Authorized User / Radiation Safety Officer Training for Veterinary Users

Module 3: Interaction of Radiation with Matter

Chad A. Smith, PhD, CHP, DABR

Satish Nair, PhD, CHP, DABMP

F.X. Massé Associates, Inc. www.fxmasse.com

info@fxmasse.com

978-283-4888

Introduction

- It is very important to discuss how radiation interacts with matter, since this is fundamental to understanding radiation-related biological effects and even radiation detection.
- This module introduces basic interaction of radiation with matter, including how charged particles interact with atoms and major mechanisms of photon and neutron interactions with matter.
- After completing this module, the reader should have basic knowledge about:
  - The classification of different types of radiation
  - How each type of radiation can cause ionization in matter.
- Properties of radiation emitted from ^{131}I NaI radioiodine, ^{90}Y IsoPet®, and ^{117m}Sn Synovetin OA™ are discussed in the last section.
- Assigned reading:

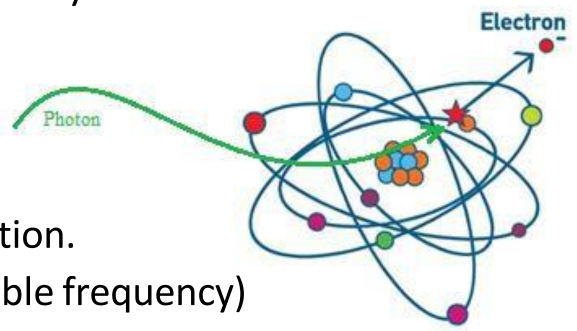
Turner, James E. 2007. Atoms, Radiation, and Radiation Protection. Wiley-VCH, Germany (optional textbook)

Outline

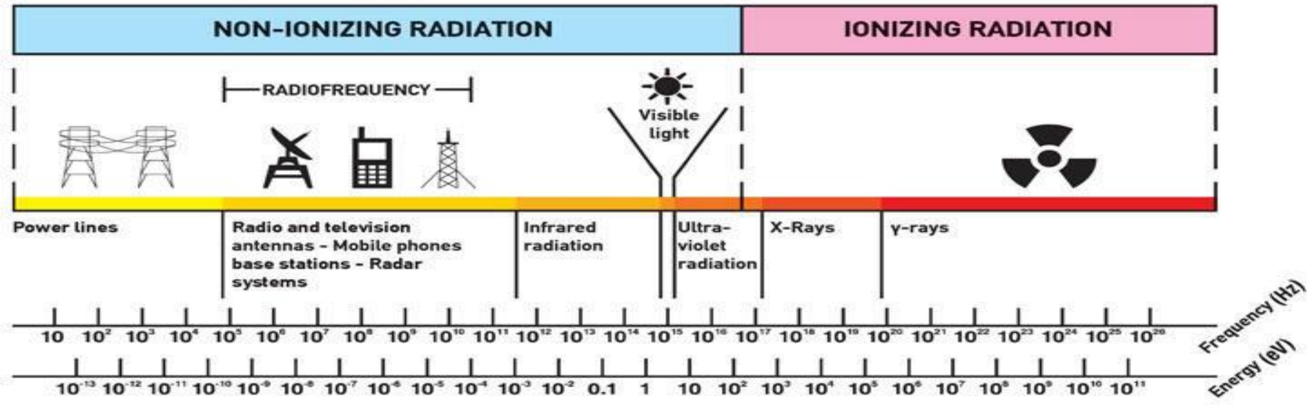
- The Interaction of Ionizing Radiation with Matter:
  - Modes of radiation interaction
- The Interaction of Charged Particles with Matter:
  - Heavy charged particles
  - Electrons and positrons
- The Interaction of Uncharged Particles with Matter:
  - Photons
  - Neutrons
- Specific Interaction Properties of ^{131}I NaI radioiodine, ^{90}Y IsoPet®, and ^{117m}Sn Synovetin OA™
- Quiz

The Interaction of Ionizing Radiation with Matter

- Radiation is divided into two classes, ionizing and non-ionizing. The separation is based on the binding energy of the Hydrogen orbital electron.
- Radiation is **ionizing** if it is energetic enough to eject electrons from atoms.
  - Ionizing radiation includes charged particles(alpha, beta, positrons), uncharged particles (neutrons), X-rays and gamma rays (high-frequency electromagnetic(EM) radiation).
  - Note that neutrons can be ionizing radiation, although they are not charged particles.



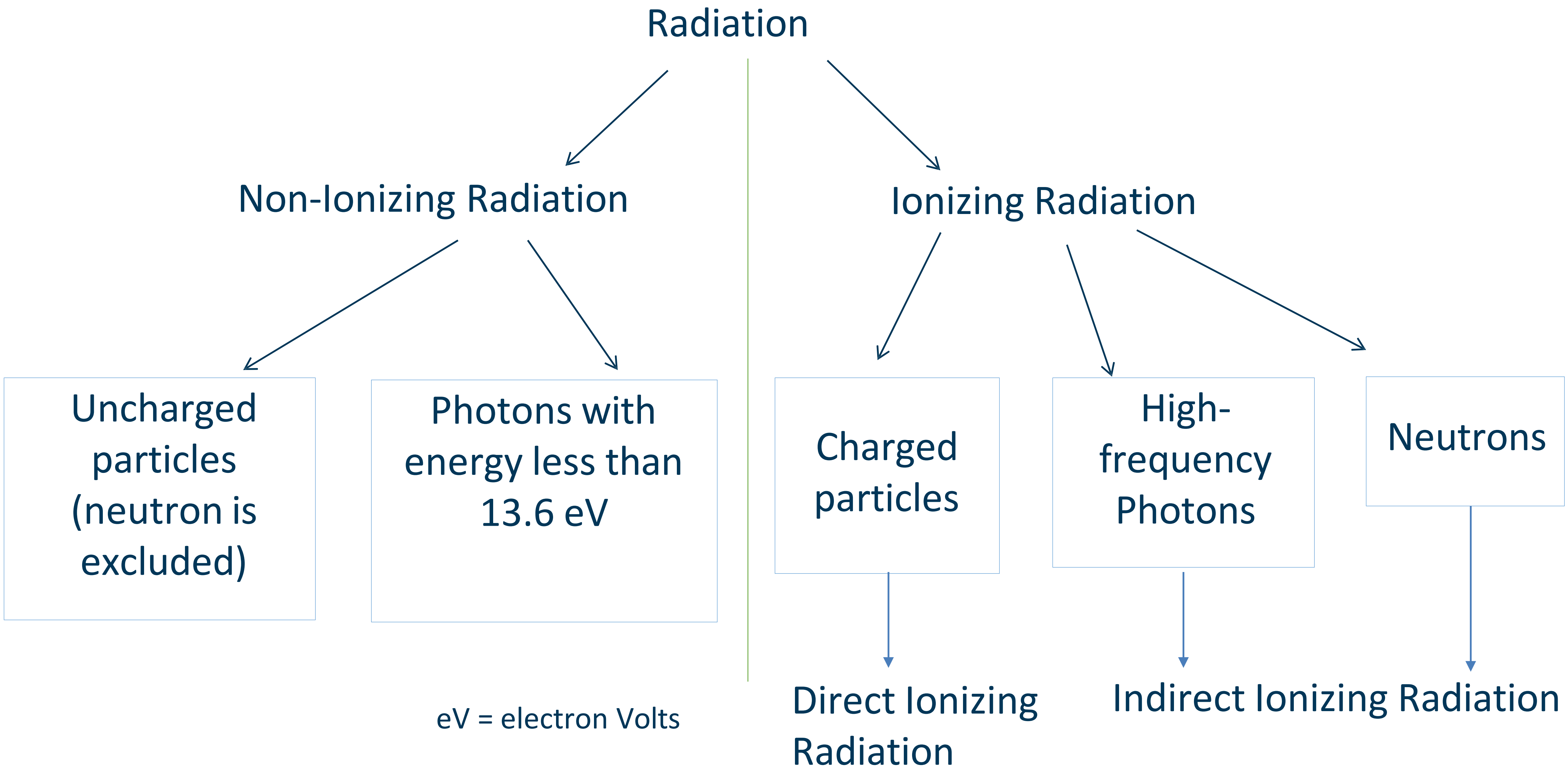
- **Non-ionizing** radiation includes very low energy electromagnetic radiation and non-charged particle radiation.
  - Non-ionizing EM radiation is a photon with low frequency, such as infrared radiation (light below visible frequency) or RF radiation (used for radio station broadcasts).
- Either ionizing or non-ionizing radiation can create heat by energy deposition.



