# α, β, γ Penetration and Shielding

## What it Shows

The interactions of the various radiations with matter are unique and determine their penetrability through matter and, consequently, the type and amount of shielding needed for radiation protection. Being electrically neutral, the interaction of gamma rays with matter is a statistical process and depends on the nature of the absorber as well as the energy of the gamma. There is always a finite probability for a gamma to penetrate a given thickness of absorbing material and so, unlike the charged particulate radiations which have a maximum range in the absorber where *all* are stopped regardless of source strength, *some* gammas will always get through and, given a strong enough source, a lot may get through.

## How it Works

This demo is usually presented in conjunction with the **Sources and Detection** demo; details about the radionuclides and detectors used here can also be found **in that writeup**.

(1) **Alpha** particles interact with matter primarily through Coulomb forces between their positive charge and the negative charge of the atomic electrons within the absorber. The range of alphas of a given energy is a fairly unique quantity in a specific absorber material.[1] For a given energy, alpha particles are much slower than beta particles, giving rise to greater impulses. Additionally, its double charge (+2*e*) makes an alpha particle have a very high rate of energy loss in matter, thus making it heavily ionizing radiation. Consequently, the penetration depth of alpha particles is very small compared to the other radiations. For low density materials, the range[2] of 5.5 MeV alphas (from Am-241) is between 4.5 to 5 mg/cm$^2$; higher density materials give a range between 5 and 12 mg/cm$^2$. The table below gives some specific values.

Absorbing materials and their alpha particle penetration depths.

| Absorber | Density | Alpha Range | Comments |
|---|---|---|---|
| air (STP) | 1.2 mg/cm$^3$ | 3.7 cm | - |
| paper (20lb) | 0.89 g/cm$^3$ | 53 μm | one sheet = 89 μm |
| water (soft tissue) | 1.0 g/cm$^3$ | 45 μm | will not penetrate skin |

The thickness of a single sheet of paper (0.0035") is enough to stop all the alphas.[3]

(2) **Beta** particles also interact through Coulomb forces with the atomic electrons. Betas have much higher speeds due to their smaller mass, and smaller impulses are involved in collisions. Their penetration into matter is thus considerably greater than alphas, but because of the nature of the Coulomb force interactions, betas too are stopped by very little matter (compared to gammas). Because their masses are identical to the scattering electrons, large deviations in the beta particle path are possible, and even thin absorbers will attenuate betas by virtue of the fact that they readily get scattered out of the direct beam. Another difference that complicates the comparison is that,

unlike mono-energetic alphas, beta particles come in a continuous spectrum of energies, with the average energy being about 1/3 the maximum. The low energy betas are rapidly attenuated.
A useful rule-of-thumb for the maximum range of electrons is that the range (in gm/cm$^2$) is half the maximum energy (in Mev).[4] This is of course complicated by the density: electron ranges tend to be about 2 mm per MeV in low-density materials, and about 1 mm per MeV in medium density absorbers. For our Sr/Y-90 source (maximum beta energy = 2.27 MeV, average energy = 1.13 MeV), more precise beta ranges are tabulated below:
Absorbing materials and their beta particle maximum penetration depths.

| Absorber | Density | Depth (2.3 MeV)[5] | Depth (1.1 MeV)[5] |
|---|---|---|---|
| air | 1.2 mg/cm$^3$ | 8.8 m | 3.8 m |
| water (soft tissue) | 1.0 g/cm$^3$ | 11 mm | 4.6 mm |
| plastic (acrylic) | 1.2 | 9.6 | 4.0 |
| glass (Pyrex) | 2.2 | 5.6 | 2.2 |
| aluminum | 2.7 | 4.2 | 2.0 |
| copper | 8.9 | 1.2 | 0.5 |
| lead | 11.3 | 1.0 | 0.4 |

C-14 gives off betas with a maximum energy of 0.156 MeV and average energy of 0.049 MeV. The maximum range of C-14 betas is only 0.25 mm (0.01") in plastic. We have both sources and it's nice to contrast them. A Harvard ID card is about 0.8 mm thick and stops all C-14 betas. Not so when you switch over to the Sr-90 source. A 3/8" (9.6 mm) thick piece of plastic is required to stop all the Sr-90 betas.
(3) **Gamma** ray interactions with matter are entirely different from that of charged particles. The lack of charge eliminates Coulomb interactions and allows gamma rays to be much more penetrating. The interactions that *do* occur are by way of the photoelectric effect, Compton scattering, and pair production. The probability for any of these happening is specified by a cross section, and the linear attenuation coefficients for gamma rays are defined by these cross sections.
Since linear attenuation coefficients vary with the density of the absorber, even for the same absorber material, the *mass attenuation coefficient* $\mu/\rho$ (linear attenuation coefficient $\mu$ in 1/cm$^{-1}$ divided by the density $\rho$ in g/cm$^3$) is more useful, and the attenuation law is written as

