HPS 102/RAD 102
Module 2

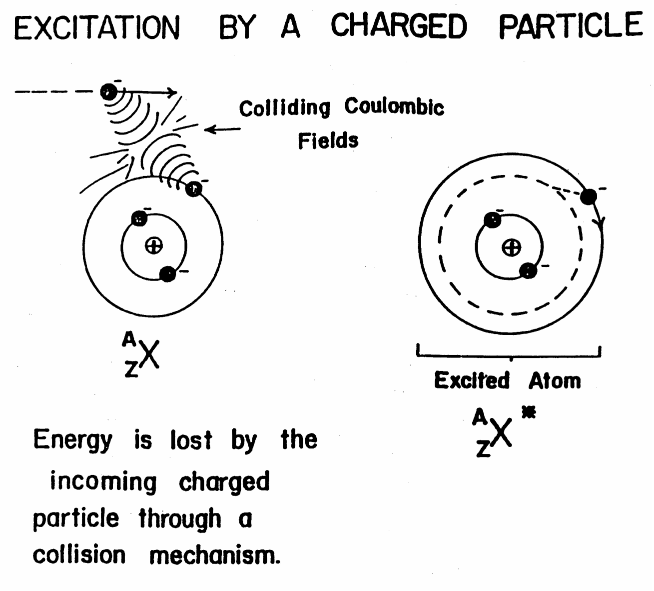
VI. Interaction of Charged Particles With Matter

Charged particles (e.g., alpha particles, beta particles, etc.) interact primarily with extranuclear electrons of matter by electrostatic attraction (Coulomb attraction). There are three primary mechanisms by which charged particles interact with matter:

A. Excitation

The incoming charged particle transfers some of its energy to the extranuclear cloud of an atom (via a Coulomb interaction) => the transferred energy raises an electron to a higher energy level, but does not remove it from the atom. When the electron returns to ground level, energy is emitted as electromagnetic radiation called flourescence. Up to about 10 eV of energy transferred from the charged particle will cause an excitation to occur.

Diagram of the excitation process:

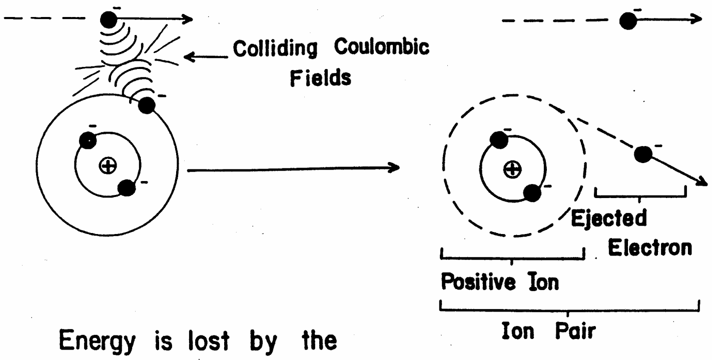


B. Ionization

Sufficient energy is transferred from the incoming charged particle via Coulomb interaction (typically > 10 eV for most atoms/molecules) to cause the removal of an electron from the atom and an ion pair is formed.

Diagram of the ionization process:

PRIMARY IONIZATION BY A CHARGED PARTICLE



Energy is lost by the incoming charged particle through a collision mechanism.

Ionization potential is defined as the amount of energy per unit charge needed to remove an electron from a given kind of atom or molecule.

Ionization potentials of some atoms and molecules of interest:

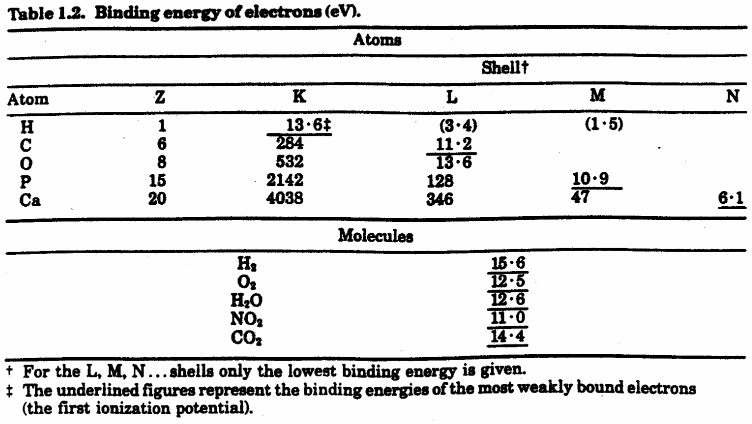


Table 1.2. Binding energy of electrons (eV).

