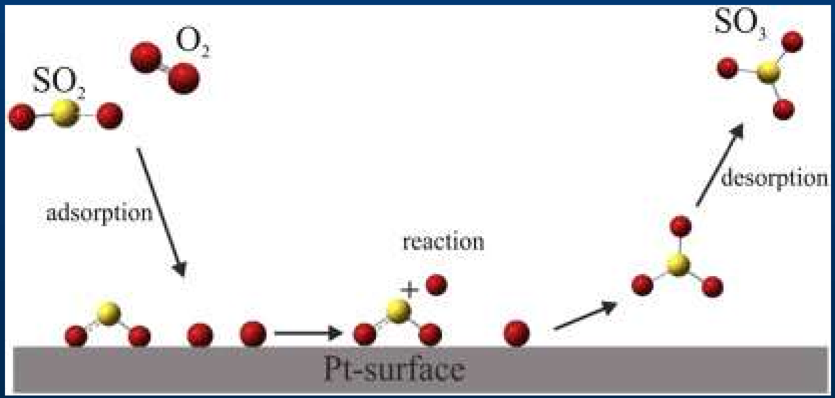
Radioactive Decay, Attenuation, and Shielding

“You mean, then,” I cried in amazement, “that he should accompany us?"
“To the interior of the earth, yes,” replied my uncle. “Why not?”
—Henry Lawson in “Journey to the Center of the Earth” by Jules Verne.

Rate of Radioactive Decay

Chemical kinetics—the rate by which a chemical reaction occurs.

Zero-order reactions—the reaction rate is independent of concentration (adding more reactant will not speed up the reaction). These are rare in nature. Often catalytic surfaces containing the reactant.



Half-Life Calculations

In a first-order reaction, the reaction rate depends on the concentration of the reactant.

That is, the less of the reactant, the slower the reaction.

Radioactive decay is a first-order reaction. The reaction rate decreases with time exponentially.

Half-Life Calculations

Decay calculations are often done to determine to determine the amount of a radionuclide remaining at a given time. Given that radioactive decay can be described by an exponential model, it follows that calculations can take the form

$$N = N_o e^{-\lambda t}$$

where N = number of atoms or amount present at time (t), N_o is the initial amount, and λ is the decay constant.

Half-Life Calculations

λ is the probability that a decay reaction will occur during a given period of time.

$\lambda = \ln 2 / t_{1/2}$ where $t_{1/2}$ is the half-life.

The half life can be calculated from a linear regression of time (x) versus natural logarithm (ln) of activity.

