GAMMA RADIATION SHIELDING

Linear Attenuation Coefficient, μ

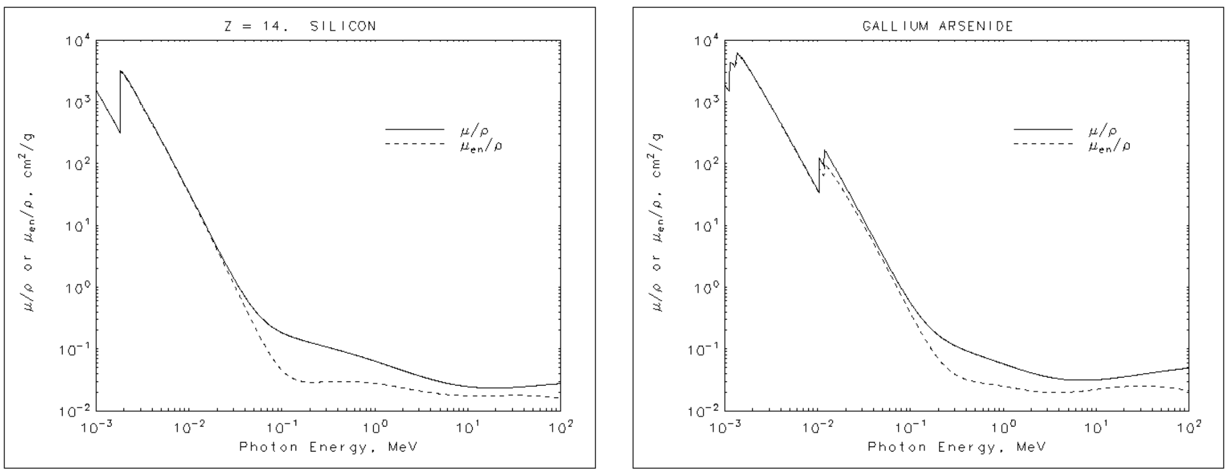
For some, the word attenuation is somewhat of a misnomer; a better word might be collision or interaction. The *linear attenuation coefficient* (μ) for photons is analogous to the macroscopic cross section (Σ) for neutrons, and hence, the μ for a mixture is

$$\mu_{mix} = \mu_1 + \mu_2 + \cdots \tag{1}$$

The *mass attenuation coefficient* is μ/ρ where ρ is the material density. For a mixture (compound) based on constituent weight fractions, ω_i

$$(\mu / \rho)_{mix} = \sum \omega_i \, (\mu / \rho)_i \tag{2}$$

The *mean free path*, which is the average distance that a photon moves between interactions, is $mfp = 1/\mu$.



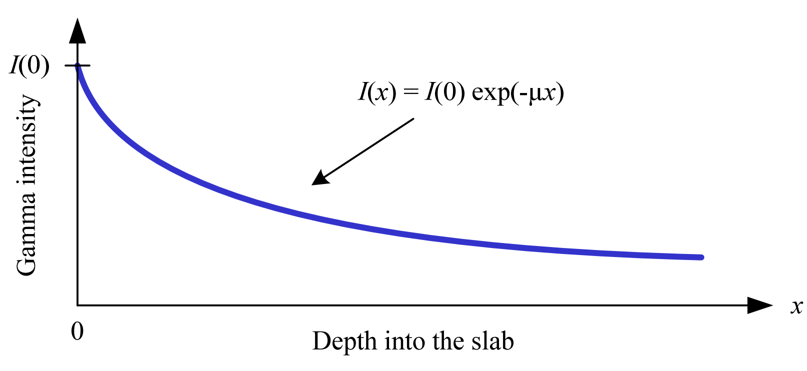
Photon mass attenuation (μ/ρ) and mass-energy attenuation (μ_{en}/ρ) coefficients for silicon and gallium arsenide [Source: NIST].

Monoenergetic Photon Attenuation

The intensity (I) of photons that penetrate a target to a distance x without a collision is

$$I(x) = I_0 \, e^{-\mu x} = I_0 \, e^{-(\mu / \rho) \rho x} \tag{3}$$

This decreasing exponential absorption characteristic is shown below. It is important to note that $I(x)$ is not necessarily all of the photons present, since some may have scattered to lower energy via Compton scattering or annihilation radiation may have been produced.



