Indian Journal of Pure & Applied Physics
Vol. 45, March 2007, pp. 198-203

Comparative study of attenuation and scattering of gamma-rays through two intermediate rocks

A El-Taher*
Physics Department, Faculty of Science, Al-Azhar University, Assuit, Egypt

and

H M Mahmoud, Adel G E Abbady
Physics Department, Faculty of Science, South Valley University, Qena, Egypt

Received 9 November 2005; revised 17 July 2006; accepted 9 January 2007

With the extensive applications of radioactive materials, it is necessary to look for locally available and cheep materials to be efficient absorbers appropriate for shielding from radiation hazards. The attenuation and scattering coefficients of gamma-rays of different energies in thirty samples from two igneous rocks: diorite and andesite, the effects of sample density, ρ, with radiation energy (*E*) ranging from 0.36 to 1.33 MeV, were investigated by using a scintillation detector NaI (Tl). The chemical composition of major elements measured by X-ray fluorescence (XRF). The results showed an inverse proportionality between the linear attenuation coefficient μ and *E*, and μ has a direct proportionality with the sample density, ρ. The side scattering coefficient ϕ, is directly proportional to E_γ, but at the same time ϕ has an inverse proportionality with the sample density. The results showed an inverse proportional between the half value layers and the sample density ρ.

Keywords: Intermediate rock, Attenuation, Side scattering, Half value layer

IPC Code:G01T

1 Introduction

The photon attenuation coefficient is an important parameter for characterizing the penetration and diffusion of X-rays and gamma-rays in multi-element materials. Photon attenuation coefficients are required in a variety of nuclear science technology and medical applications. The radiation could be harmful which has lead to the development of wide variety of shields to protect against it. As a technology advances, there is a need to develop materials which can be used under most harsh conditions such as nuclear radiation exposure. Materials to be used should have certain specifications to cut off these hazards or at least to minimise it to the permissible doses. The most important character for such materials is to have high density and to be free or almost free from radioactive elements. The propagation of gamma-rays through natural rocks diorite and andesite (fifteen samples from each rock) have been investigated in the present paper to study the attenuation and scattering of gamma-rays of different energies through absorbers composed of two natural rocks diorite and andesite.

The most important parameter characterizing the penetration and diffusion of gamma-radiation in extended matter is the attenuation coefficient (μ) which depends on the photon energy (*E*) and atomic number (*z*) of the medium[1]. Hence, we are primarily interested in evaluating μ and the side scattering of radiation for different gamma energies for many samples different in their chemical composition.

The quantity widely used in calculating gamma-ray penetration and energy-deposition in biological shielding and other materials is the mass attenuation coefficient μ/ρ. A narrow beam of monoenergetic photons is attenuated according to the familiar exponential absorption law[1]. For more complicated situations than narrow beam, the attenuation is still basically exponential, but is modified by two additional factors. The first of these, sometimes called a geometry factor, depends essentially on the source geometry. The other factor is called the buildup factor, which takes into account secondary photons produced in absorber as a result of one or more compton scattering. For thin shield and narrow beam, the buildup factor is unity.When the sample thickness,

---

*E-mail: Atef_Eltaher @hotmail.com

t, is small and the detector size can be neglected the gamma-ray flux density at the detector[1] is given by:

$$\Phi = \frac{S}{4\pi R^2} e^{-\mu(E)t} \qquad \ldots \quad (1)$$

where S is the source strength, $\mu(E)$ the linear attenuation coefficient (cm^{-1}), t the shield thickness (cm), and R is the source detector distance. As the thickness of the shield is increased or as the width of the beam is increased, the flux density[1] is given by:

$$\Phi = \frac{S}{4\pi R^2} B^{(E_o - \mu t)} e^{-\mu(E_o)t} \qquad \ldots \quad (2)$$

where B is the buildup factor.

2 Experimental Details

2.1 Preparation of samples

In this experiment, diorite and andesite as ignious rocks were investigated as shielding materials, where silicon is the predominant essential constituent element[2]. All samples of natural rocks in this investigation have been cut in the form of circular discs 3 cm in diameter. The thickness of each disc 1 cm. Tables 1 and 2 present the chemical composition of major elements measured by X-ray fluorescence (XRF).