The Interaction of Ionizing Radiation with Matter *(continued)*

- Ionizing radiation is further divided in two groups: direct and indirect.
- Charged particles (electrons, positrons, alpha particles) are called **direct** ionizing radiation because they ionize matter directly through electric force.
- Uncharged particles (photons and neutrons) are classified as **indirect** ionizing radiation, because they primarily ionize atoms by secondary charged particles (electrons). In this context, photons (x-ray and gamma) are considered ‘particles’ because they are essentially ‘packets of energies’ that have both particulate and wave-like characteristics.

The Interaction of Ionizing Radiation with Matter *(continued)*



Interaction of Charged Particles with Matter

- Common charged particle radiation is alpha, proton, and beta radiation (electron or positron).
- Charged particles interact with an atom either through collision with atomic orbital electrons or through collision with nuclei.
- "**Stopping Power**" (SP) is the quantity which describes how much energy loss a charged particle exhibits along its traveling path in matter.
- Because the mass of a beta particle is about 1/2000 of the mass of a proton, we call proton and alpha particles "**heavy charged particle radiation**."
  - This difference in mass allows the electron to possess a unique interaction mode: **bremsstrahlung radiation** (braking radiation).

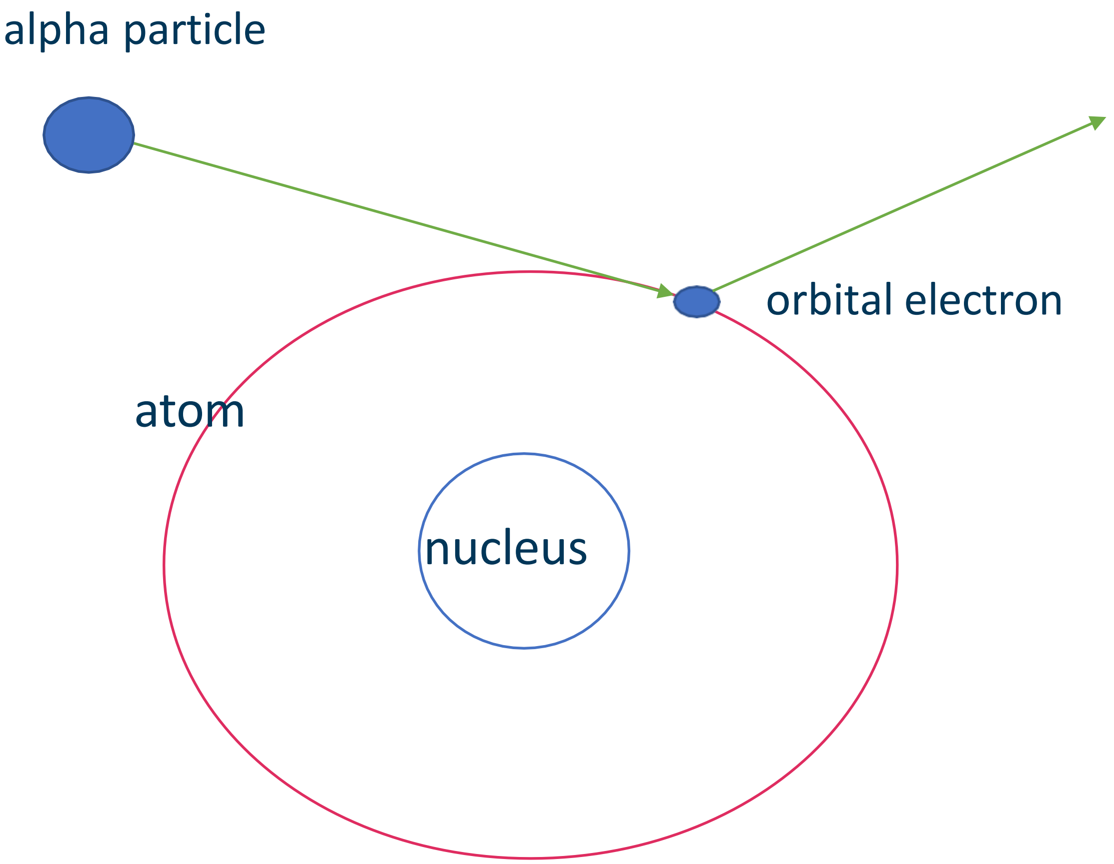
Interaction of Charged Particles with Matter: Heavy Charged Particles

