Chapter 8

ATTENUATION OF GAMMA RADIATION

9/4/2007

8.1 INTRODUCTION

In nuclear reactions a product nucleus can be formed in an excited state having internal energy in excess of its ground state. Gamma photons are emitted within a short period for the nucleus to reach its ground state. The energy of the photons is equal to the difference in energy levels between the two states involved in the transition. Sometimes, the transition from the higher excited state directly to the ground state is forbidden. In this case a cascade of photons occurs from the higher to intermediate stages then to the ground state (Fig. 1). Some transitions are forbidden transitions.

X rays, bremsstrahlung, and annihilation radiation are not strictly gamma rays since they do not arise from nuclear transitions. However, they are identical to gamma rays in their fundamental nature as electromagnetic radiation. The only difference concerning their interaction with matter is related to the generally higher energy of the gamma rays.

For low atomic number Z elements the first excited state is at least 1 MeV above the ground state. The separation between the levels is of the same order of magnitude. As the energy of the photon increases, the separation between the levels decreases.

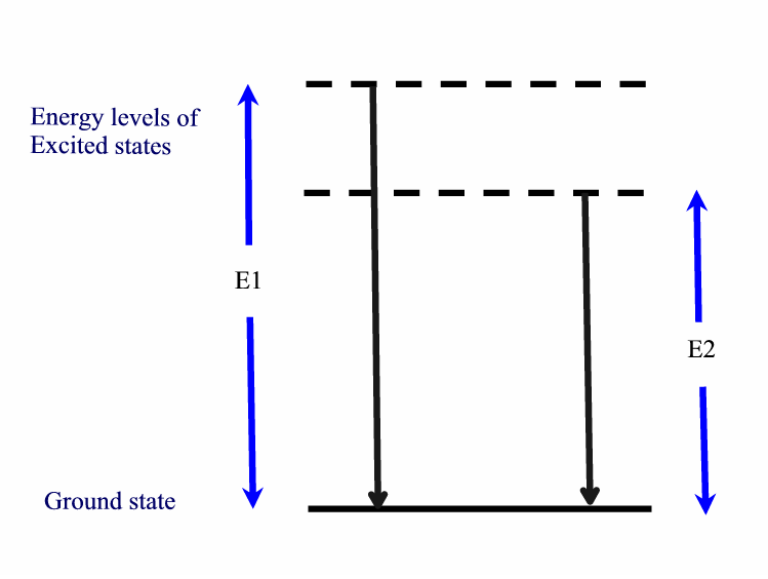

Fig. 1: Gamma ray emissions from the excited states of a nucleus.

For nuclei of large Z elements, the minimum excitation energy is less than 1 MeV. In the heaviest nuclei, the first excited state may be just 0.1 MeV above

the ground state. In Fig. 2, the alpha decaying U^{236} nucleus shows the possible emission of two gamma photons with energies of 0.0494 and 0.1621-0.0494=0.1127 MeV. This is compared in the same figure to the negative beta decay of the Co60 isotope associated with main gamma photons of energies 1.3325 and (2.5058 – 1.3325 = 1.1733 MeV.

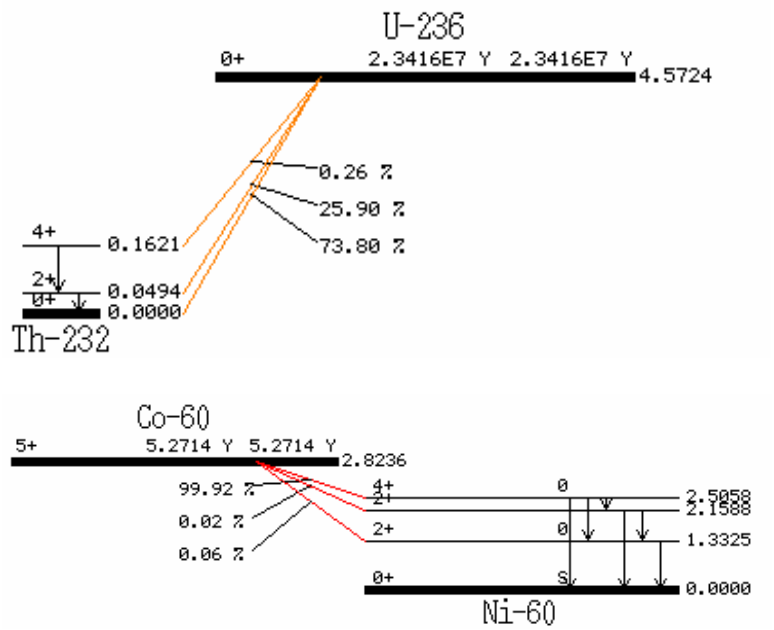

Fig. 2: Decay diagram for the U^{236} isotope, showing alpha decays and for the Co^{60} isotope showing negative beta decay, both with gamma emissions.

The magic number nuclei, such as Bi^{209}, offer an exception to the rule, in that they behave like the light nuclei with an energy separation of 1 MeV between the lower levels.

The essential differences between gamma rays and x rays is that x rays originate outside the nucleus and have lower energies and longer wave lengths. Otherwise they are both electromagnetic radiation.

8.2 BREMSSTRAHLUNG RADIATION

In German bremβen means brakes, and strahlung means radiation. Thus bremsstrahlung literally means "braking radiation. These are continuous x rays produced when electrons or beta particles of high speed lose their energy in passing through matter.

They should be distinguished from the characteristic x rays, which, as their name implies, have definite energies and wave lengths that are characteristic of the elements emitting them from transitions between the energy levels of the atom.

When electrons of energies of 1 MeV or higher interact with the electrons of atoms of high atomic number Z such as Pb, the resulting bremsstrahlung, even though originating outside the nucleus, is indistinguishable in its behavior from gamma rays originating in nuclear transitions.