2.2 Sources, detector, collimator and scaler

Three sources of gamma - radiation have been used: ^{60}Co, ^{137}Cs, and ^{133}Ba. Each source is housed in its own lead container. The radiation is confined to a narrow beam by a lead collimator having a small hole. A scintillation detector NaI (Tl) was used in this experiment. Our collimator is a hole with 8 cm in length and 1 cm in diameter bored through a cubic lead block having an edge of 8 cm. This is followed by a similar block containing a narrow bored hole with 7 mm diameter, and the two lead blocks are arranged such that the two bored holes are aligned with the source to give a narrow collimated beam with reasonable intensity. The collimator thickness allows for the absorption of radiation scattered out of the beam inside the collimator so that the scattered radiation does not emerge in the room.

To determine the side scattering coefficients, the detector was fixed at a certain distance from the sample's edge (2 cm) and directed perpendicular to the direction of the incident beam, then different measurements were taken along the extension of sample by varying the thickness of absorber.

3 Results and Discussion

3.1 Linear attenuation coefficients and relaxations length

Linear attenuation coefficients (μ) of gamma-rays in diorite and andesite as natural rock for different sources ^{60}Co ^{133}Ba, ^{137}Cs have been calculated graphically from the attenuation curves by using the following equation.

$$n/n_o = \exp(-\mu x) \Rightarrow \log(n/n_o) = 0.4343\ \mu\ x \qquad \ldots \quad (3)$$

where n_o is primary photons per second, n the photons per second passes normally through a foil containing N atoms/cm^3, μ the linear attenuation coefficient and x is the thickness of the absorber. The mass attenuation coefficients μ/ρ were evaluated for the three radiation sources and presented in Tables 3 and 4. It is possible to see that μ/ρ varies linearly with ρ according to Eq. (4).

$$\mu/\rho = k \quad \text{or } \mu = k\,\rho \qquad \ldots \quad (4)$$

where k is a constant which depends on the kind of absorber. It can be see that the relaxation length, λ, decreases linearly with ρ according to the following empirical formula.

$$\lambda = -A\,\rho + K \qquad \ldots \quad (5)$$

where A represents the rate of change of λ with ρ and K is a constant which depends on the kind of absorber. It is seen that λ increases linearly with ρ in the energy range of interest.

As the rock contains many of heavier elements by high ratios, the density ρ increases, and the number of scattering centers increases causing more elimination of photons from the incident beam, hence more attenuation[3,4].

3.2 Half value layer

The half value layer is the absorber thickness required to reduce the intensity of the incident radiation to half its initial value. The following

Table 1—Chemical composition and density for fifteen samples of diorite rock

Rock No.	Density g/cm^3	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	N_2O	K_2O	TiO_2	P_2O_5	CO_2	S	H_2O^-	H_2O^+	$H_2O^\pm$
1	2.7298	44.13	15.42	9.19	5.95	0.01	6.31	9.94	4.51	2.67	1.07	Tr.	0	0.09	0.28	0.30	0
2	2.7268	49.32	18.62	8.40	3.72	0.08	3.87	7.89	.3.86	0.96	2.29	0.01	0	0.07	0.70	0.56	0
3	2.6496	48.30	17.20	6.98	3.48	0.17	5.88	9.59	3.89	2.86	0.45	Tr.	0	0.10	0.43	0.28	0
4	2.5985	53.36	16.24	5.74	5.28	0.14	2.13	8.13	3.59	0.50	1.91	0.65	0.29	0	0	0	0
5	2.5589	54.70	17.30	3.40	4.70	0.10	4.95	8.20	2.90	1.50	0.80	0.20	0	0	0	0	0,
6	2.5563	54.21	19.38	2.00	3.47	0.08	1.67	6.80	3.71	6.47	0.92	0.03	0	0.08	0.60	0.30	0
7	25531	64.14	15.10	3.97	2.68	0.09	2.70	4.75	3.54	2.10	0.40	Tr.	0	0.08	0.40	*0.38*	0
8	2.5403	55.31	17.10	3.21	4.61	0.10	4.60	7.90	3.00	1.60	0.80	0.20	0	0	0	0	0
9	2.5055	53.86	16.41	2.63	6.97	0.18	5.21	7.41	3.36	1.34	1.50	*0.35*	0	0	0	0.82	0
10	2.4997	64.04	14.47	1.91	2.70	0.07	1.74	5.80	4.04	3.06	0.55	Tr.	0	0.09	0.77	0.50	0
11	2.4949	61.01	16.02	2.19	0.08	0.08	2.02	6.53	3.91	2.93	0.80	0.38	0	0	0	0.61	0
12	2.4943	61.70	15.90	2.33	0.07	0.07	2.36	8.65	3.84	2.80	0.60	0.20	0	0	0	0.63	0
13	2.4760	52.98	16.08	2.29	0.09	0.09	4.88	5.53	8.61	1.52	1.20	0.34	0	0	0	0.90	0
14	2.4588	46.04	22.26	0.99	0.16	0.16	4.94	11.64	2.39	0.62	2.10	0.09	0.27	0	0.13	0.79	0
15	2.4074	52.20	21.28	2.27	0.67	0.11	6.75	8.71	3.50	1.65	1.90	0.34	0	0	0	0	0.62