Atoms

		Shell†			
Atom	Z	K	L	M	N
H	1	13·6‡	(3·4)	(1·5)	
C	6	284	11·2		
O	8	532	13·6		
P	15	2142	128	10·9	
Ca	20	4038	346	47	6·1

Molecules

H_2	15·6
O_2	12·5
H_2O	12·6
NO_2	11·0
CO_2	14·4

† For the L, M, N...shells only the lowest binding energy is given.
‡ The underlined figures represent the binding energies of the most weakly bound electrons (the first ionization potential).

W-value is defined as the average energy expended by a charged particle to form an ion pair in air. This value is typically about 34 eV for most types of charged particles and materials.

Problem:

> If a 5 MeV alpha particle is traveling in air, how many ion pairs will it create, on average, before it gives up all of its energy?

$$\frac{5{,}000{,}000\text{ eV}}{34\text{ eV/ip}} = 147{,}059\text{ ips}$$

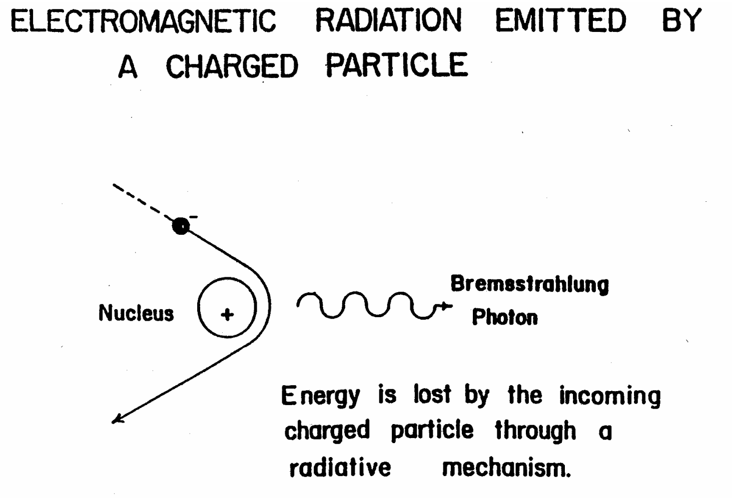
If the electron created as part of the ion pair acquired sufficient during the ionization process, it may leave track of the primary particle and go on to produce excitation and ionization of its own. These are called **delta rays**.

Specific ionization is defined as the number of ion pairs produced by a charged particle per unit pathlength. Units of ips/cm.

A final interaction mechanism experienced by charged particles:

C. Bremsstrahlung

A charged particle interacts in the vicinity of a nucleus and experiences a change in direction and velocity (and gives up energy). When a charged particle is accelerated in such a manner, electromagnetic radiation in the form of x-rays are given off:



Bremsstrahlung is the name of the mechanism and it is the term given to the electromagnetic radiation given off by the process. Alpha particles do not interact by bremsstrahlung, however, beta particles do. The amount of bremsstrahlung produced by beta particle interactions increase as the energy of the beta particle increase and the Z of the material it is interacting with increases.

Stopping power (- dE/dx or S)- the amount of energy a charged particle gives up (by excitation, ionization and bremsstrahlung) to matter per unit pathlength it travels. Units of MeV/cm.