The fraction of the kinetic energy of the electron converted into bremsstrahlung is proportional to the energy of the electron and with the atomic number of the material in which it is slowed down.

The energy of the bremsstrahlung covers a large energy range. The maximum is close to the energy of the electron, but the average is much less.

8.3 ČERENKOV RADIATION

Charged particles of high energy emit visible electromagnetic radiation in their passage through a transparent medium, provided that their velocity is greater than the velocity of light in that medium. This radiation is designated as Čerenkov radiation.

The bluish glow which is seen in reactor cores cooled by water, used fuel element racks, and stored Co^{60} sterilization irradiators is the Čerenkov radiation generated by Compton electrons produced by fission product gamma rays.

8.4 LINEAR ATTENUATION COEFFICIENT

The loss dφ of gamma rays in a small thickness of matter dx at any point in a medium is proportional to the radiation intensity at that point φ, and to the thickness traveled dx, or:

$$d\varphi(x) \; \alpha_\ell \; \varphi(x)dx \qquad (1)$$

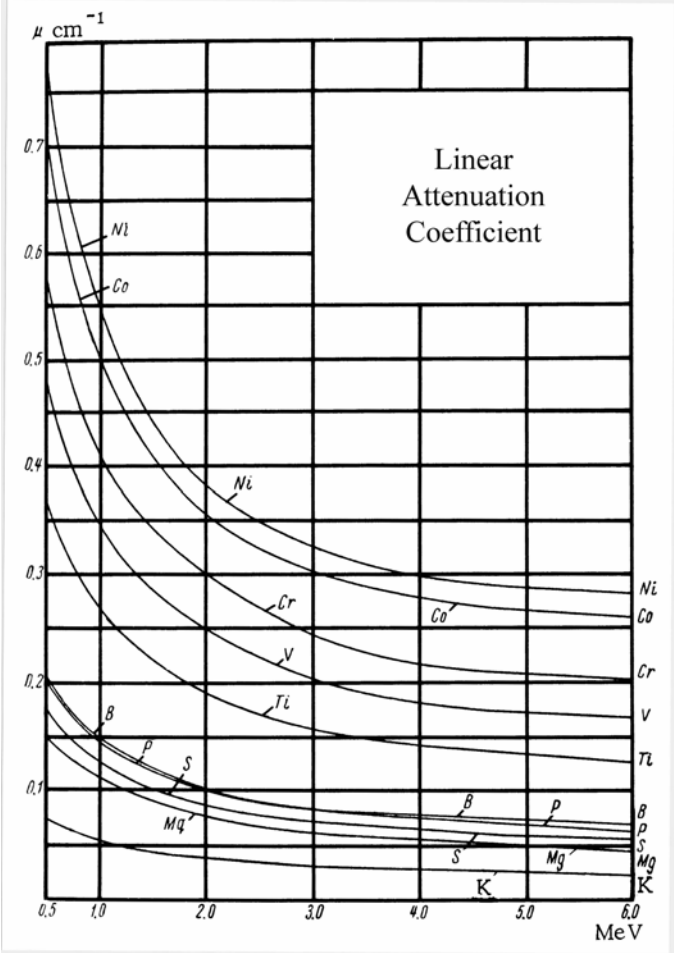

Fig. 3: Linear attenuation coefficients for gamma rays in Ni, Cr, V, Ti, B, P, S, Mg, K, and Co.

The proportionality symbol can be replaced by a proportionality constant bearing in mind that the change is negative to yield:

$$d\varphi(x) = -\mu\varphi(x)dx \qquad (2)$$

The intensity φ (x) can be expressed as photons or MeV per cm^2 per second. The proportionality constant μ is called the linear attenuation coefficient of the absorber for the given radiation. It is usually given in units of inverse length such as [cm^{-1}].

The linear attenuation coefficients for intermediate mass elements are shown in Fig. 3 and for heavy elements in Fig. 4. If elements data are not available, normally interpolation is used to obtain the appropriate values.