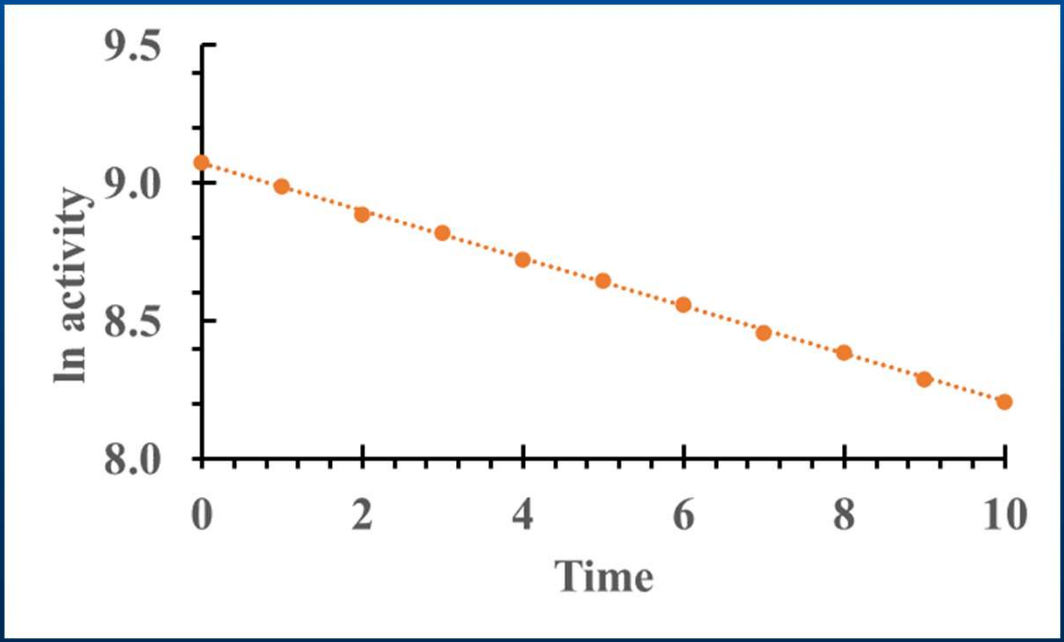
Half-Life Calculations

Take the natural log of $N_{(t)} = N_0 e^{-\lambda t}$

$$\ln N_{(t)} = \ln N_0 - \lambda t$$

Regress time versus the ln activity.

$y = mx + b$, where m is the slope and b is the intercept. Slope = $-\lambda$.



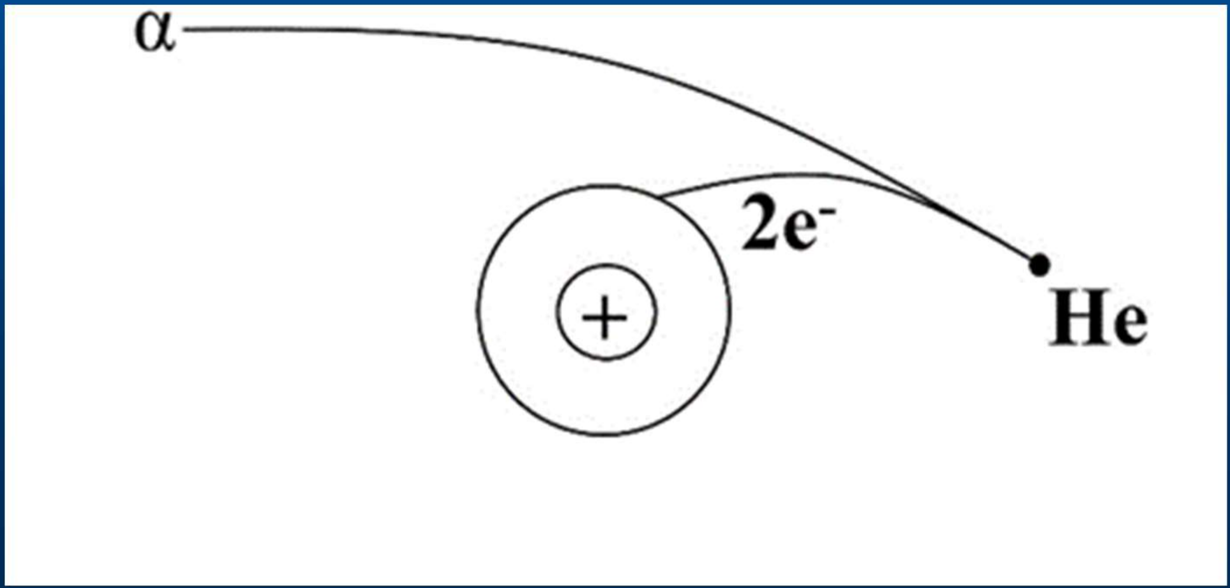
Alpha Attenuation

The radiation from radioactive wastes is subject to scattering and absorption by solid matter. Because alpha radiation or particles are composed of divalent helium ions (He^{2+}), they interact significantly with solid matter resulting in relatively short travel paths. The particles lose kinetic energy during each interaction.