Half and Tenth Thickness

The *half value layer* (or half thickness) is the thickness of any particular material necessary to reduce the intensity of an X-ray or gamma-ray beam to one-half its original value.

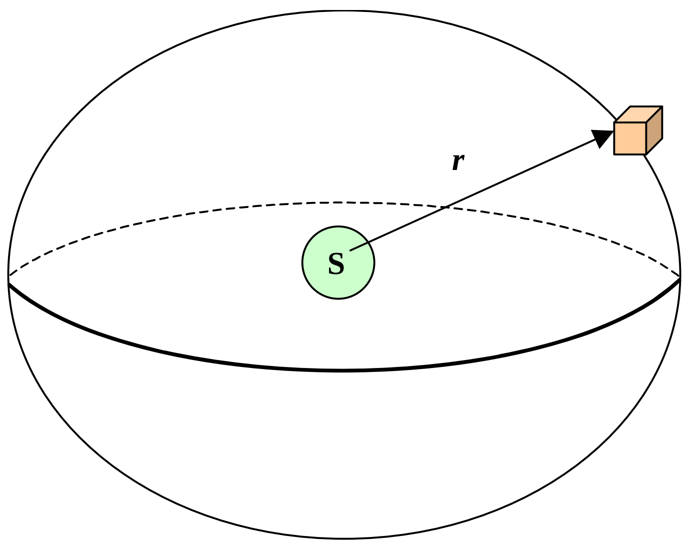
$$\frac{I(x_{1/2})}{I(0)} = \frac{1}{2} = e^{-\mu x_{1/2}} \quad \Rightarrow \quad x_{1/2} \equiv \frac{\ln(2)}{\mu} \tag{4}$$

In similar fashion, one can define a *tenth thickness* as the depth required to reduce the photon intensity by a factor of ten.

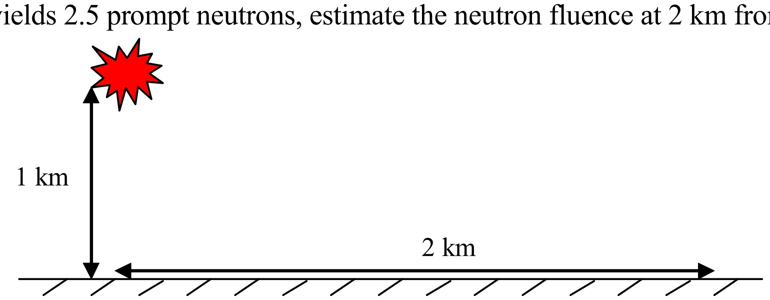
Point Source

For suitable geometry, the point source approximation is oftentimes employed for isotropic emission from a source, which emits S particles per unit time. The expression below, which assumes no attenuation (*e.g.*, in a vacuum), nonetheless is useful in describing a source in air:

$$\phi(r) = \frac{S}{4\pi r^2} = \frac{A(t)\,(no.\,particles\,/\,disint)}{4\pi r^2} \tag{5}$$



Example: A nuclear weapon is exploded at an altitude of 1 km. Assuming 10^{18} fissions in the explosion and that each fission yields 2.5 prompt neutrons, estimate the neutron fluence at 2 km from ground zero.



Solution: First, the linear distance from the explosion point to the location of interest is computed:

$$r = \sqrt{(1000\,\text{m})^2 + (2000\,\text{m})^2} = 2236\,\text{m}$$

Treating the explosion as a point source and neglecting the attenuating effect of air.

$$\Phi_n = \frac{(10^{18}\text{ fissions})(2.5\,\text{neutrons/fission})}{4\pi\,(2236\,\text{m})^2} = 3.98\times 10^{10}\ \frac{\text{neutrons}}{\text{m}^2}$$

Inverse Square Law

For point sources of gamma and X radiation, the photon flux (or intensity) is inversely proportional to the squared distance from the source. Since the exposure rate ($\dot{X}$) and dose rate ($\dot{D}$) are directly proportional to the flux (ϕ), then the ratio of intensities at distances R_1 and R_2 from the point source are

$$\frac{I_1}{I_2} = \frac{\phi(R_1)}{\phi(R_2)} = \frac{R_2^2}{R_1^2} = \frac{\dot{X}(R_1)}{\dot{X}(R_2)} = \frac{\dot{D}(R_1)}{\dot{D}(R_2)} \qquad (6)$$

This leads to a well-known radiation shielding rule that doubling the distance from the source decreases the radiation by a factor of four.