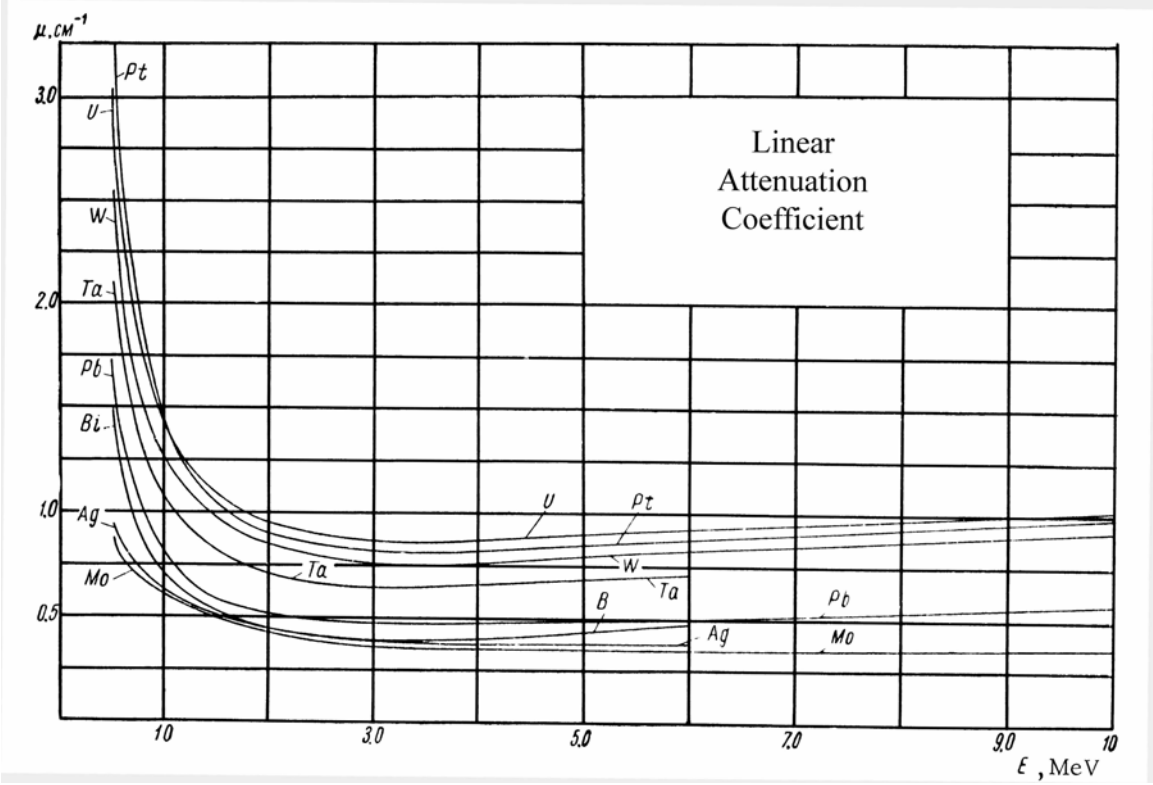

Fig. 4: Linear attenuation coefficients for gamma rays in Pt, U, W, Pb, Mo, Ta, Bi, and Ag.

8.5 MASS ABSORPTION COEFFICIENT

The mass absorption coefficient is used alternatively with linear attenuation coefficient in calculations. It is defined as:

$$\mu_m = \frac{\mu}{\gamma}[\frac{cm^2}{gm}]$$

$$\gamma\, is\, density[\frac{gm}{cm^3}]$$

It is a measure of the probability of interaction of a gamma photon in a unit mass of a substance, usually taken to be 1 gram.

The mass attenuation coefficients for some light elements including tissues are shown in Fig. 5.

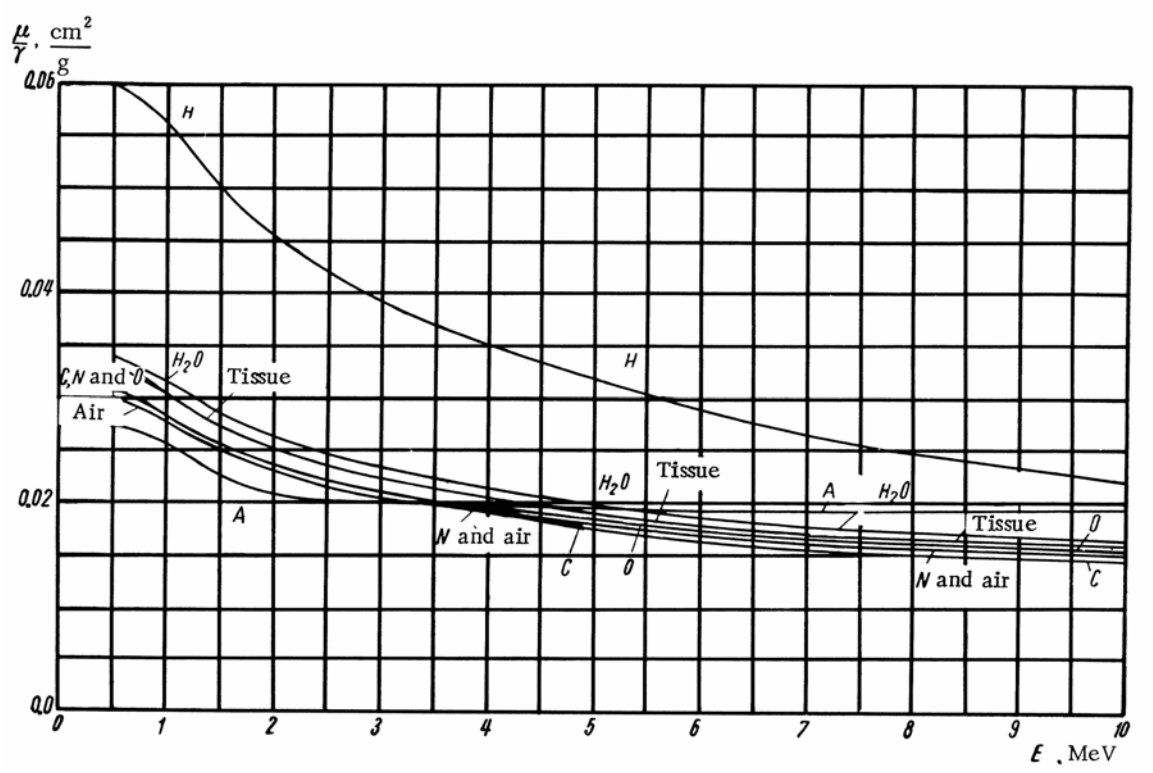

Fig. 5: Mass attenuation coefficients of gamma rays in H, H2O, tissue, air, C, N, O, and A.

8,6 NARROW BEAM GEOMETRY

The attenuation of a narrow or collimated beam in good geometry as shown in Fig. 6, of either gamma rays or neutrons of a given energy can be obtained by separating the variables and integrating Eqn. 2..

$$\int_{\varphi_0}^{\varphi(x)} \frac{d\varphi(x)}{\varphi(x)} = -\mu \int_0^x dx$$

$$\ln \frac{\varphi(x)}{\varphi_0} = -\mu x \qquad (3)$$

$$\varphi(x) = \varphi_0 e^{-\mu x}$$

Thus the intensity falls in an exponential manner.