Alpha attenuation

Eventually each alpha particle attracts 2 electrons and becomes helium gas at rest mass (i.e., no significant kinetic energy):

$$\alpha \quad + \quad 2e^- \quad \rightarrow \quad He\uparrow$$



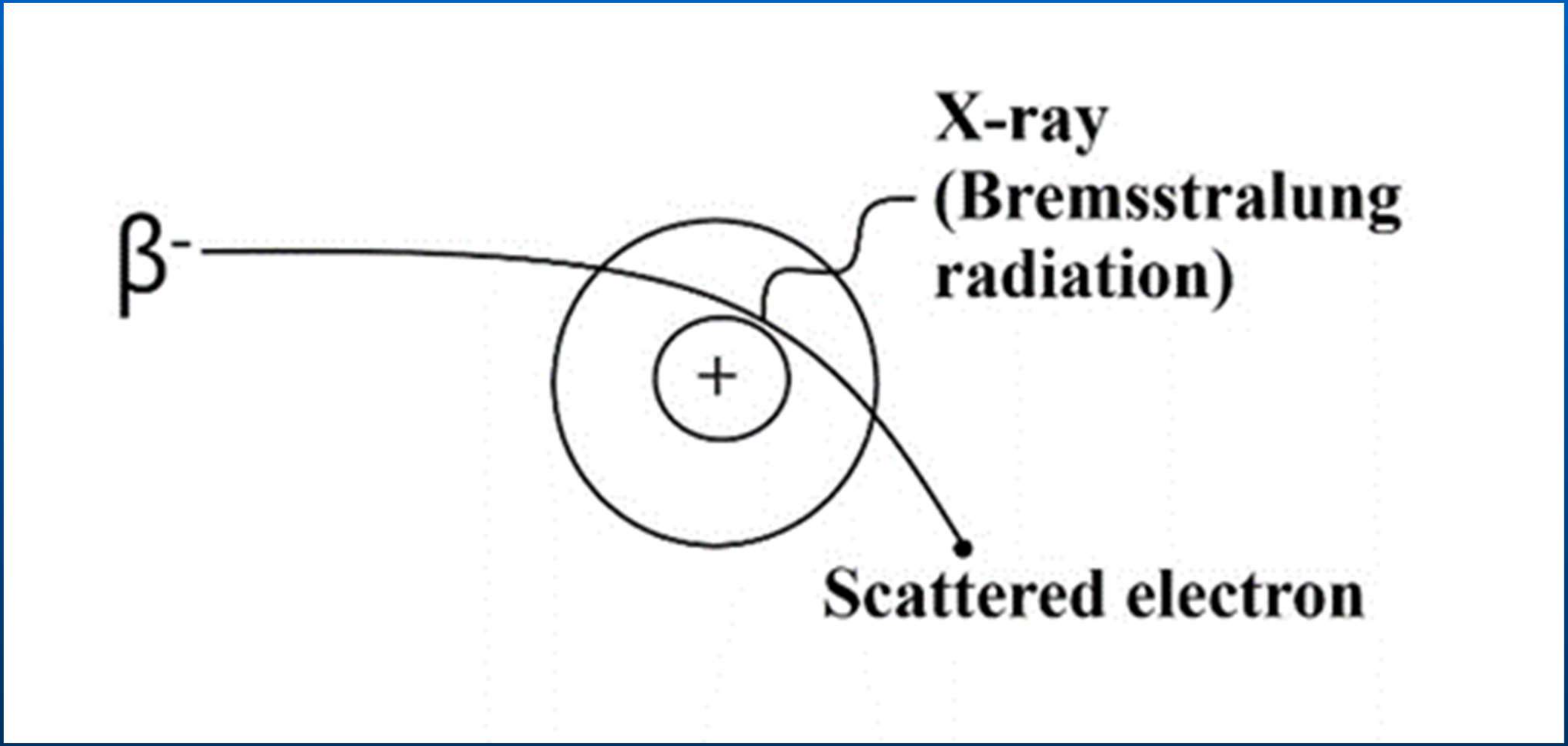
Beta attenuation

Beta radiation can also ionize atoms in solid matter, but to a lesser extent than alpha particles. As it moves near atoms, it can be slowed down in which some of the kinetic energy is covered into x-rays called Bremsstralung Radiation. This is a form of secondary radiation resulting from the interaction of beta radiation with solid matter.