Table 2—Chemical composition and density for fifteen samples of andesite rock

Rock No.	Density G/cm^3	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TIO_2	P_2O_5	CO_2	S	H_2O^-	H_2O^+	$H_2O^\pm$
1	2.5947	62.21	16.32	2.86	2.91	0	2.90	5.04	4.32	1.55	0.21	0.12	0	0	0	0	1.61
12	2.5726	55.23	17.06	5.69	1.94	0.11	3.72	7.91	2.70	1.55	0.96	0.27	0	0	0	2.28	0
3	2.5506	60.92	15.96	3.99	2.94	0.09	2.87	4.14	4.18	2.21	0.93	0.26	0	0	0	1.25	0
4	2.5394	60.04	16.12	3.49	3.40	0.10	3.15	5.49	3.93	2.29	0.81	0.15	0	0	0	0.43	0
5	2.5169	61.65	15.39	3.02	4.47	0.10	2.73	4.96	3.64	1.93	0.83	0.20	0	0	0	0.70	0
6	2.5022	54.96	15.01	3.40	5.81	0.13	4.35	6.34	3.10	1.93	1.50	0.49	0	0	0	2.64	0
7	2.4900	56.83	18.21	2.32	4.01	0	3.98	5.72	4.77	1.62	0.60	0.23	0	0	0	0	1.51
8	2.4786	58.83	17.21	2.43	3.93	0	3.63	5.19	4.62	1.53	0.58	0.23	0	0	0	0	1.63
9	2.4705	61.45	16.81	2.44	2.81	0	3.11	5.34	4.12	1.61	0.33	0.14	0	O	0	0	1.43
10	2.4699	61.71	16.21	2.59	2.69	0	3.82	5.16	4.31	1.23	0.42	0.25	0	0	0	0	1.36
11	2.4694	53.61	15.59	2.92	6.57	0.18	5.51	7.97	2.69	1.14	123	0.28	0	0	0	1.45	0
12	2.4573	59.92	18.71	3.31	2.42	0	3.20	5.31	4.01	1.21	0.65	0.22	0	0	0	0	0
13	2.4546	60.80	17.15	2.00	3.33	0	3.60	5.38	4.21	1.14	0.52	0.22	0	0	0	0	1.31
14	2.4514	60.61	16.90	2.13	3.65	0	3.71	5.42	4.11	1.31	0.21	0.11	O	0	0	0	1.23
15	2.4304	59.64	17.33	2.21	3.65	0	3.71	3.36	4.31	1.62	0.53	0.14	0	0	0	0	1.42

relationship exists between the half layer and the linear absorption coefficient.

When $X = X_{½}$ - then $I = 1/2\ I_0$

$1/2\ I_o = I_o \exp(-\mu X_{1/2}) \Rightarrow \qquad 1/2 = \exp(-\mu X_{1/2}) \Rightarrow$

$\ln 2 = -\mu X_{1/2} \Rightarrow$

$$X_{1/2} = \ln 2/\mu \Rightarrow X_{1/2} = 0.693/\mu \text{ cm} \qquad \ldots (6)$$

Using Eq. (6) the half value layer $X_{½}$ is determined and presented in Tables 5 and 6.

It was shown that $T_{½}$ increased linearly as the density (ρ) decreases. This relation could be represented by the empirical formula.

$$X_{½} = -B\rho + e \qquad \ldots (7)$$

where B represents the rate of change of $T_{½}$ with ρ, and e is a constant which depends on the kind of absorber, the change of $T_{½}$ with ρ can be explained by the fact that as the density (ρ) increases the voids decrease and the multiple scattering increases. This increases the attenuation of the incident radiation inside the absorber consequently the half value layer decreases[5].