The same behavior would apply to a narrow beam of neutrons with the attenuation coefficient replaced by the total macroscopic cross section:

$$\phi(x) = \phi_0 e^{-\Sigma_t x}. \qquad (4)$$

where Σ_t is the total macroscopic cross section for the neutron interactions in the given medium.

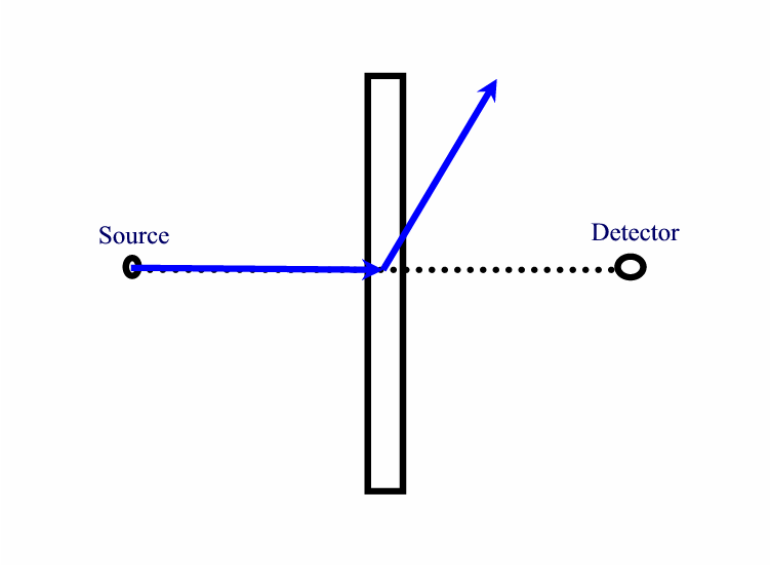

Fig. 6: Thin shield in good geometry for thin radiation beam.

It should be noted that for gamma rays, the attenuation coefficient is the total attenuation coefficient including the Compton scattering and the photoelectric and pair production absorptions. This is different from the wide beam case where the attenuation coefficient must account for the spreading of the beam.

An interesting consequence of the exponential attenuation of gamma rays is that although the amount of radiation absorbed by a specified thickness of material is proportional to the initial intensity, the fraction absorbed or emerging, is independent of the intensity.

This implies that one needs the same thickness of absorber to decrease the intensity of gamma rays of a given energy from 100 to 10 percent of its initial intensity, as needed to reduce its intensity from 10 to 1 percent.

Another important implication is that nobody can claim a total absolute shielding against the radiation. An infinite thickness of material is theoretically needed to absorb the gamma radiation totally. In shielding applications a finite thickness is used to reduce the intensity to a relatively insignificant amount.

The linear attenuation coefficients for different materials are shown in Table I. The attenuation coefficients decrease with increasing gamma ray energy at around 5 MeV. This implies that with higher energy photons, a higher thickness of material is needed to attenuate a given fraction of the radiation.

Table I: Linear attenuation coefficients for different materials.

Gamma ray Photon Energy	H_2O	Concrete	Al	Fe	Pb

[MeV]					
0.5	0.0966	0.204	0.227	0.651	1.64
1.0	0.0706	0.149	0.166	0.468	0.776
1.5	0.0575	0.121	0.135	0.381	0.581
2.0	0.0493	0.105	0.117	0.333	0.518
3.0	0.0396	0.0853	0.0953	0.284	0.477
4.0	0.0339	0.0745	0.0837	0.259	0.476
5.0	0.0301	0.0674	0.0761	0.246	0.483
8.0	0..0240	0.0571	0.0651	0.232	0.520
10.	0.0219	0.0538	0.0618	0.231	0.554

The total attenuation coefficient for Pb is about six times that of Al. The reason is that all three processes of absorption of gamma rays in matter increase as the atomic number Z increases.

In Al, the photoelectric effect is small and makes no significant contributions for photon energies above 0.2 MeV. Compton scattering in Al is dominant up to energies of more than 4 MeV.

Because the photoelectric and Compton scattering cross sections decrease with energy, whereas the pair production cross section increases with energy, a minimum in the in the total attenuation cross section may occur. Such a minimum occurs in Pb at around 3 to 4 MeV. This minimum provides an energy window at which radiation can leak from a given field. The use of a mixture of materials becomes necessary in shielding applications to close such energy windows.

EXAMPLE

We consider a 2 inches or 2 x 2.54 = 5.08 cms thick lead shield used to shield against a narrow beam radiation from Cobalt^{60}. The Co^{60} isotope emits two different gamma photons of energies 1.17 and 1.33 MeV. Our goal is to estimate the fraction of the initial radiation penetrating the shield or its attenuation. The linear attenuation coefficient in lead is noticeably different for the two photon energies. Thus we must consider the two radiations separately.

From Table I linear interpolation yields:

$$\mu_{Pb}(1.17\,MeV) = 0.70$$
$$\mu_{Pb}(1.33\,MeV) = 0.62$$

From Eqn. 3 the attenuation for the two gamma photons are:

$$\frac{\varphi}{\varphi_0}(1.17MeV) = e^{-\mu(1.17MeV)x} = e^{-0.70x5.08} = 0.029 = 2.9\%$$

$$\frac{\varphi}{\varphi_0}(1.33MeV) = e^{-\mu(1.33MeV)x} = e^{-0.62x5.08} = 0.045 = 4.5\%$$

It can be noticed that for a small difference in the photons energy, the attenuation is remarkably different.