- A heavy charged particle kicks out orbital electrons through electric force.
- Because the mass of the heavy charged particle is much greater than the mass of an orbital electron, the heavy charged particle travels along a straight path in matter.
- “**Range**” is the depth of penetration that a heavy charged particle travels in matter. It depends on particle energy and type of medium.
- The stopping power (SP)—energy loss of a charged particle per unit length along its path—of a heavy charged particle depends on its charge, its velocity, and the atomic number (Z) of the target matter.
  - However, its mass does not affect the stopping power.
- Rules of thumb for a heavy charged particle:

  1. The more charge it carries, the higher the SP
  2. The slower the velocity it travels, the higher the SP
  3. The higher the target atomic number, the higher the SP

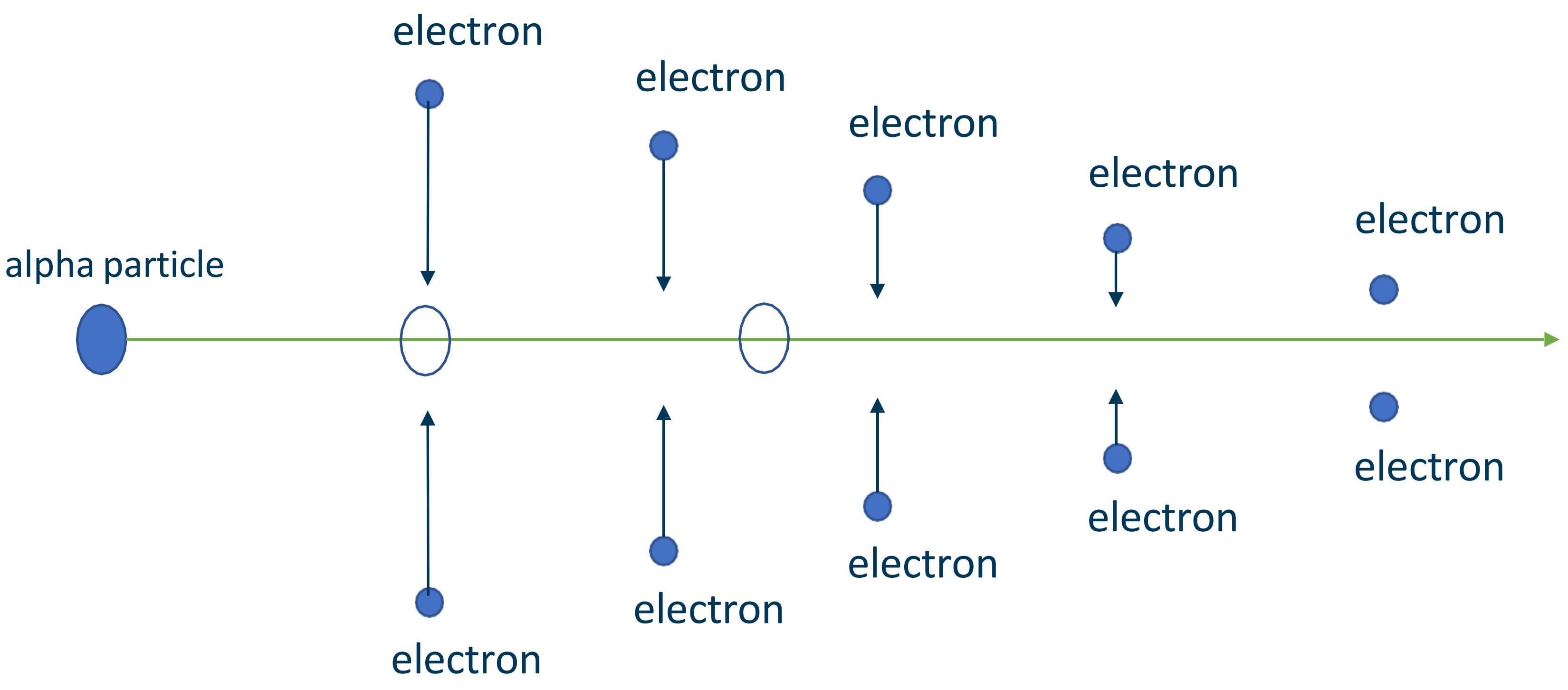
Interaction of Charged Particles with Matter: Heavy Charged Particles *(continued)*

An alpha particle “kicks out” an orbital electron through electrical force.



Interaction of Charged Particles with Matter: Heavy Charged Particles *(continued)*

An alpha particle travels along a straight line in matter, pulling on electrons.



Interaction of Charged Particles with Matter: Electrons and Positrons

- Electrons and positrons interact with orbital electrons through electrical force (similar to heavy particles). However, since electrons and positrons are much lighter in mass, they can cause interactions which emit **photons**.
- When a beta particle travels near a nucleus, the electrical force pulls the beta particle, dramatically changing its travel path because of its very small mass.
- This sudden deflection of direction causes the moving beta particle to emit a certain amount of energy in the form of a photon, called bremsstrahlung radiation.
- Bremsstrahlung ('braking')radiation is unique to beta particles.

Interaction of Charged Particles with Matter: Electrons and Positrons *(continued)*

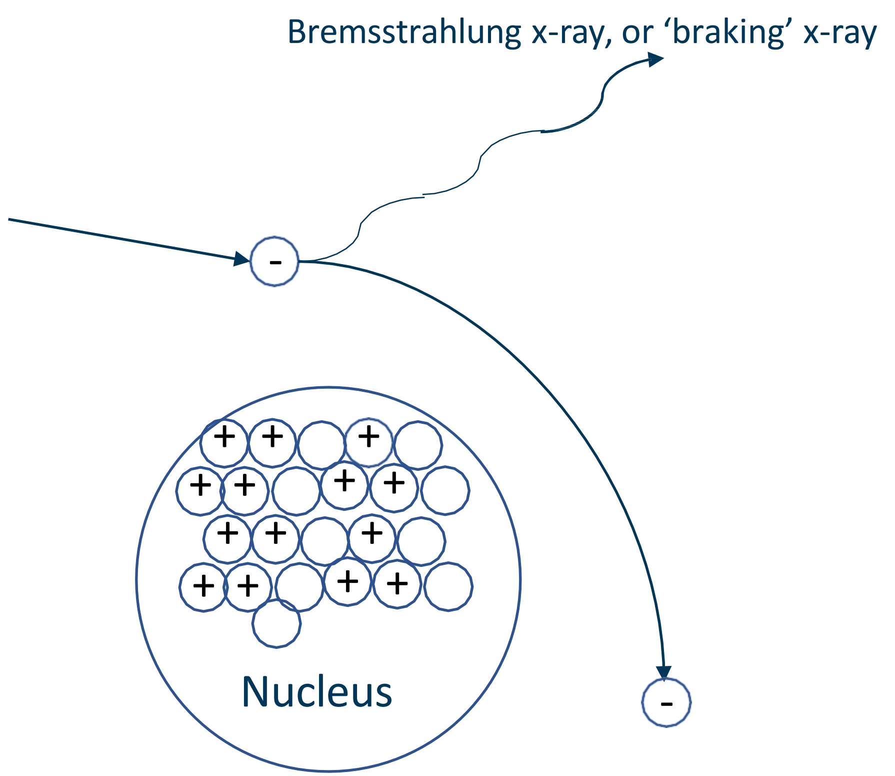
- Total stopping power of a beta particle = collision stopping power + radiative stopping power.