Beta attenuation

As the beta particle loses its energy after collisions with atomic electrons, it eventually joins with orbital electrons. A positron will also experience atomic collisions, but will be attracted to electrons and the two will be annihilated releasing another secondary gamma radiation.

Beta attenuation



Gamma attenuation

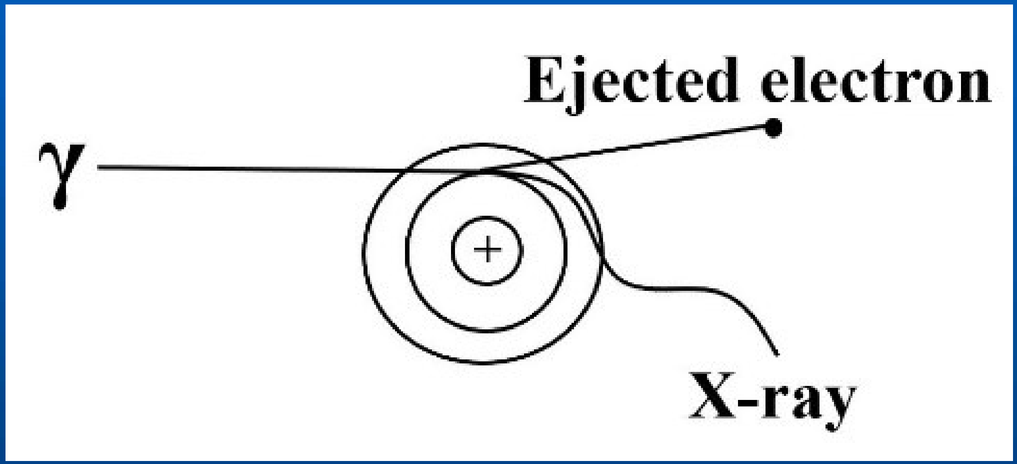
Because gamma radiation is composed of relatively energetic photons, they do not interact significantly with solid matter. Gamma radiation produces the photoelectric effect in which the kinetic energy of the gamma photon is transferred to an ejected electron, and the photon vanishes.