8.7 PRACTICAL WIDE UNCOLLIMATED BEAM GEOMETRY

The simple attenuation Eqn. 1 is based on the tacit assumption that scattered particles are completely removed from the radiation beam. The quantity $\phi(x)$ then gives what is called the "uncollided flux" or the radiation flux which has no been involved in any collisions in its passage through a thickness x of tissue or a shield. With this definition of $\phi(x)$, Eqn. 1 is applicable to a broad collimated beam of radiation as shown in Fig. 7.

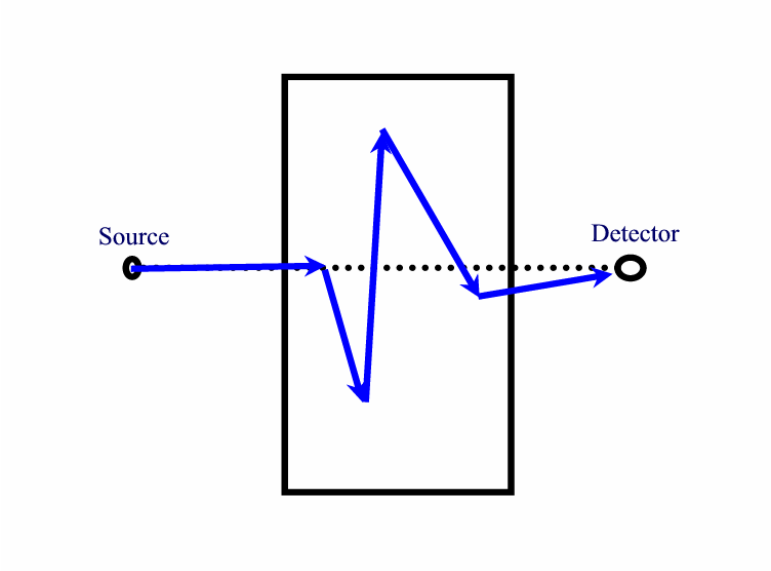

Fig. 7: Thick shield for broad radiation beam.

For a relatively thin layer of of attenuating material for a thin shield Eqn. 1 is a good approximation for the measured or total flux, even for a broad collimated beam especially for photons of high energy.

This is because the probability that a scattered radiation particle will reach the observation point or detector after a single collision is small. The total flux measured is then essentially the same as the uncollided flux.

On the other hand if the shield is relatively thick, some particles which have suffered two or more scattering collisions within the absorber may reach the detector. In this case the scattered particles are not removed and the flux atbthe observation point exceeds the uncollided flux. The simple exponential Eqn. 1 will then give broad beam values for the flux that are an underestimate of the true value.

8.8 BUILDUP FACTOR

The effect of the scattered radiation is allowed for by means of what is referred to as the "buildup factor," which is a function of the shield material and thickness and the energy of the radiation, and also of the particular quantity being observed.

For a given shield and radiation the value of the buildup factor would be different for the number flux for:

1. The number flux [particles/(cm^2.sec)]
2. The energy flux [MeV/(cm^2.sec)]
3. The dose rate [Gray/sec], [Sievert/sec].

Assuming the number flux is under observation, the attenuating Eqn. 4 would be modified to the form:

$$\phi(x) = B(\mu x, E)\phi_0 e^{-\mu x} \tag{5}$$

where $B(\mu x)$ is the appropriate buildup factor and E is the energy of the gamma ray photon.

The build up factor is thus defined as the ratio of the actual gamma ray flux

$$B = \frac{\text{Actual gamma ray flux}}{\text{Flux using an exponential attenuation law and linear attenuation coeficient}}$$

It is generally expressed as a function of μx since the attenuation coefficient depends on the material and energy of the radiation and the shield thickness x.

Although the buildup factor concept can in principle be applied to both gamma rays and to neutrons, it is generally used for the former only.

In calculations involving gamma rays attenuation, it is useful to express the buildup factor in analytical form:

$$B(\mu x, E) = 1 + b(\mu x) \tag{6}$$

where b is obtained from Table II

For instance when (μx) is 10, and the gamma ray energy is 4 MeV, the buildup factor coefficient b for water is 6.94, so that B is 7.94.

Table II: Linear equation coefficients b, for dose buildup factors for gamma ray isotropic point source.

	(μx)	Gamma ray energy [MeV]						
		1	**2**	**3**	**4**	**6**	**8**	**10**
H_2O	**1**	2.13	1.83	1.69	1.58	1.46	1.38	1.33
	2	3.17	2.77	2.42	2.17	1.91	1.74	1.63
	4	7.68	4.88	3.91	3.34	2.76	2.40	2.19
	7	16.2	8.46	6.23	5.13	3.99	3.34	2.97
	10	27.1	12.4	8.63	6.94	5.18	4.25	3.72
	15	50.4	19.5	12.8	9.97	7.09	5.66	4.90

	20	82.2	27.7	17.0	12.9	8.85	6.95	5.98
Concrete 2.35 [gm/cm^3]	**1**	2.2	1.7	1.65	1.6	1.55	1.4	1.35
	2	3.6	2.8	2.4	2.25	1.95	1.75	1.65
	4	7.8	4.9	3.8	3.3	2.75	2.4	2.2
	7	15.0	8.4	6.2	5.0	4.0	3.3	3.0
	10	24	12.3	8.6	6.8	5.2	4.3	3.8
	15	43	19	12.6	9.9	7.1	5.7	5.1
	20	70	27	17	13	9.1	7.3	6.3
Fe	**1**	1.87	1.76	1.55	1.45	1.34	1.27	1.20
	2	2.89	2.43	2.15	1.94	1.72	1.56	1.42
	4	5.39	4.13	3.51	3.03	2.58	2.23	1.95
	7	10.2	7.25	5.85	4.91	4.14	3.49	2.99
	10	16.2	10.9	8.51	7.11	6.02	5.07	4.35
	15	28.3	17.6	13.5	11.2	9.89	8.5	7.54
	20	42.7	25.1	19.1	16.0	14.7	13.0	12.4

8.9 EXPONENTIAL EXPRESSION

An alternative expression for the dose buildup factor is as the sum of two exponential terms:

$$B(\mu r, E_0) = A_1 e^{-\alpha_1 \mu(E_0) r} + A_2 e^{-\alpha_2 \mu(E_0) r}$$
$$A_1 + A_2 = 1 \qquad (7)$$

which can give results of an accuracy of about five percent or better. The coefficients for this formula are given in Table III.