Bethe developed the following equation to calculate the stopping power for heavy charged particles, such as the alpha particle:

$$\frac{dE}{dx} = \frac{4\pi z^2 q^4 NZ \times (3 \times 10^9)^4}{Mv^2 \times 1.6 \times 10^{-6}} \left[\ln \frac{2Mv^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right] \frac{\text{MeV}}{\text{cm}}$$

Let's examine two terms in the equation:

1. q^4 - represents the charge of the incoming particle. According to the equation, the charge of the incoming particle is directly proportional to the stopping power (both q^4 and dE/dx are in the numerators). Therefore, we can say that as the charge of the incoming particle increases, so does its stopping power. Another way of saying it - as the charge of the particle increases, the amount of energy it gives up per unit pathlength it travels increases.

2. v^2 - represents the velocity of the charged particle. According to the equation, the velocity of the incoming particle is indirectly proportional to the stopping power (v^2 is in the denominator on one side of the equation, dE/dx is in the numerator on the other side of the equation). Therefore we can say that as the velocity of the incoming particle increases, it stopping power decreases. Another way of saying it - as the velocity of the particle increases, the amount of energy it gives up per unit pathlength it travels decreases.

Bethe also developed a stopping power equation for light charged particles, such as beta particles:

$$\frac{dE}{dx} = \frac{2\pi q^4 NZ \times (3 \times 10^9)^4}{E_m \beta^2 (1.6 \times 10^{-6})^2} \left\{ \ln\left[\frac{E_m E_k \beta^2}{I^2(1 - \beta^2)} \right] - \beta^2 \right\} \frac{\text{McV}}{\text{cm}},$$

Compare/contrast the stopping power of alpha particles and beta particles based on their characteristics. Compare/contrast the stopping power of a 5 MeV alpha vs. a 6 MeV alpha.

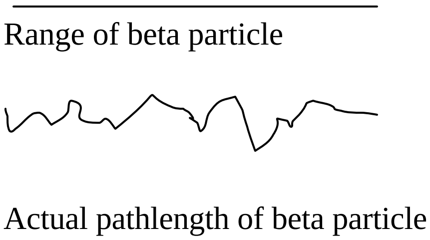
Additional definitions:

Range - overall distance a particle travels in matter (cm)

Pathlength - actual distance a particle travels in matter (cm)

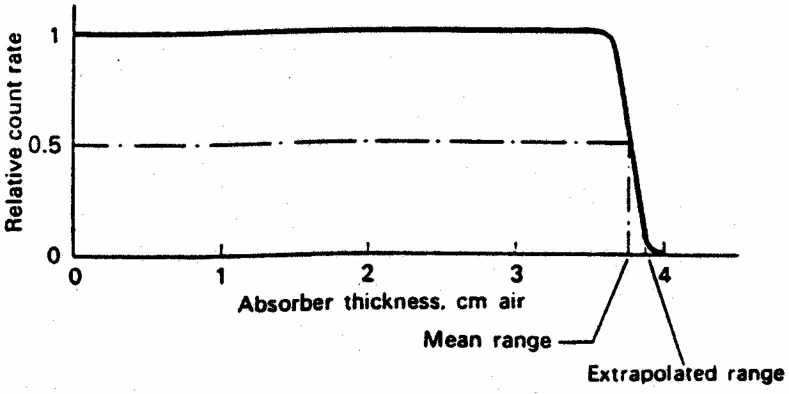
The range of an alpha particle is approximately the same as its pathlength because alphas do not easily scatter in matter due to their relative large mass. **Scatter** - change in direction.

The range of a beta particle is usually shorter than its pathlength because betas typically experience scatter as they travel through matter:



Range of alpha particles

Alphas are monoenergetic, therefore, within an energy group, they will lose all of their energy at approximately the same distance from their point of origin:



Range of beta particles

Betas are polyenergetic and will not lose all of their energy, within an energy group, at the same distance from their point of origin:

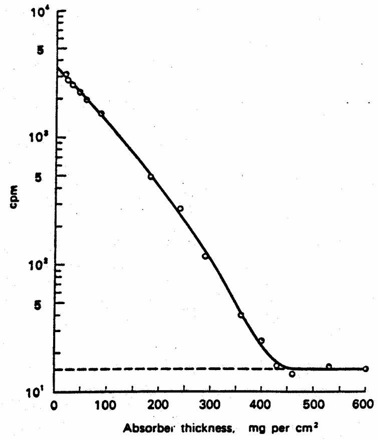
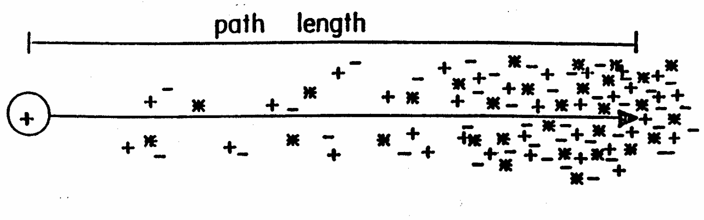


FIGURE 5.2. Absorption curve (aluminum absorbers) of ^{210}Bi beta particles. 1.17 MeV. The broken line represents the mean background counting rate.

Alphas have a range of about 1 cm in air and only microns in tissue. Higher energy betas travel meters in air. Gammas can travel several meters in air and easily travel through a human body without interacting.

Note that every loss of energy a charged particle experiences through an excitation or ionization event, causes the particle to slow down (decreases in the particles kinetic energy).

RECTILINEAR PATH OF HEAVY CHARGED PARTICLES IN A MEDIUM



1.) +,-,✱ ⇒ Ionization and Excitation Energy Losses

2.) Ionization and Excitation increase as the heavy charged particle nears the end of its path.

Ultimate Fate of Radiations in Matter

Alpha particles - as they slow down and reach the end of their track, they acquire an electron to become the $^4He^+$ species, and then acquire another electron to become a neutral atom of helium, ^4He.

Negatrons - they become a normal electron in the population of electrons

Positrons - eventually they interact with an electron and annihilate (interaction between an electron and positron that results in the transfer of mass to energy and creates two 0.511-MeV photons that are emitted in 180^o of one another).

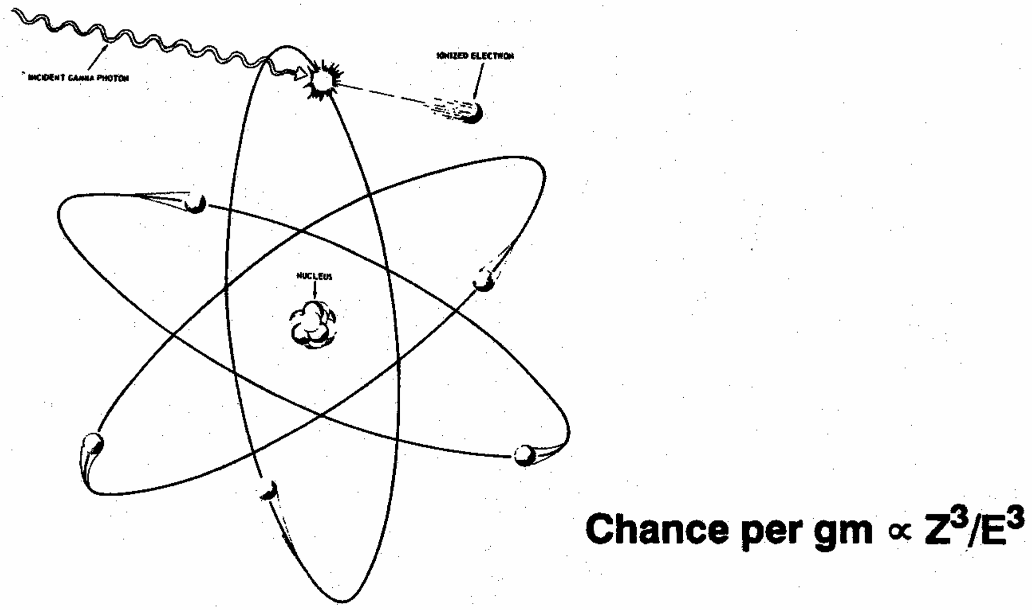
Gamma rays - disappear

VIII. Interactions of Photons With Matter

Photons have no mass, no charge, and travel at the speed of light. They interact by an electromagnetic effect. There are three primary mechanisms by which photons interact with matter:

A. Photoelectric effect

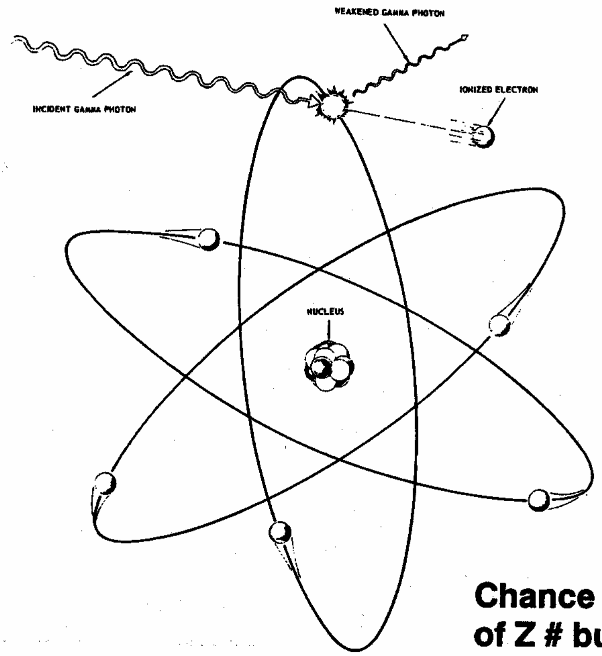
An incoming photon interacts with a tightly bound electron and transfers sufficient energy to the electron to remove it from the atom. The photon disappears. The electron removed from the atom is called a photoelectron and is able to produce secondary excitation and ionization:



The energy of the incoming photon is deposited in matter through the excitation and ionization of the photoelectron. That is why gamma radiation is considered to be an indirectly ionizing radiation. Note that there is a probability associated with a photon interacting by the photoelectric effect, just as there is a probability of a photon not interacting at all with the medium of interest. This probability is proportional to the cube of the atomic number of the medium (Z^3) and indirectly proportional to cube of the energy of the photon (E^3). This indicates that the probability of a photon interacting by the photoelectric effect is increased for low energy photons interacting in high Z materials.

B. Compton Effect

An incoming photon interacts with a loosely bound electron (valence electron) and transfers sufficient energy to the electron to remove it from the atom. The electron removed from the atom is called a Compton electron and is able to produce secondary excitation and ionization. A second photon is emitted during the process:



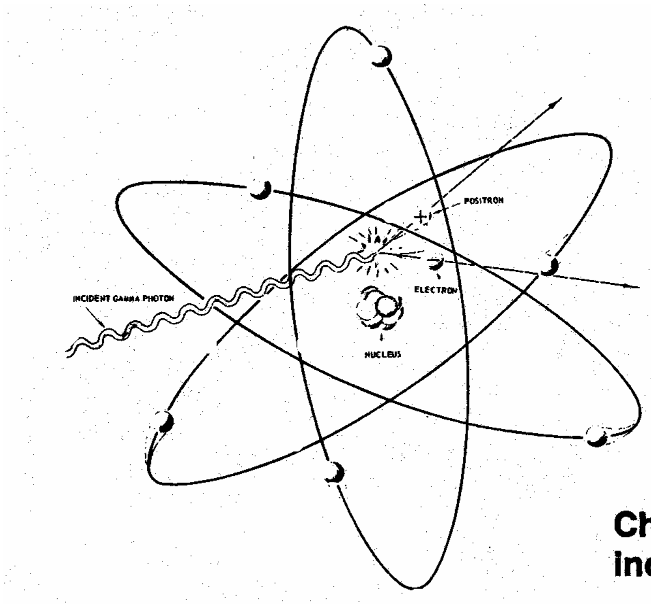
Chance per gm independent of Z # but decreases with E

The energy of the incoming photon is deposited in matter through the excitation and ionization of the Compton electron and any other subsequent interactions of the secondary photon. The secondary photon can go on to interact with the medium through the photoelectric effect or a second Compton effect.

