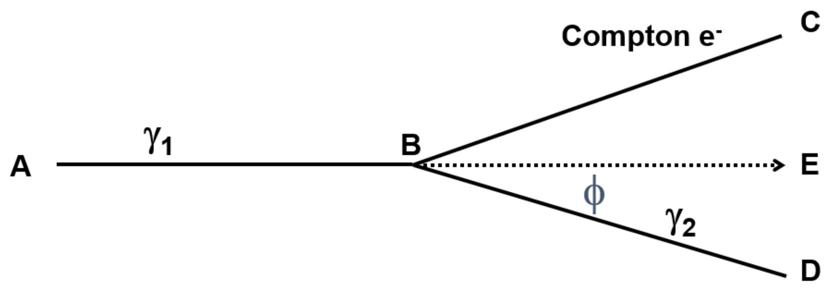
ϕ = angle between incident & deflected photons

4. **Quiz question 1.** In the diagram below, which angle is angle ϕ?

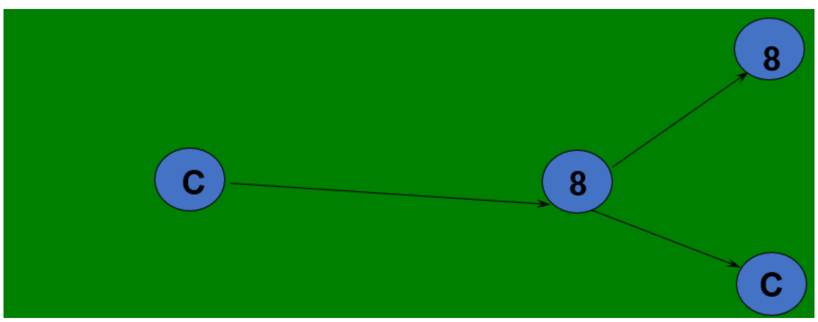


a. Angle ABC
b. Angle ABD
c. Angle CBD
d. None of the above

Answer: None of the above. One must extend the line of incidence from A to B to E (refer to diagram below). The angle ϕ is then the angle between incidence (ABE) and deflection (ABD), that is, angle EBD. There is no reason to assume that angle EBC and angle EBD are equal, even though they appear to be in the diagram.



5. Pool table analogy to Compton Effect: a mechanical example analogous to a quantum mechanical example

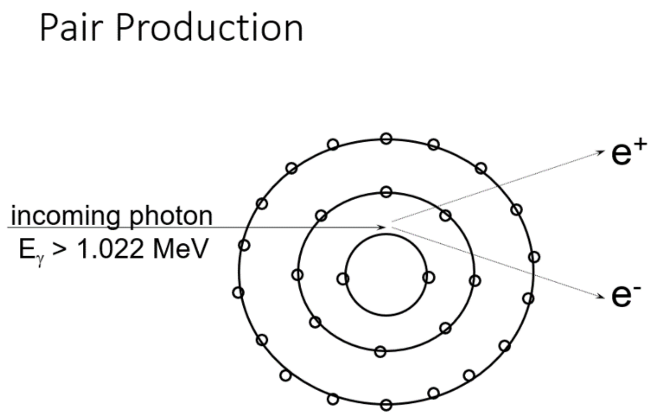


The cue ball hits the 8 ball a glancing blow on the right side, making a partial transfer of energy. The 8 ball is deflected toward upper left and the cue ball is deflected toward the lower right. This is analogous to the partial transfer of energy when a high energy photon ejects an electron in one direction and the deflected photon travels in a different direction.

Pair Production

1. When a gamma photon has E >1.022 MeV, **in the presence of matter**, Pair Production *can* take place. The gamma ray disappears and, in its place appear a positive electron and a negative electron. There is total conversion of energy to matter. The angle between the electrons is indeterminate.

2. Diagram for Pair Production



3. To reconcile this mass/energy relationship, a simple calculation will prove that the rest mass of 2 electrons is equivalent, according to Einstein's equation, to an energy value of 1.02 MeV.

4. The positron emitted as part of the pair reacts with an electron in matter and both electrons are destroyed in the process called annihilation and their rest mass is converted back to 1.02 MeV of energy. This total is shared by two gamma photons, each of which possesses 0.511 MeV of energy and which are at 180^o to each other.

5. If the energy of the incident photon is much greater than 1.022 MeV, the *excess energy above the 1.022 MeV required to form the pair* is shared by the two electrons as kinetic energy. This excess energy is lost by collisions with other nuclei, reducing the energy of the electrons to a low enough level that the positron and another electron can annihilate each other.

6. **Quiz question 1:** *True/False*: in Pair Production the electron pair is emitted at a 180^o angle to each other

   Answer: False. The angle is indeterminate.

   Quiz question 2: *True/False*: High kinetic energy positrons <u>immediately</u> annihilate electrons in matter

   Answer: False. A highly energetic positron will collide with whatever is in its path, undergoing ionization events as it loses energy. Only when its kinetic energy has been reduced to a very low level can it undergo annihilation.

Quiz question 3. Assume that a 3.02 MeV γ-ray undergoes pair production. True or False: The kinetic energy of each electron in the pair is half that value, 1.51 MeV

Answer: False. Here's the math:

$$KE = \frac{(E_\gamma - 1.02\ \text{MeV})}{2} = \frac{(3.02\ \text{MeV} - 1.02\ \text{MeV})}{2}$$

$$KE = \frac{2.00}{2} = 1.00\ \text{MeV}$$

The gamma ray energy must be reduced by 1.02 MeV, the energy required to form the pair. The balance is then shared equally by the two particles.