Table III: Exponential equation coefficients for dose buildup factors for gamma ray isotropic point source.

		Gamma ray energy [MeV]						
		1	**2**	**3**	**4**	**6**	**8**	**10**
H_2O	**A_1**	11	6.4	5.2	4.5	3.55	3.05	2.7
	α_1	-0.104	-0.076	-0.062	-0.055	-0.050	-0.045	-0.042
	α_2	0.03	0.092	0.11	0.117	0.124	0.128	0.13
Concrete	**A_1**	10.0	6.3	4.7	3.9	3.1	2.7	2.6
	α_1	-0.088	-0.069	-0.062	-0.059	-0.059	-0.056	-0.050
	α_2	0.029	0.058	0.073	0.079	0.083	0.086	0.084
Fe	**A_1**	8.0	5.5	4.4	3.75	2.9-	2.35	2.0
	α_1	-0.089	-0.079	-0.077	-0.075	-0.082	-0.083	-0.095
	α_2	0.04	0.07	0.075	0.082	0.075	0.055	0.012

Other common forms for the expressions of the build up factors are used. For small values of μr, the build up factor can be expressed as:

$$B(\mu r, E_0) = 1 + \beta(E_0)\mu(E_0)r \qquad (7)'$$

For large values of μr the following form is used:

$$B = \beta(E_0)(\mu r)^{\alpha} \qquad (7)''$$

The dimensionless parameters are chosen to be independent of μr.

The coefficients for estimating the dose build up factors in Al and Pb, are shown in Figs. 8 and 9 respectively.

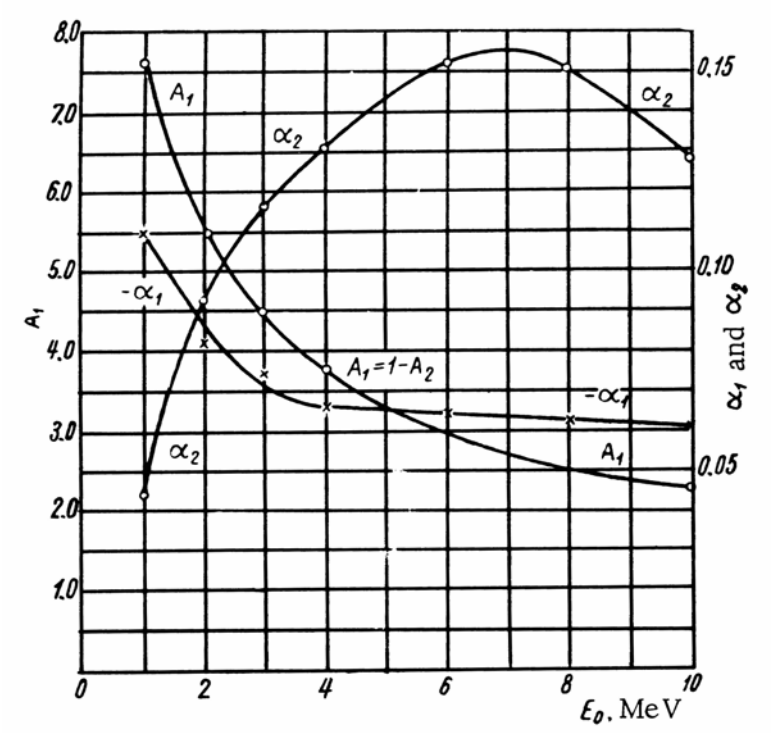

Fig. 8: Coefficients for dose build up factor estimation in Al.

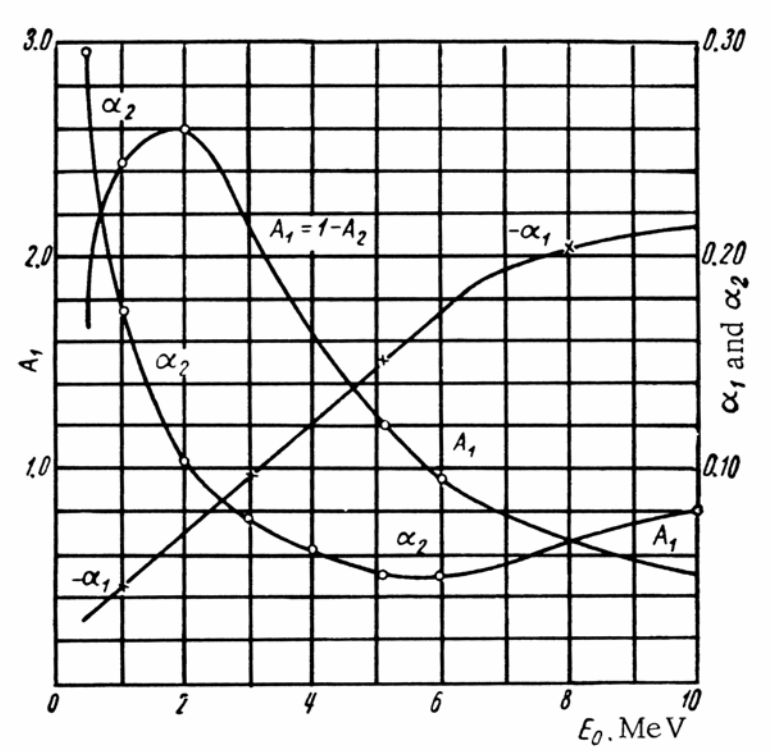

Fig. 9: Coefficients for dose build up factor estimation in Pb.