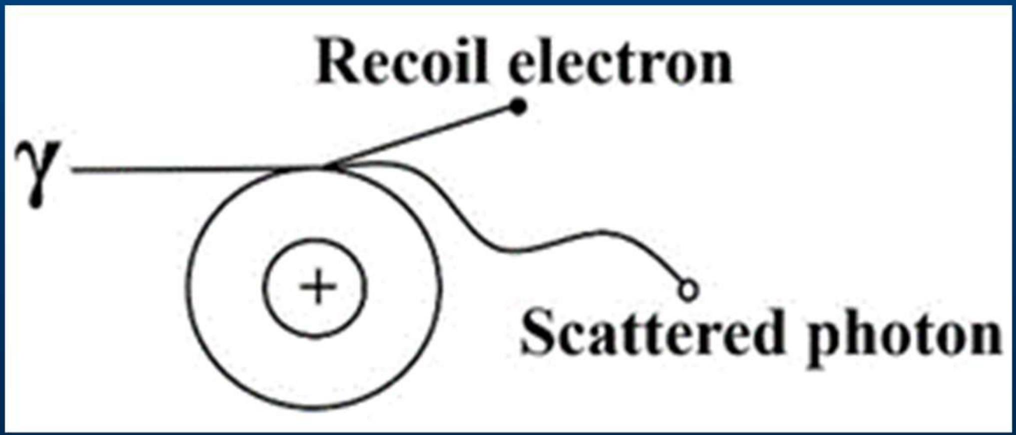
Gamma attenuation

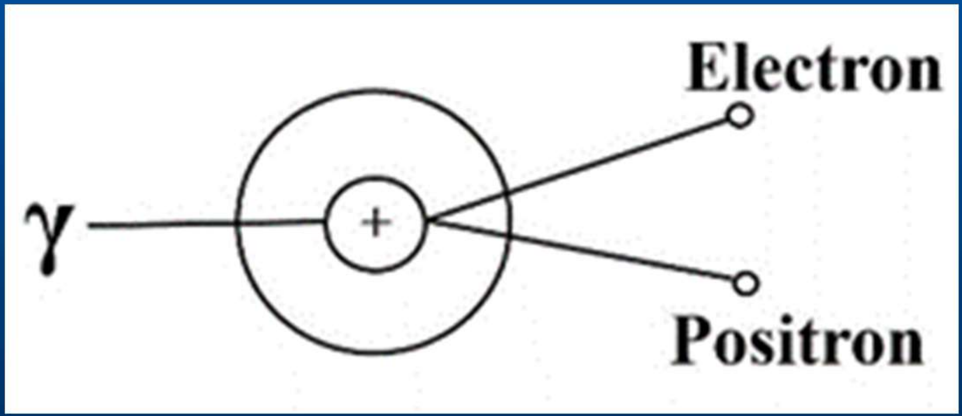
Compton scattering is another reaction in which the kinetic energy of gamma radiation is dissipated between electron recoil and a scattered photon. During **pair production**, the gamma photons collide with the nucleus forming an electron-positron pair:

$$\gamma + \text{nucleus} \rightarrow e^{-} + e^{+}$$

Photoelectric effect (top left) Compton scattering (bottom left) and pair production (right).





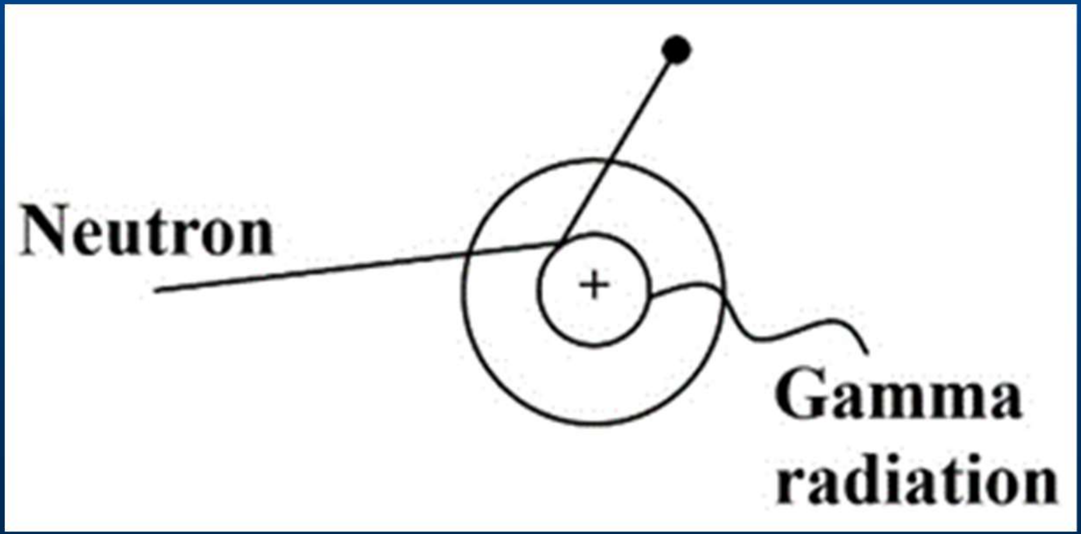


Neutron attenuation

Because neutrons have no charge, they do not interact with the electrons of atoms. Neutrons interact with atomic nuclei by elastic scattering (deflected by collisions with the nuclei), and by absorption or capture in which they are combined with the nucleus.

Neutron attenuation

In elastic scattering, some of the kinetic energy is transferred to the nucleus leaving it in an excited stated. When the scattered nucleus relaxes, it emits gamma rays as a secondary radiation.