Buildup Factor, B

Attenuation of gamma intensity through a material is more realistically described by:

$$\phi(x) = \phi(0)\, B\, e^{-\mu x} \qquad\qquad B \geq 1 \qquad (7)$$

where $\phi(x)$ is the intensity at x, $\phi(0)$ is the intensity before attenuation, x is the thickness of material, and B is the *buildup factor* to account for buildup by scattering, or secondary gamma emission on absorption of the original gamma ray.

$$B = \frac{\textit{intensity of primary and secondary radiation}}{\textit{intensity of primary radiation only}} = \frac{\phi_b}{\phi_u} \qquad (8)$$

where ϕ_u is the uncollided flux and ϕ_b is the buildup flux. The buildup factor, B, accounts for the amount of forward scattering by the shield; B is a function of material and γ-ray energy as well as geometry. B is generally determined from tables, or empirical formulas.

Definition of Common Shielding Flux Terminology

Example fluxes for a point source of γ-rays is given to the right of each term

$$\textit{Unshielded flux}:\quad \phi_0 \qquad\qquad \phi_0(R) = \frac{S_{point}}{4\pi R^2}$$

$$\textit{Uncollided flux}:\quad \phi_u = \phi_0\, e^{-\mu x} \qquad\qquad \phi_u(R) = \frac{S_{point}}{4\pi R^2}\, e^{-\mu R} \qquad (9)$$

$$\textit{Buildup flux}:\quad \phi_b = \phi_0\, B\, e^{-\mu x} = \phi_u\, B \qquad\qquad \phi_b(R) = \frac{S_{point}}{4\pi R^2}\, B(\mu R)\, e^{-\mu R}$$

where μR = number of mean free paths (*mfp*).

Example:

First, determine the unshielded flux 5 cm from a 100-mCi point source that emits a 0.5 MeV gamma ray for each decay. Second, if a 10-cm diameter, spherical lead shield encapsulates the point source, determine the uncollided gamma flux on the surface of the shield. For lead, the linear attenuation coefficient at 0.5 MeV is 1.64 cm^{-1}.

Solution:

The unshielded flux at a radius of 5 cm from the point source is

$$\phi_0(5\,\text{cm}) = \frac{(100\times10^{-3}\text{ Ci})(3.7\times10^{10}\text{ Bq/Ci})(1\,\gamma/\text{decay})}{4\pi\,(5\,\text{cm})^2} = 11.78\times10^6\,\frac{\gamma}{\text{cm}^2\text{ sec}}$$

The uncollided flux on the surface of the Pb shield is

$$\phi_u(5\,\text{cm}) = \frac{(100\times10^{-3}\text{ Ci})(3.7\times10^{10}\text{ Bq/Ci})(1\,\gamma/\text{decay})}{4\pi\,(5\,\text{cm})^2}\,e^{-(1.64\,\text{cm}^{-1})(5\,\text{cm})} = 3235\,\frac{\gamma}{\text{cm}^2\text{ sec}}$$

Energy Absorption Coefficient

Since photon attenuation does not mean that all the photon energy is absorbed (*e.g.*, consider Compton scattering in which only a fraction of the photon energy is liberated to an electron), it is necessary to introduce another quantity—the energy absorption coefficient, μ_{energy}. In comparing the photon attenuation versus absorption coefficient

$$\mu_{atten} \geq \mu_{energy} \tag{10}$$

To contrast the attenuation and absorption coefficients, one should use μ_{atten} in the calculation of probabilities of removing radiation from a beam, and use μ_{energy} in the calculation of radiation dose (*i.e.*, energy deposition). A note of caution when looking these values up, as some references use μ_a to denote attenuation while others use μ_a to denote absorption, so one should be careful in extracting such data.