  Expressed another way:
  Total energy loss of a beta particle = energy loss through atomic collision +
  energy loss through bremsstrahlung radiation emission.

- As the energy of a beta particle increases, the radiative energy loss contribution to the total energy loss also increases.
- Unlike heavy charged particles that travel through matter in a straight line, a beta particle travels through matter on a zig-zag path. This is because the beta particle is very light in mass and carries a charge, making it very easily attracted, deflected, and scattered by surrounding atoms and charge.
- The range or depth of the beta particle in tissue is much shorter than the actual distance it travels when you total the scattered paths.

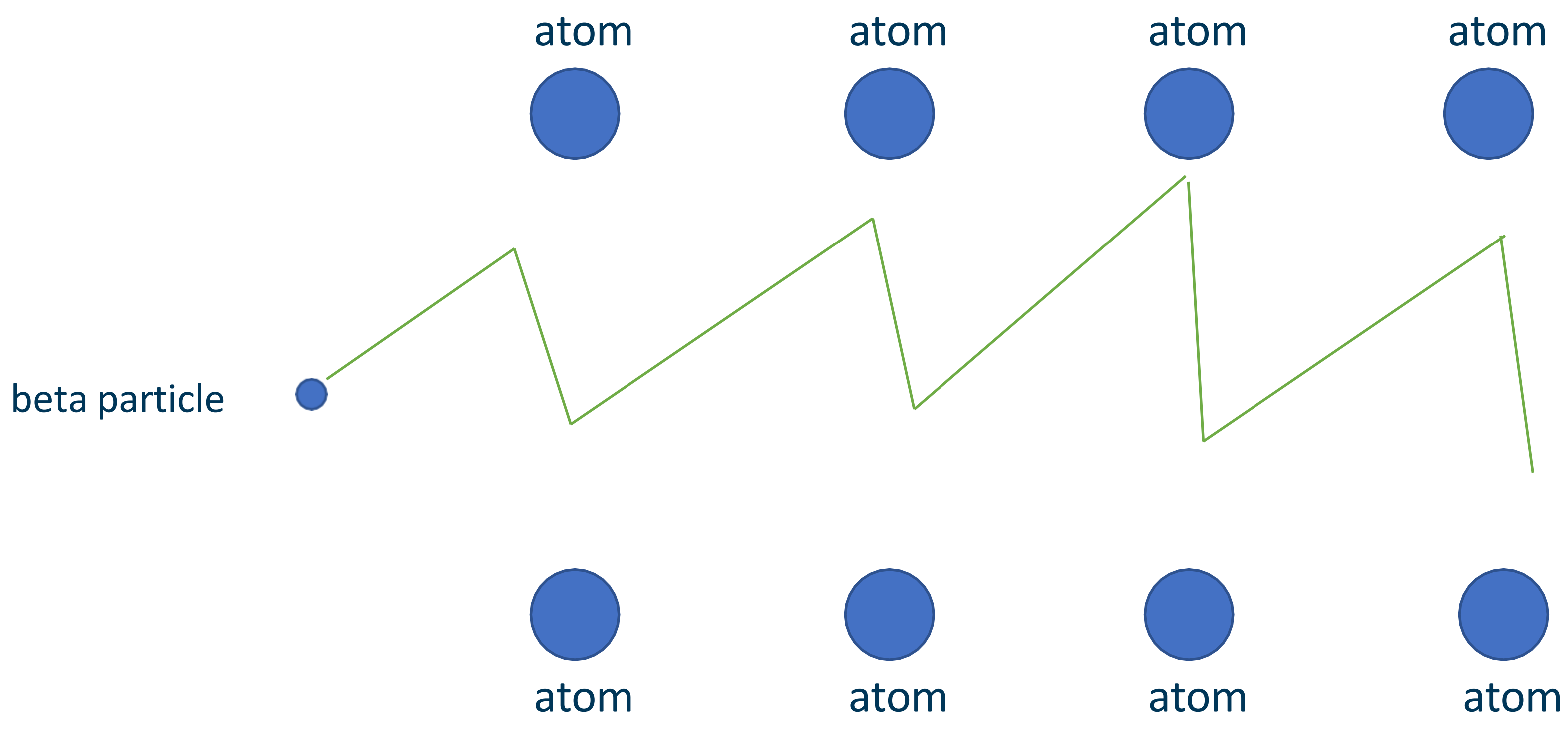
Interaction of Charged Particles with Matter: Bremsstrahlung

A beta particle emits a photon when attractive forces cause the beta particle to change direction and lose energy. The conservation of energy dictates the energy of the bremsstrahlung photon.



Interaction of Charged Particles with Matter: Electrons and Positrons *(continued)*