8.10 TYPES OF BUILDUP FACTORS

If we consider a point source of gamma radiation of strength S_0 [gamma photons/sec], located in an infinite medium, the dose rate D at a distance r from the source is given by:

$$D(r) = K_\gamma \frac{S_0}{4\pi r^2} B[\mu(E)r, E].e^{-\mu(E)r} \tag{8}$$

K_γ is the flux to dose conversion factor

One must distinguish between the different definitions of the build up factor.
1. The number build up factor is the ratio of the actual flux of photons of all energies to the flux of uncollided photons beyond a shield. For a mono energetic beam of photon, it is given by:

$$B_N(\mu(E)r, E_0] = \frac{\int_0^{E_0} \varphi(E)dE}{\varphi_0(E)} \quad (9)$$

$\varphi_0(E)$ is the flux of unscattered photons

E_0 is photons energy in the incident beam

$\varphi(E)dE$ is the gamma ray flux in the interval [E , E + dE]

2. The energy build up factor which is the ratio of the actual energy flux to the energy flux of the unscattered beam:

$$B_E(\mu(E)r, E_0] = \frac{\int_0^{E_0} E\varphi(E)dE}{E_0\varphi_0(E)} \quad (10)$$

3. The absorption of energy build up factor is the ratio of the specific energy absorbed per unit volume of the absorbing medium to the specific energy absorbed as a result of absorption of the unscattered beam:

$$B_a(\mu(E)r, E_0] = \frac{\int_0^{E_0} \sigma_{en}(E)E\varphi(E)dE}{\sigma_{en}(E_0)E_0\varphi_0(E)} \quad (11)$$

4. The dose build up factor is a special case of the absorption of energy buildup factor where the absorbing medium is tissue for calculation of the effective dose, or air for the calculation exposure:

$$B_D(\mu(E)r, E_0] = \frac{\int_0^{E_0} \sigma_{en}^{tissue,air}(E)E\varphi(E)dE}{\sigma_{en}^{tisue,air}(E_0)E_0\varphi_0(E)} \quad (12)$$

The daily intake in the human body of different elements, the fractions reaching the critical organs through mouth and respiratory intake and their biological half lives are given in Table IV. This information can be used to determine the dose in different critical organs.

Table IV: Composition of Human tissue.

Element	Critical organ	Average daily intake [gm]	Mouth intake fraction reaching	Respiratory intake fraction reaching	Biological half life T_B [days]

			critical organ.	critical organ	
H	Whole body	250	1	0.75	19
Li	Whole body	-	1	-	4
Be	Bones	-	$4x10^{-3}$	0.09	400
C	Fatty tissue	300	0.5	0.36	35
F	Bones	$5x10^{-3}$	0.1	$8x10^{-2}$	140
Ne	Whole body				
Na	Whole body	4	0.95	0.73	19
P	Bones	1.4	0.2	0.2	1600
S	Skin	1.3	0.08	0.074	22
Cl	Whole body	6.7	0.95	0.073	19
Ar	Whole body				
K	Muscles	2.8	0.7	0.53	37
Ca	Bones	0.8	0.25	0.41	18,000
Sc	Spleen		$2x10^{-5}$	$8x10^{-3}$	15
V	Bones	-	$5x10^{-4}$	0.025	50
Cr	Kidneys	Trace	$7x10^{-4}$	$4x10^{-3}$	110
Mn	Kidneys	$4x10^{-3}$	$4x10^{-3}$	$2x10^{-2}$	2.5
Fe	Liver	$1.2x10^{-2}$	$1x10^{-2}$	$9x10^{-2}$	5
Co	Blood	Trace	0.8	0.65	65
Ni	Liver	Trace	$4x10^{-3}$	$7x10^{-3}$	8
Cu	Liver	$2x10^{-3}$	$9x10^{-2}$	0.13	39
Zn	Bones	$1.7x10^{-2}$	$2x10^{-2}$	$5x10^{-2}$	23
Ge	Kidneys	-	$2x10^{-4}$	$5x10^{-3}$	6
As	Kidneys	-	$3x10^{-4}$	$3x10^{-3}$	37
Se	Kidneys	-	-	-	3
Rb	Muscles	-	0.42	0.33	13
Sr	Bones	$3x10^{-4}$	0.25	0.22	4,000
Y	Bones	-	$3x10^{-4}$	0.14	500
Zr	Bones	-	$1x10^{-4}$	$5.8x10^{-2}$	180
Nb	Bones	-	0.13	0.12	50
Mb	Bones	Trace	$2x10^{-4}$	$2x10^{-4}$	150
Tc	Kidneys	-	$3x10^{-3}$	$3x10^{-3}$	4
Ru	Kidneys	-	$2x10^{-5}$	$1x10^{-2}$	20
Rh	Kidneys	-	$1x10^{-2}$	$2x10^{-2}$	28
Pd	Kidneys	-	$1x10^{-2}$	$2x10^{-2}$	28
Ag	Liver	-	$1x10^{-4}$	$2x10^{-3}$	3
Cd	Liver	-	$2x10^{-3}$	0.10	100
Sn	Bones	-	$2.6x10^{-3}$	$7.6x10^{-2}$	72
Sb	Bones	-	$3x10^{-4}$	-	5
Te	Kidneys	-	$7x10^{-4}$	$2x10^{-2}$	15
I	Thyroid	$2x10^{-4}$	0.2	0.15	120
Cs	Muscles	-	0.48	0.36	17
Ba	Bones	-	$7x10^{-2}$	0.2	200