Note that there is a probability associated with a photon interacting by the Compton effect, just as there is a probability of a photon not interacting at all with the medium of interest. This probability is essentially independent of the atomic number of the medium (Z) and indirectly proportional to the energy of the photon (E). This indicates that the Z of the material has little effect on the probability of a photon interacting by the Compton effect and the probability decreases as the energy of the incoming photon increases.

C. Pair Production

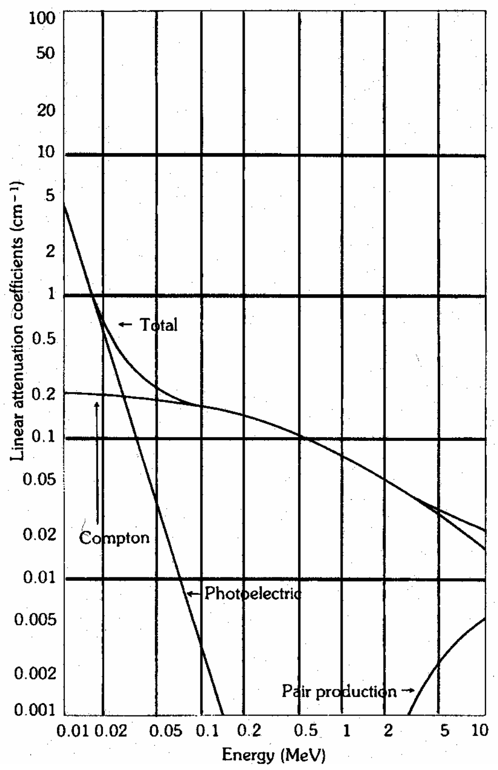
An incoming photon interacts in the vicinity of a nucleus. The energy of the photon is transferred to the mass of an electron/positron pair, which are emitted at 180^o of one another. Because the energy of the photon is converted into the masses of the electron/positron pair, it must have at least 1.02 MeV (rest masses of the electron and positron) in order to interact by the pair production mechanism. As mentioned previously, the electron of the pair loses its energy through excitation and ionization events until it becomes a normal electron in the population. The positron also excites and ionizes until it interacts with an electron and annihilates. Therefore, the energy of the incoming photon is deposited in matter through the excitation and ionization of the electron and positron, and any subsequent interaction of the 2-0.511 MeV photons that are produced by the electron/positron annihilation:



Chance per gm $\propto Z^1$ and increases with E

Note that there is a probability associated with a photon interacting by pair production, just as there is a probability of a photon not interacting at all with the medium of interest. This probability is proportional to the atomic number of the medium (Z) and directly proportional to the energy of the photon (E) once the energy of the incoming photon is above the threshold value of 1.02 MeV. This indicates that the probability of a photon interacting by the photoelectric effect is increased for high-energy photons interacting in high Z materials.

The linear attenuation coefficient is a quantity that loosely describes this probability of a photon interacting with matter. The following graph illustrates the linear attenuation coefficient (interaction probability) of each of the interactions vs. the energy of the incoming photon in water:



VIII. Interactions of Neutrons With Matter

Neutrons have no charge and with a mass slightly greater than that of proton, do not interact directly with electrons but are restricted to interactions with nuclei. The nucleus of an atom is about 10,000 times smaller than the electron cloud surrounding it, therefore, the chance of neutrons interacting with a nucleus are very small, allowing neutrons to travel long distances through matter before interacting.

Neutrons are normally divided into several energy classes. Various authors disagree about the exact energy ranges, but they are approximately as follows:

0 - 0.025 eV, cold neutrons
0.025 eV, thermal neutrons
0.025 - 0.4 eV, epithermal neutrons
0.4 - 0.6 eV, cadmium neutrons
0.6 - 1 eV, epicadmium neutrons
1 eV - 10 eV, slow neutrons
10 eV - 300 eV, resonance neutrons
300 eV - 1 MeV, intermediate neutrons
1 MeV - 10 MeV, fast neutrons
greater than 20 MeV, relativistic neutrons

Note that a thermal neutron has the same energy and moves at the same velocity as a gas molecule at a temperature of 20 ^{o}C. The velocity of a thermal neutron is 2,200 m/sec, or about 5,000 miles per hour. All neutrons are initially fast neutrons (high energy) which lose kinetic energy in collision with atoms until they become thermal neutrons (low energy) which are captured by nuclei in matter.