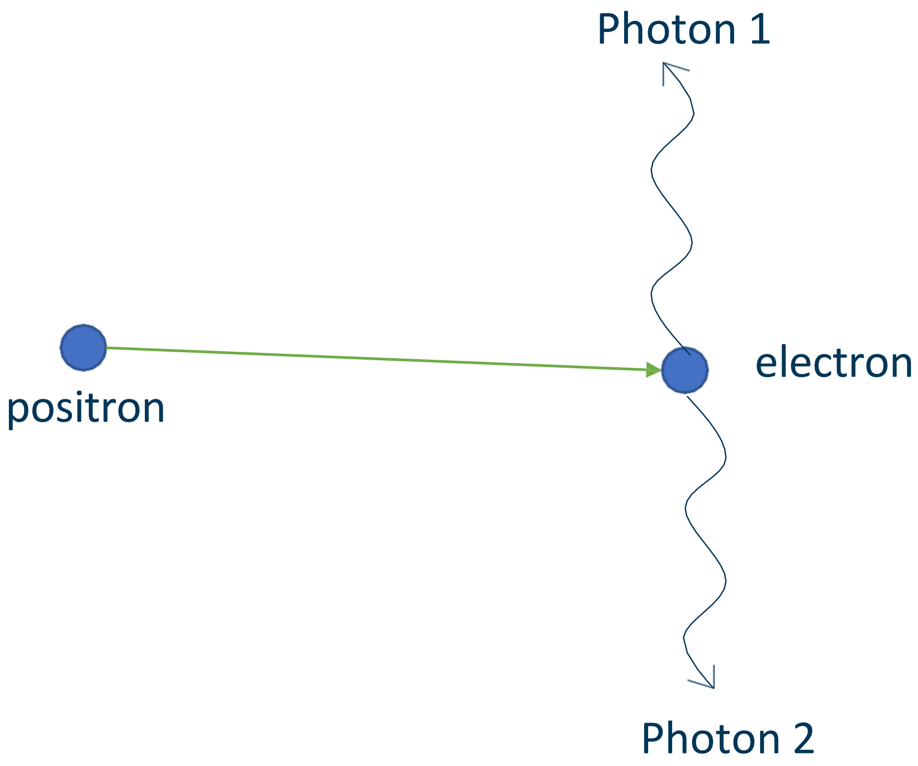
A beta particle travels in a zig-zag path in matter.



Interaction of Charged Particles with Matter: Electrons and Positrons *(continued)*

A **positron** carries one unit of positive charge. When it comes to rest, a positron "annihilates" with a free electron, emitting two 0.511 MeV gamma ray photons.

This is the process used when imaging PET isotopes such as ^{18}F. The low-yield positrons emitted by ^{90}Y have been successfully used for PET imaging as well, and serves as means of IsoPet® post-treatment dose quantification and evaluation. See *supplemental reading* for references.



Interaction of Uncharged Particles with Matter

- Photons and neutrons are uncharged particles that interact with matter through direct collision with no electric force.
  - A neutron walks into a bar and asks for a drink. The bartender gives the neutron a drink. The neutron asks the bartender how much he owes, and the bartender says, “for you, no charge.”
- Because photons and neutrons have no charge, they can travel a long distance without interacting with an atomic nucleus or electron.
- Photons interact with matter in three major ways:
  - The photoelectric effect
  - Compton scattering
  - Pair production.

  The probability of each reaction largely depends on photon energy, and the target density.
- Neutrons can be classified as thermal, slow, intermediate, fast, and relativistic based on energy.
- Neutrons can be scattered or captured when traveling in matter, depending on energy.

Interaction of Uncharged Particles with Matter: Photons

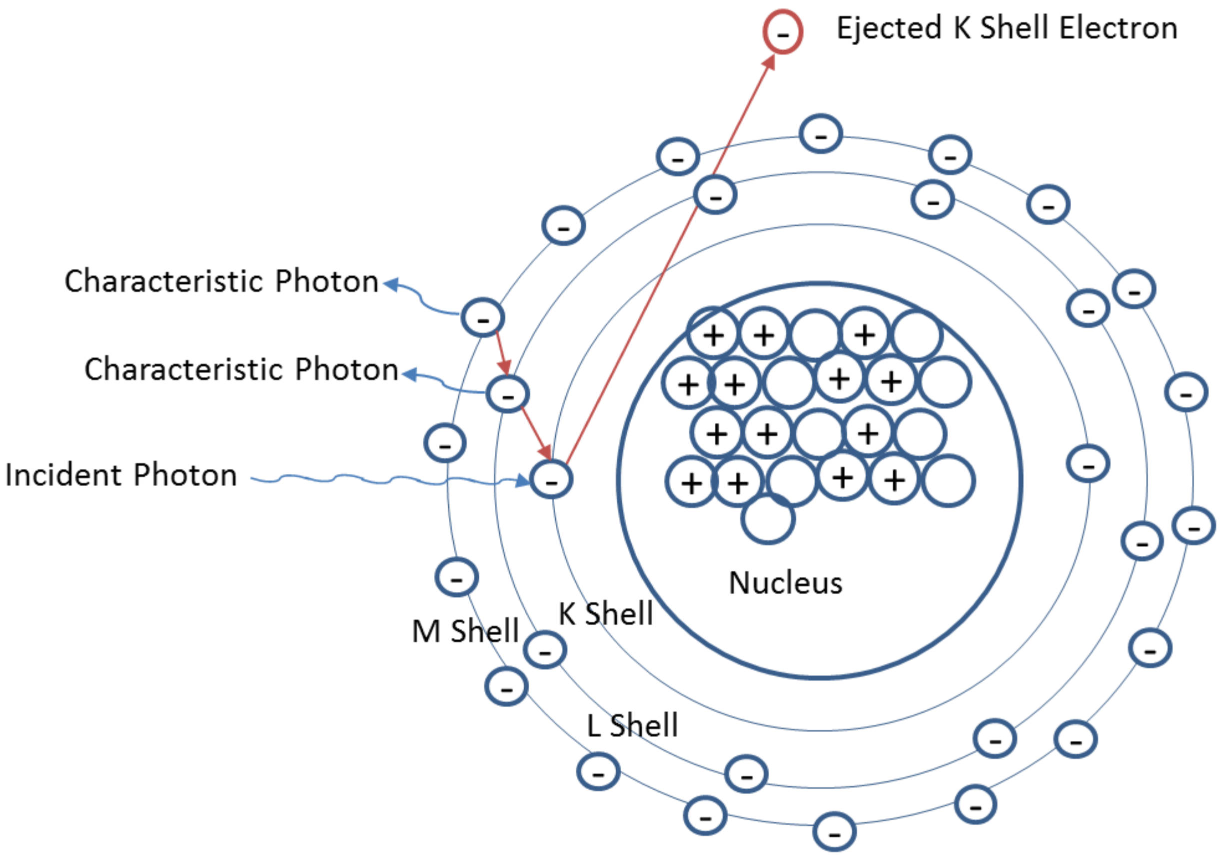
- The **photoelectric effect** was discovered by Einstein in 1905. He received the Nobel Prize in 1921 for this discovery.
- The photoelectric effect is produced when an energetic photon beam strikes material:
  - Photons collide with an inner shell atomic electron (the shell which is the closest to nucleus in an atom). The innermost shell is the K shell, then L, then M and so on.
  - After collision, an electron is ejected from the atom, and the incident photon is absorbed.
  - The ejected electron is called a photoelectron.
- The kinetic energy of the photoelectron equals photon energy minus electron binding energy (electron binding energy is the energy required to remove the electron from its orbit)

$$T_{electron} = E_{photon} - \text{Binding Energy}$$

- Conditions needed for photoelectric effect to occur:
  - Photon energy is relatively low, up to several hundreds of keV.
  - The target electron is an inner shell electron.