Shielding Applied to Radioactive Wastes

Alpha particles readily react with solid matter via Coulombic forces in a barrier. Estimating the thickness of material needed for shielding can be accomplished by first experimentally measuring how far alpha particles travel in air before coming to rest (referred to as the "range").

Shielding alpha radiation

Their range in solid matter estimated using empirical relationships. The resulting solid-phase estimate is then divided by the density of the shielding material to calculate the thickness needed. For example, alpha particles from Pb-210 would require aluminum foil with a thickness of only about 25 µm to effectively stop all the alpha particles.

Shielding beta radiation

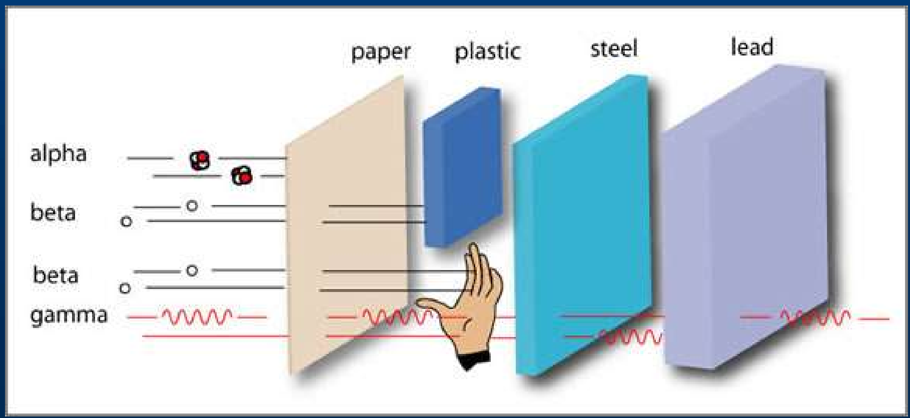
Estimating the minimum thickness for shielding from beta radiation can be estimated experimentally by determining a relationship between the kinetic energy of the radiation and the range in different types absorbents such as air, water, or aluminum.

Shielding beta radiation

The aluminum foil above would need to be at least 0.93 cm thick to completely stop 2.27 MeV of beta radiation from Y-90. Radioactive wastes/sources yielding only beta radiation would be adequately shielded by containers made of wood, aluminum, or hard plastic.

Shielding gamma radiation

Gamma radiation is more penetrating than alpha or beta radiation. The attenuation of gamma radiation can be reduced by increasing the thickness of shielding material, but it cannot be completely absorbed.



Beer's Law

The reduction in the intensity of the gamma radiation can be calculated by Beer's Law:

$I = I_0 \exp(-\mu_l t)$

where I = intensity of the shielded gamma radiation.

I_0 = intensity of the unshielded gamma radiation.

μ_l = linear attenuation coefficient.

t = thickness of the shielding material.