La	Bones	-	$1x10^{-3}$	0.1	35
Ce	Bones	Trace	$2x10^{-4}$	0.1	500
Pr	Bones	-	$1x10^{-3}$	0.63	50
Nd	Bones	-	-	-	35
Pr	Bones	-	$2x10^{-4}$	$9x10^{-2}$	100
Sm	Bones	-	$3x10^{-5}$	$5x10^{-2}$	$4x10^{-4}$
Eu	Bones	-	$2x10^{-4}$	$9x10^{-2}$	1,400
Tb	Bones	-	-	-	170
Ho	Bones	-	$1x10^{-4}$	$7x10^{-2}$	37
Tm	Bones	-	$4x10^{-4}$	0.18	110
Yb	Bones	-	$1x10^{-4}$	-	-
Lt	Bones	-	$2x10^{-4}$	$7.5x10^{-2}$	6
Hf	Spleen	-	-	-	10
Ta	Liver	-	$2x10^{-4}$	$7.5x10^{-2}$	130
W	Bones	-	$8x10^{-3}$	$2.4x10^{-2}$	5
Rh	Thyroid	-	$1x10^{-3}$	$1x10^{-3}$	0.5
Ir	Kidneys	-	$1x10^{-2}$	$2x10^{-2}$	23
Pt	Kidneys	-	$1.1x10^{-2}$	$3.3x10^{-2}$	64
Au	Kidneys	Trace	$2.4x10^{-2}$	$7.2x10^{-2}$	50
Tl	Muscles	-	0.24	0.26	17
Pb	Bones	$3x10^{-4}$	$5x10^{-2}$	0.098	730
Po	Spleen	-	$6x10^{-4}$	$4x10^{-3}$	57
As	Thyroid	-	$7x10^{-2}$	$5x10^{-2}$	180
Ra	Bones	$7x10^{-13}$	$1.5x10^{-2}$	$2.6x10^{-2}$	2x10-4
Ac	Bones	-	$9x10^{-3}$	-	1,200
Th	Bones	-	$4x10^{-4}$	0.2	40,000
Pa	Bones	-	$2x10^{-4}$	-	400
U	Kidneys	$2x10^{-6}$	$2x10^{-4}$	$8x10^{-2}$	30
Np	Bones	-	$5x10^{-4}$	-	100
Pu	Bones	-	$1x10^{-4}$	0.18	43,000
Am	Bones	-	$1x10^{-4}$	$6.3x10^{-2}$	890
Cu	Bones	-	$1x10^{-4}$	$6.3x10^{-2}$	600

8.11 BUILD UP FACTORS FOR HOMOGENEOUS SHIELD MIXTURES

Homogeneous shield mixtures of elements of various atomic masses such as concrete are encountered in shield calculations. This would also apply to layered shields if the thicknesses of the layers do not exceed the mean free path of the considered rays at the energy of interest. In this case, the effective values of the attenuation coefficients can be determined from:

$$\mu_{eff} = \sum_{i=1}^{n} \mu_i(E) \frac{N_i}{N_{i0}} \qquad (12)$$

or:

$$\mu_{m,eff} = \sum_{i=1}^{n} \mu_{m,i}(E) a_i \qquad (13)$$

where: N_i is the nuclide density of the i-th element,
N_{i0} is the nuclide density of the pure element,
a_i is the fraction of the mixture by weight made up by the i-th element.

8.12 BUILD UP FACTORS FOR HETEROGENEOUS SHIELDS

Most shields contain mixtures of different elements such as lead and water or iron and water. We consider a two layer heterogeneous shield and the case of a point source. The dose build up factor in this case depends on the order of the layers.

If the layer closer to the source consists of a low (L) atomic number Z, the build up factor can be represented as that of a slab of the high Z component (H) with a thickness equal to that of the composite shield:

$$B_{L+H} = B_H(\mu_L x_L + \mu_H x_H) \qquad (14)$$

If the layer of high Z substance is closer to the source, the build up factor for the composite shield should be taken as the product of the build up factors of the two components:

$$B_{H+L} = B_H(\mu_H x_H).B_L(\mu_L x_L) \qquad (15)$$

The argument for these choices is based on the observation that the build up factor for the low Z components such as water, is very large as a consequence of the small probability of absorption of the gamma photons that have been slightly degraded in energy by Compton scattering. This results from the cross sections for the photoelectric absorption of a low Z element being small.

If the high Z element is outside the low Z component the gamma rays lose energy by scattering in the low Z component, and are effectively absorbed in the high Z component. The effective build up factor of such a combination is less than the product of the build up factors of the layers and is close to the build up factor of the high Z component, hence Eqn 14 can be used.

If the high Z element is closer to the source, gamma rays scattered in the high Z component are slightly degraded in energy and are weakly absorbed in the low Z component. The effective build up factor of the combination is consequently close to the product of the build up factors of the layers, and Eqn. 15 can be used.

If the shield contains a large number of layers, the effective build up factor can be taken as the product of the build up factor for the high Z layers and the sum of the build up factors for the low Z components:

$$B_{composite} = B_H(\mu_H x_H).\sum_i B_{L,i}(\mu_{Li} x_{Li}) \quad (16)$$

EXERCISES

1. For a narrow beam configuration, compare the thicknesses of H_2O, Fe, Al, concrete and Pb that will reduce the intensities of the gamma photons from Co^{60} to 1 percent of their initial intensity.
2. For a wide beam configuration, accounting for the build up factor, compare the thicknesses of H_2O, concrete and Fe that will reduce the doses from the gamma photons from Co^{60} to 1 percent of their initial intensity. Compare to the results obtained from the narrow beam approximation.

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