Interaction of Uncharged Particles with Matter: Photons *(continued)*

Photoelectric effect: an incident photon is absorbed by an inner shell electron and a photoelectron is ejected from the atom



- The K shell is the innermost shell of electrons, then the L, then the M shell and so on.
- Incident photons are external from the target material.
- The released characteristic photons are discrete energies which correlate to the electron binding energies of the ejected shell electron.
- These properties are widely used in radiography.

Interaction of Uncharged Particles with Matter: Photons *(continued)*

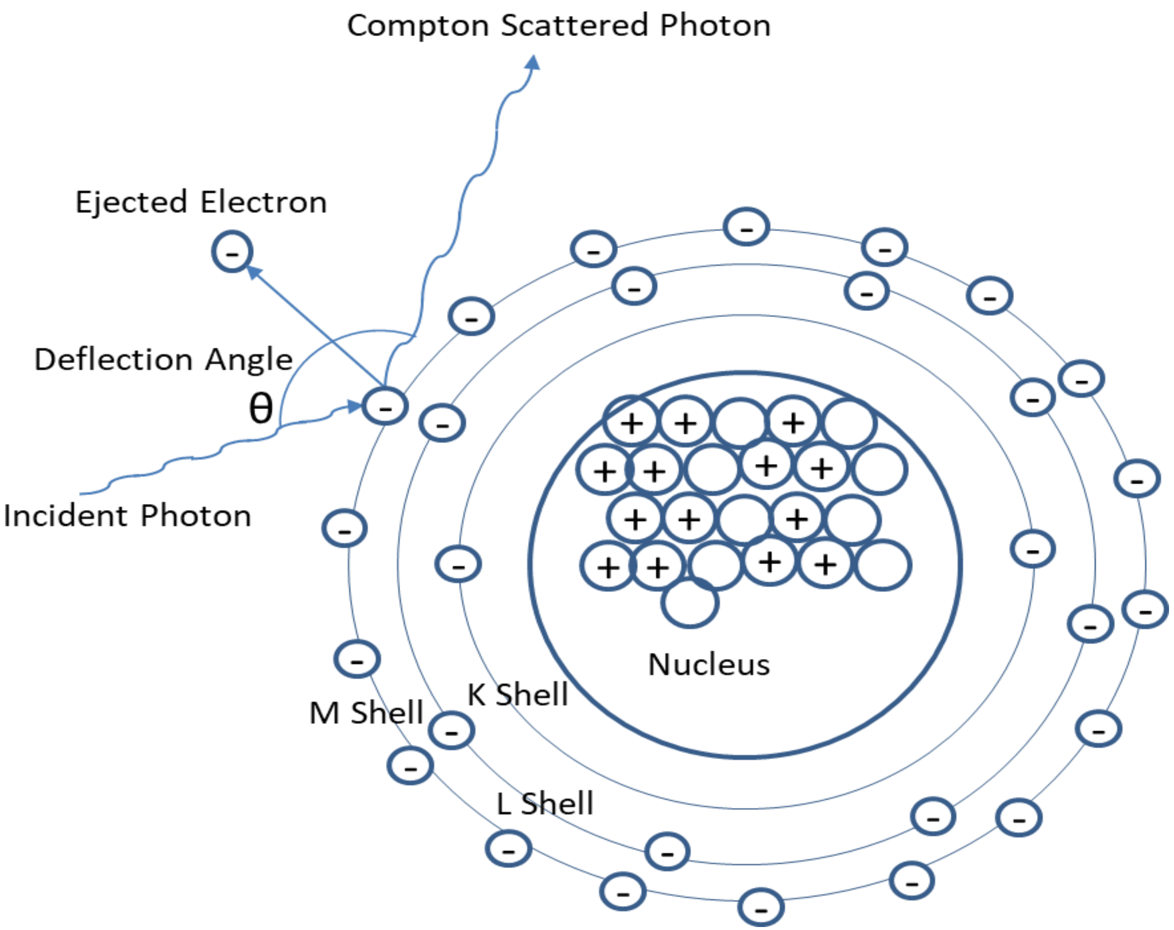
- As the photon energy increases, the possibility of photoelectric effect becomes smaller, while the Compton scattering effect becomes increasingly significant.
- **Compton scattering** is the process during which an incident photon interacts with a "free" electron, resulting in a scattered photon and a recoiled electron. A "free" electron is a valence electron which is very weakly bound to the nucleus (outer shell).
- The scatter angle of the photon ranges from 0 to 180 degrees. The energy of the scattered photon depends on scattering angle. For a highly energetic Compton scatter interaction, the energy of a 180-degree scattered photon is 0.255 MeV (backscatter).
- The recoil angle of the electron ranges from 0 to 90 degrees. The kinetic energy of the recoiled electron is the difference between the incident photon energy and scattered photon energy.

$$T_{recoiled\ electron} = E_{photon} - E_{scattered\ \ photon}$$

- Conditions needed for Compton scatter to occur:
  - Photon energy is relatively high, in the range of hundreds of keV to MeV.
  - The target electron is a free electron (very weakly bound).

Interaction of Uncharged Particles with Matter: Photons *(continued)*

Compton scattering effect: an incident photon strikes a "free" electron, photon is scattered, electron is ejected.