August Beer

German physicist/chemist

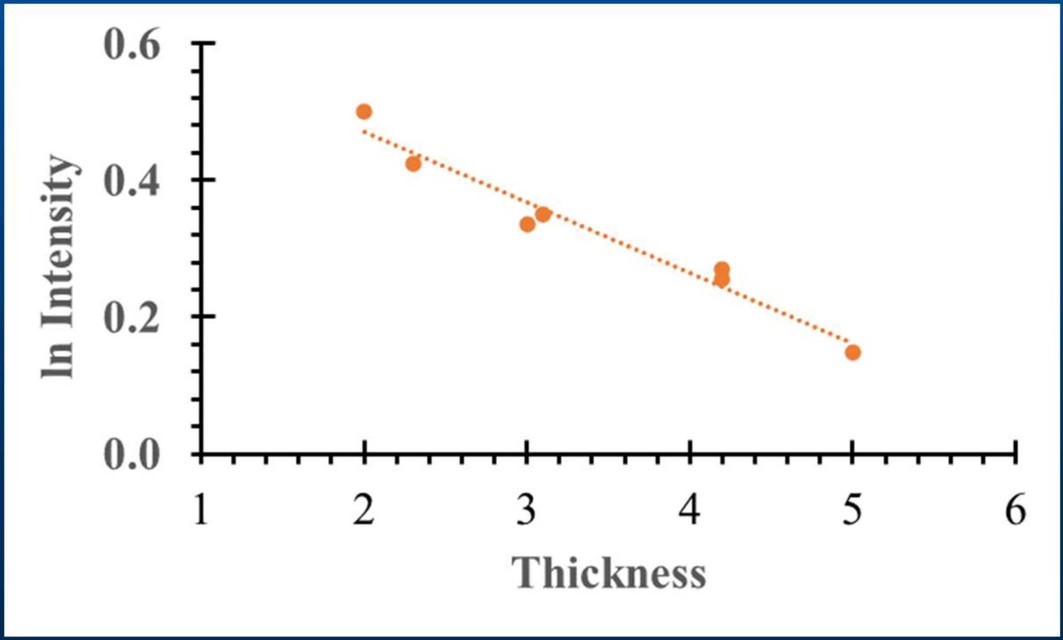
Shielding Calculations

Take the natural log of $I = I_0 \exp(-\mu_l t)$

$\ln I = \ln I_o - \mu_l t$

Regress thickness versus the ln intensity.

$y = mx + b$, where m is the slope and b is the intercept. Slope = $-\mu_l$ (linear attenuation coefficient).



Attenuation of gamma radiation

The linear attenuation coefficient is determined experimentally as the slope of a regression of transmitted gamma radiation versus the thickness of the absorbent which is the independent variable. The linear attenuation coefficient is the summation of

$$\mu_l = \mu_{pe} + \mu_{cs} + \mu_{pp}$$

i.e., photoelectric effect (pe), Compton scattering (cs), and pair production (pp)

Practical shielding

For practical shielding from gamma radiation, the linear attenuation coefficient is measured and used in designing waste containers that are typically made of relatively thick layers of concrete, steel, or lead.

Attenuation of neutrons

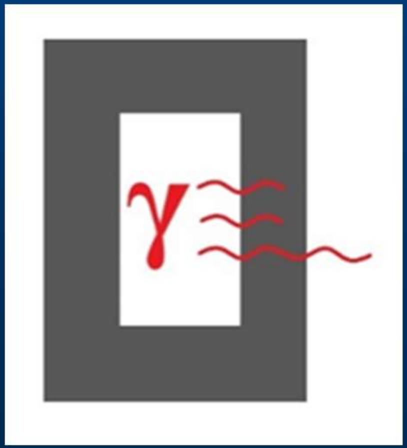
Depending on the energy of the neutrons, shielding may be accomplished using iron or lead to first slow the neutrons, then absorb them. A layer of hydrogen-containing material can also be used to absorb the neutrons once they have been slowed by a thicker and more dense material.

Attenuation of neutron

Relatively small neutron sources are often shielded with polyethylene or paraffin. Shielding for larger neutron sources can be composed of concrete alone, or concrete made with elements that have a significant cross section for capturing neutrons. These additives include boron carbide, boron oxide, sodium boron, iron-boron alloys, barite ($BaSO_4$), and others.

Representative materials used in shielding radioactive sources

Alpha radiation can be stopped by a sheet of paper. For practical management, however, a carboard box will shield from external exposure. Beta sources can be stopped by a wooden container (shown), sheets of aluminum, or rigid plastic. Gamma radiation cannot be completely shielded. Relatively thick walls of lead, concrete, or steel are used to shield gamma radiation from wastes.



Representative materials used in shielding radioactive sources

Neutron radiation can be shielded by combinations of iron, lead, and material composed of light elements such as hydrogen (left) or concrete mixed with elements that exhibit significant cross sections for capturing neutrons (right).

Questions?