$$I = I_o e^{-(\mu/\rho)\rho t} \quad \text{Equation (1)}$$

where $I$ is the intensity of the radiation and $t$ is the thickness. The product $\rho t$ is the significant parameter and the units (as with β and α particles) are mg/cm$^2$, making the exponent in Equation (1) dimensionless.
Unlike charged particles, a certain percentage of gammas will always make it through the absorber, and it is useful to consider the half-value thickness of a given absorbing material for the gamma ray energies of interest. The half-value thicknesses are determined from Equation (1) using the linear attenuation or mass attenuation coefficients found in the references below.[6] Absorbers of these thicknesses attenuate the radiation reaching the detector by a factor of two and some of the common ones are tabulated below for Co-60 (1.33 and 1.17 MeV) and Cs-137 (662 keV).
Absorbing materials and penetration thicknesses for different gamma emitters. The half-value thickness (HVL) and 1/10-value thickness (1/10 VL) are listed for Co-60 and Cs-137 in units of

centimeters.

| Absorber Material | Co-60 HVL (cm) | Cs-137 HVL (cm) | Co-60 1/10 VL (cm) | Cs-137 1/10 VL (cm) |
|---|---|---|---|---|
| water (soft tissue) | 13 | 9.5 | - | - |
| plastic (acrylic) | 11 | 7.9 | - | - |
| steel | 2.1 | 1.6 | 6.9 | 5.3 |
| lead | 1.0 | 0.6 | 4.0 | 2.1 |

## Setting it Up

A Co-60 source (labeled #9) from the Phys 191 lab is the most convenient source for this demonstration in terms of strength (4 micro Ci as of 2016 ... half-life is 5.27 yrs). Position it approximately 2.5 inches in front of the Geiger-Muller tube. A 1/2" thick piece of lead cuts the count rate down by a factor of two and a 1.5" thick piece reduces the rate by a factor of ten.
Plastic, aluminum, steel, lead, and many other absorbers are available as needed. They range in thicknesses from hundreds of microns (foils) to several centimeters. The absorber is simply placed over the thin end-window of the G-M tube.

## Comments

One doesn't really want to turn a simple demonstration into a lengthy laboratory exercise, so it's best to decide beforehand the salient features one wants to impress on the audience and use the appropriate absorbers and thicknesses to make the point.

## References


*AIP Physics Desk Reference*, edited by E. Richard Cohen, David R. Lide, George L.. Trigg, (Springer, New York, 2003)

G.F. Knoll, *Radiation Detection and Measurement*, 2nd ed, (Wiley, NY, 1989)

G.W. Morgan, *Some Practical Considerations in Radiation Shielding*, Isotopes Division Circular B-4, (U.S. Atomic Energy Commission, Oak Ridge)

*CRC Handbook of Radioactive Nuclides*, edited by Y. Wang, (Chemical Rubber Company, Ohio, 1969)

A.H. Wapstra, G.J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables*, (North Holland, Amsterdam, 1959)

*X-ray Attenuation Coefficients from 10 keV to 100 MeV*, National Bureau of Standards Circular No. 583

**https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html**

**https://physics.nist.gov/PhysRefData/XrayMassCoef/tab2.html**


[1] Indeed, in the early days of radiation measurement, alpha particle energies were measured indirectly by determining the absorber thickness equivalent to their mean range.

[2] The range is expressed in terms of (density)×(thickness), which is written as the mass/unit area of the absorber of a given thickness. Historically the units have been mg/cm$^2$. Density·thickness (also sometimes referred to as mass·thickness) is a useful concept when discussing the energy loss of alphas and betas because, for absorber materials with similar neutron/proton ratios, a particle will encounter about the same number of electrons passing through absorbers of equal density·thickness. Therefore the stopping power and range, when expressed in these units, are roughly the same for materials that do not differ greatly in Z.

[3] The paper weighs 4.77 gm/sheet which gives it a density of 0.89 gm/cm$^3$ and a density·thickness of 7.9 mg/cm$^2$

[4] This rule of thumb is applicable only when E > 0.8 MeV. For other energy ranges, see Wang, p 912.
[5] Values are from Y. Wang (*reference*). Another rule-of-thumb is that the half-value range is approximately 1/7 of the maximum range but may vary between 1/5 and 1/10 (depending on beta energy and absorber density).
[6] The mass absorption coefficient also depends on the energy of the radiation. To calculate the half-value layer for a particular material and specific radiation energy, then one has to look up the "mass energy absorption coefficient" in the *CRC Handbook* or *AIP Physics Desk Reference*, or whichever reference is handy.

See also: **Quantum Physics and Relativity**, **Radiation and Radioactive Decay**, **[M]**, **[t+]**, **[★★★]**

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