Interaction of Uncharged Particles with Matter: Photons *(continued)*

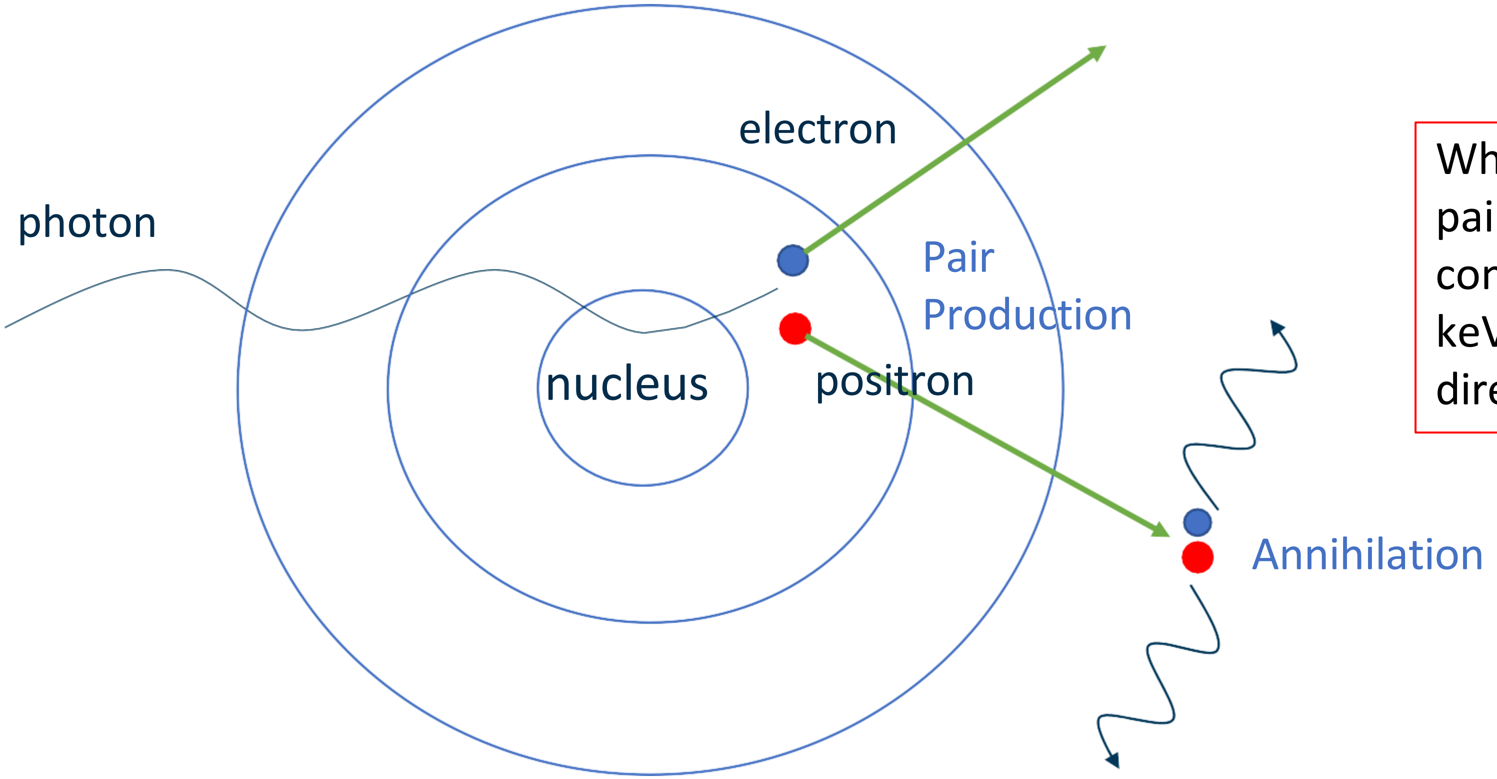
- For photon energies greater than 1.022 MeV, pair production becomes the dominant photon/electron interaction.
- **Pair production** occurs in the vicinity of a nucleus. Under the influence of a nuclear electric field, a photon can be converted to an electron–positron pair.
- Each electron and positron has a rest energy of 0.511 MeV. The excess energy of the incident photon is converted to kinetic energy and shared by the electron and positron.

$$E_{photon} = 1.022\ \text{MeV} + T_{electron} + T_{positron}$$

- Conditions needed for the pair production effect to happen:
  - Photon energy is higher than 1.022 MeV.
  - Occurs in the vicinity of a nucleus.

Interaction of Uncharged Particles with Matter: Photons *(continued)*

Pair production: an incident photon is converted to an electron–positron pair in the vicinity of a nucleus.



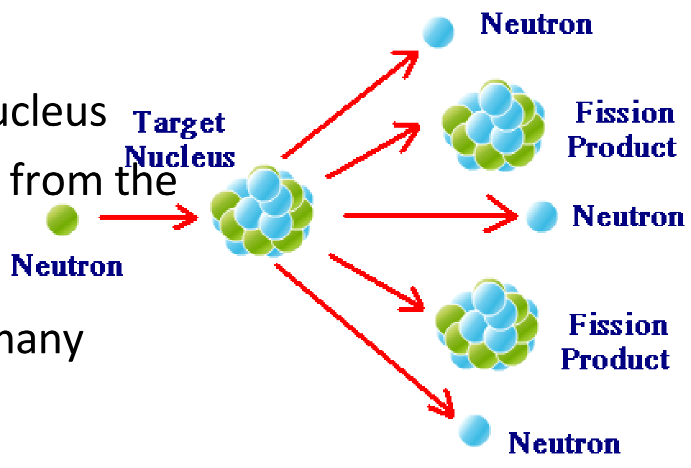
When a positron meets a free electron, the pair undergo an annihilation reaction and get converted to two photons, each carrying 511 keV (or 0.511 Mev), and traveling in opposite directions.

Interaction of Uncharged Particles with Matter: Neutrons

- The neutron was first discovered in 1932 by British scientist James Chadwick. He was awarded the Nobel Prize in 1935 for his discovery.
- Neutrons come in one shape but many different energies:
  - Ultracold $E_n < 2\text{x}10^{-7}$ eV
  - Very cold $2\text{x}10^{-7}$ eV $< E_n < 5\text{x}10^{-5}$ eV
  - Cold $5\text{x}10^{-5}$ eV $< E_n < 0.025$ eV
  - Thermal $E_n = 0.025$ eV (ish)
  - Epithermal 1 eV $< E_n <$ 1 keV
  - Intermediate 1 keV $< E_n <$ 0.1 MeV
  - Fast $E_n >$ 0.1 MeV

Interaction of Uncharged Particles with Matter: Neutrons *(continued)*

- Because the neutron has no electric charge, it does not interact with atoms through electrical force. It can travel a long distance in matter without any interaction.
- The neutron is one kind of heavy particle. Both neutron/nucleus collision and neutron capture are major interactions for this particle.
- Fast-moving neutrons are slowed down during scattering effect through neutron/nucleus collisions. The recoiled nucleus acquires part of the neutron energy and is removed from the atom, becoming a heavy charged particle.
- A neutron particle is thermalized (slowed down) by losing most of its energy after many scattering events or collisions.
- A thermalized neutron is captured by a nucleus which leads to fission reaction.
- Sometimes an energetic neutron can also be captured by a nucleus, raising the nucleus to an excited state, emitting a gamma ray or a heavy charged particle.