A. Elastic Scattering

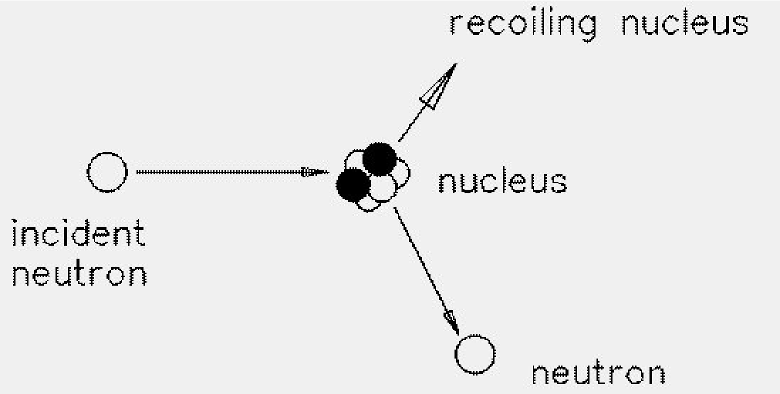
The most important mechanism in slowing down fast neutrons. Elastic collisions are billiard ball collisions resulting in the sharing of kinetic energy between the target nucleus and the impacting neutron. Thus leaving a less energetic neutron and a highly energize recoil nucleus. The fraction of energy transferred to the target nucleus increases as the mass of the target approaches that of a neutron:

$E = E_o \ (M - m/M + m)^2$

where:

E = energy of scattered neutron
E_o = initial energy of neutron
M = mass of the scattered nucleus
M = mass of neutron

Diagram of elastic scattering:



Since a neutron is slightly heavier than a proton, the element which most closely approximates the mass of a neutron is hydrogen. In neutron-hydrogen collisions, the average energy transferred to the hydrogen nucleus is about half of the energy originally contained in the neutron. What % of the original energy would a neutron retain if it interacted by elastic scattering with an oxygen nucleus?

Materials with large hydrogen content like water of paraffin become very important for slowing down neutrons.

B. **Inelastic Scattering**

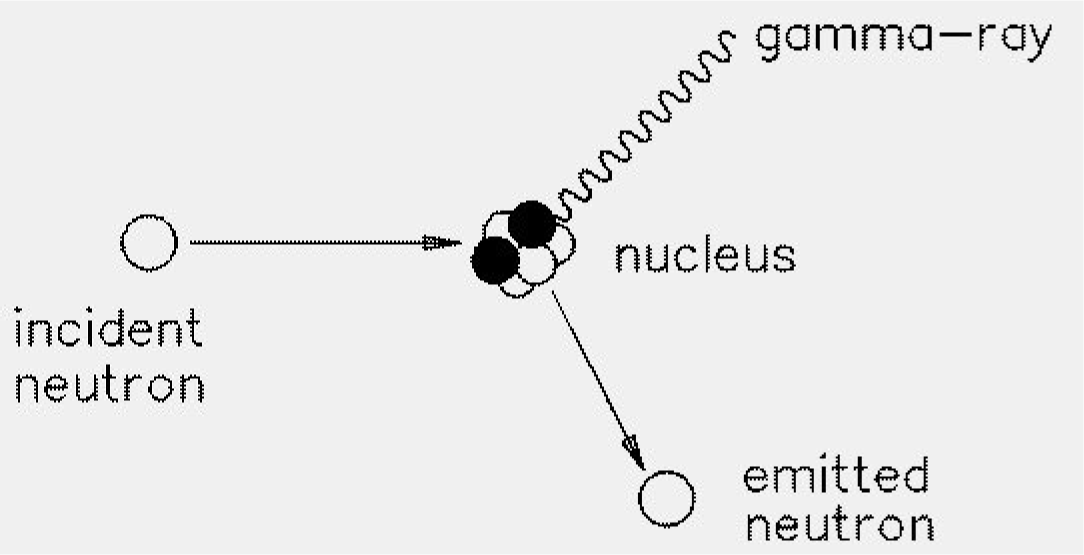
In this case, the neutron's energy is absorbed by the target nucleus. The nucleus will then de-excite with the emission of a photon. The probability of this type of event increases with increasing energy of the neutron and the size of the target nucleus. The energetics of inelastic scattering can be described by the following equation:

$E = E_o - E_\gamma$

E = energy of the neutron after collision

E_o = initial energy of the photon

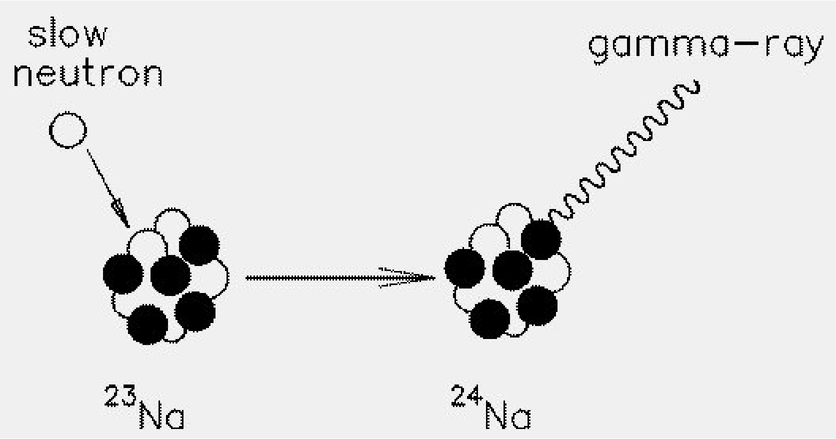
E_γ = energy of the emitted photon or particle



C. **Neutron Capture**

Once neutrons have lost sufficient energy through scattering, they can interact directly with the nucleus of the absorbing material in a process called neutron capture. If the energy of the neutron is known, the probability of capture by a specific nucleus can be defined by a term called capture cross section which is expressed in barns (1 barn = 10^{-24} cm). The capture cross section is different for each target nucleus, each isotope of the target nucleus, and for each energy of neutron. The probability of capture is inversely proportional to the energy of the neutron, therefore, thermal neutrons have the highest probability for capture.

When a neutron is captured by a nucleus, the resulting nucleus has an increased mass number of 1 and will emit a particle, electromagnetic radiation, or result in a fission of the nucleus. The progeny itself may also be unstable and decay by emitting types of ionizing radiation.



An example of neutron capture with photon emission:

$^{1}n + {}^{1}H \rightarrow {}^{2}H + \gamma$

An example of neutron capture with particle emission:

$^{1}n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$

Fission:

$^{1}n + {}^{235}U \rightarrow$ fission products + neutrons + gamma rays

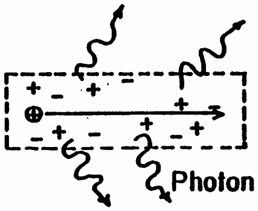
Linear Energy Transfer (LET)

Up to now, terms like stopping power, etc. focused on the energy loss experienced by the incoming particle. When attention is focused on the absorbing medium, as is the case in radiobiology, we are interested in the linear rate of energy absorption by the absorbing medium as the particle traverses the medium. This rate can be expressed as Linear Energy Transfer (LET) in keV/µm:

LET ≡ The instantaneous energy deposited "locally" by a charged particle per unit path length.

$$\therefore \text{LET} = \left(-\frac{dT}{dx}\right)\text{collision}$$

Since,



Photon energy leaves the local vicinity of the path.

Specification of an energy cut-off suggests that only energy deposited within a limited range of the particle is considered - "energy locally transferred" is used to describe this situation.