Specific Interaction Properties of Radioiodine: Sodium Iodide ($Na^{131}I$)

- The thyroid gland synthesizes the hormones thyroxine or tetra-iodo-thyronine (T_4) and tri-iodo-thyronine (T_3). Both these molecules which are derivatives of the amino acid tyrosine, contain iodine atoms: the former has 4, and the latter, 3 iodine moieties. The iodine required for this synthesis is transported into the thyrocytes by the sodium / iodide symporter from the blood, and subsequently enters the iodide cycle: a series of transport, oxidation and coupling steps. Excessive thyroid hormone secretion results in hyperthyroidism, a condition characterized by elevated basal metabolic rate – which in turn results in food being burned up faster, generate more body heat, and hyperactivity.

- The thyroid cannot differentiate between stable iodine and radioactive iodine when presented as sodium iodide. When $Na^{131}I$ is administered to a hyperthyroid cat, it is taken up actively, to be utilized to synthesize hormones. The concentration of iodine in the thyroid gland is 500 times that in the blood. The cell-killing action of ^{131}I is derived from its beta emission, while the local irradiation (radiation dose) comes 90% from beta, and 10% from gamma photons. The beta particles penetrate 0.5 to 2 mm (average 0.8 mm) into the thyroid follicles, causing the cells to undergo pyknosis (irreversible condensation of chromatin in the nucleus), necrosis, and fibrosis of the gland. The process can take several weeks to achieve fibrosis.

- Excretion of ^{131}I takes place via urine, with 35-75% of the administered dose excreted, depending on the cat's renal function.

- The gamma emission of ^{131}I makes it suitable for nuclear medicine imaging using a planar or SPECT gamma camera.

Specific Interaction Properties of ^{90}Y – IsoPet®

- ^{90}Y emits beta (β^-) particles with maximum energy of 2.3 MeV, and a maximum range in soft tissue of 11 mm. The average energy of these particles is 0.94 MeV, and they travel an average distance of 4.7 mm in soft tissue. Particles of ^{90}Y inorganic phosphate are in a colloidal suspension in a polymer matrix. Once the liquid polymer is injected into the tumor, it solidifies in about 15 seconds, immobilizing the particles. Over the next 10 days, 90% of the beta radiation dose is delivered to the tumor tissue over a short range, causing cell death.
- For larger tumors, multiple parallel injections are made 5-8 mm apart, thereby creating an even radiation field that bathes the tumor with beta particles.
- ^{90}Y betas can also produce bremsstrahlung radiation. Upon interaction with bone *in vivo*, a small percentage (1.7%) of its energy can convert to x-rays. A higher percentage (10.2%) can be converted to x-rays if lead is used for shielding. Plastic materials are best suited for stopping beta particles, with almost negligible yield of bremsstrahlung x-rays [more about this in module 6].
- ^{90}Y positron emissions, although negligible when compared to beta yields, have been successfully used for post-treatment evaluation and dosimetry by PET imaging.

Specific Interaction Properties of Synovetin OA™ (^{117m}Sn)

- ^{117m}Sn emits monoenergetic (single energy) conversion electrons with the highest energy of 158 keV. The maximum range this electron can travel is 0.029 cm in water. This indicates that once the ^{117m}Sn colloid is injected into the joint space, the emitted electrons can diminish inflammation in the region within about 0.3 mm (diameter) of the area containing the radioactive material.
- ^{117m}Sn electrons can also produce bremsstrahlung radiation. The maximum electron energy yields a 95 eV photon through the bremsstrahlung radiation interaction process. This very low energy photon is absorbed in tissue via the photoelectric effect, and the ejected photoelectron can aid in the therapeutic effect.
- ^{117m}Sn also emits a 159 keV gamma photon that can be used to detect the distribution and presence of ^{117m}Sn in the treatment area through SPECT imaging.

Summary of Module 3: Interaction of Radiation with Matter

- When radiation interacts with matter, it either causes ionization or creates heat in the material. The result of interaction depends on the type and energy of the incident radiation.
- Charged particles, uncharged neutrons, as well as x-ray and gamma ray photons, are ionizing radiations. Charged particles are direct ionizing radiation, as they ionize matter by direct interaction through electrical force. X-rays, gamma rays, and neutrons are indirect ionizing radiations. These types of radiation ionize matter by creating secondary particles.
- Heavy charged particles in the form of alphas or protons interact with atomic electrons. Since their particle mass is much greater than electron mass, they travel a straight line through matter. They create dense ionization continuously along the path.
- Electrons and positrons are charged particles, which ionize matter through interactions with atomic electrons. When electrons or positrons travel in matter, they follow a zig-zag path. Electrons and positrons create less dense ionization tracks compared with heavy charged particles. The depth of penetration of electrons and positrons is less than the distance they travel in matter.
- When a high-energy electron or positron passes by a nucleus, it can be deflected and will emit bremsstrahlung radiation.

Summary of Module 3: Interaction of Radiation with Matter *(continued)*

- Energetic photons (X-rays or gamma rays) interact with matter through three major mechanisms: photoelectric effect, Compton scattering, and pair production.
  - The photoelectric effect occurs for relatively low-energy photons and interacts with inner shell orbital electrons, creating a photoelectron.
  - Compton scattering occurs for photons with higher energy. They interact with free atomic electrons, creating a recoiled electron and scattered photon.
  - Pair production occurs for high-energy photons (energy greater than 1.022 MeV) in the vicinity of a nucleus, to create an electron–positron pair.
- Neutrons interact with matter by collision and capture reactions. High-energy neutrons slow down during collisions with atomic nuclei. A thermalized neutron is captured by the nucleus, raising the nucleus to an excited state.

Supplemental Reading Material

Recommended reading material for Module 3:

Turner, James E. 2007. Atoms, Radiation, and Radiation Protection. Wiley-VCH, Germany (general textbook)

IsoPet® Treatment and PET imaging:

3.1.a. Fisher, D.R., J. Fidel, and C. A. Maitz. 2020. Direct Interstitial Treatment of Solid Tumors Using an Injectable Yttrium-90-Polymer Composite. *Cancer Biotherapy and Biopharmaceuticals*, 35(1): 1-9.

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7044762/

3.1.b. Pasciak, A.S., A. C. Bourgeois, J. M. McKinney, T. T. Chang, D. R. Osborne, S. N. Acuff, and Y. C. Bradley. 2014. Radioembolization and the dynamic role of ^{90}Y PET/CT. *Frontiers in Oncology*, 4(38): 1-12.

https://www.frontiersin.org/articles/10.3389/fonc.2014.00038/full

^{131}I Radioiodine treatment:

3.1.c. Akitkumar, G., and R. Praseeda. 2020. Hyperthyroidism in cats: An overview. Journal of Veterinary and Animal Sciences, 51(2): 101-107.

Upon successful completion of the Module 3 quiz, you may continue to Module 4.