3.3 Side scattering measurements

The radiation field at a point in space remote from the source can be divided into two components. The first component is the uncollided (or as it is sometimes called the unscattered) photons that arrive at the point without having undergone any interaction with the transported medium. The second component is composed of the collided or scattered photons. These have undergone one or more interactions resulting in changes of direction or energy or both. To

Table 3—Measured values of mass attenuation coefficients and relaxation length for diorite with different radiation sources energies

Sample No	Density ρ g/cm^3	Co^{60} (1.33 and 1.17 MeV) μ/ρ cm^2/g	λ cm	Cs^{137} (0.661MeV) μ/ρ cm^2/g	λ cm	Ba^{133} (0.36 MeV) μ/ρ cm^2/g	λ cm
1	2.7298	0.03272	11.19	0.05507	6.65	0.07347	4.99
2	2.7268	0.03272	11.21	0.05507	6.66	0.07347	4.99
3	2.6496	0.03272	11.53	0.05507	6.85	0.07347	5.14
4	2.5985	0.03272	11.76	0.05507	6.99	0.07347	5.24
5	2.5589	0.03272	11.95	0.05507	7.1	0.07347	5.32
6	2.5563	0.03272	11.95	0.05507	7.10	0.07347	5.32
7	2.5531	0.03272	11.97	0.05507	7.11	0.07347	5.33
8	2.5403	0.03272	12.03	0.05507	7.15	0.07347	5.36
9	2.5055	0.03272	12.20	0.05507	7.25	0.07347	5.43
10	2.4997	0.03272	12.22	0.05507	7.26	0.07347	5.45
11	2.4949	0.03272	12.25	0.05507	7.28	0.07347	5.46
12	2.4943	0.03272	12.25	0.05507	7.28	0.07347	5.46
13	2.4760	0.03272	12.34	0.05507	7.33	0.07347	5.50
14	2.4588	0.03272	12.43	0.05507	7.38	0.07347	5.54
15	2.4074	0.03272	12.69	0.05507	7.54	0.07347	5.65

Table 4—Measured values of mass attenuation coefficient and relaxation length for andesite with different radiation sources energies

Sample No	Density ρ g/cm^3	Co^{60} (1.33 and 1.17 MeV) μ/ρ cm^2/g	λ cm	Cs^{137} (0.661 MeV) μ/ρ cm^2/g	λ cm	Ba^{133} (0.36 MeV) μ/ρ cm^2/g	λ cm
1	2.5947	0.03272	11.78	0.05507	7.00	0.07347	5.25
2	2.5726	0.03272	11.88	0.05507	7.06	0.07347	5.29
3	2.5506	0.03272	11.98	0.05507	7.12	0.07347	5.34
4	2.5394	0.03272	12.03	0.05507	7.15	0.07347	5.36
5	2.5169	0.03272	12.14	0.05507	7.21	0.07347	5.41
6	2.5022	0.03272	12.21	0.05507	7.26	0.07347	5.44
7	2.4900	0.03272	12.27	0.05507	7.29	0.07347	5.47
8	2.4786	0.03272	12.32	0.05507	7.33	0.07347	5.49
9	2.4705	0.03272	12.37	0.05507	7.35	0.07347	5.51
10	2.4699	0.03272	12.37	0.05507	7.35	0.07347	5.52
11	2.4664	0.03272	12.39	0.05507	7.36	0.07347	5.54
12	2.4573	0.03272	12.44	0.05507	7.39	0.07347	5.54
13	2.4546	0.03272	12.45	0.05507	7.40	0.07347	5.55
14	2.4514	0.03272	12.47	0.05507	7.41	0.07347	5.55
15	2.4304	0.03272	12.57	0.05507	7.47	0.07347	5.60

measure the scattered radiation, the detector was placed perpendicular to the incident radiation at a distance of 2 cm from the edge of the samples. The detector was moved parallel to the extension of sample.

The detector was moved in a circular plane around the sample discs at 45° intervals. Then, we take the average value of the measured side scattering. Two different parameters were investigated: (a) the effect of radiation energy on side scattering using three different sources (^{60}Co, ^{137}Cs, ^{133}Ba) and (b) the density of the absorber. The scattered radiation to primary ratio (I_s/I_o) is found to decrease exponentially along the extension of the absorber. Hence, the empirical formula for side scattering is:

$$I_s = I_o \exp(\phi_s z) \qquad \ldots \quad (8)$$

Tables 7 and 8 present the measured values of side scattering coefficients for diorite and andesite with different radiation sources energies. The results show that ϕ_s decreases linearly with the density ρ of the absorber according to the derived equation:

$$\phi_s = -E\rho + F \qquad \ldots \quad (9)$$

where E represents the rate of change of ϕ_s with ρ and F is a constant depending on the kind of absorber. Also ϕ_s increases as the energy of radiation increases for the same density in the energy range of interest.

The side scattering of radiation can be attributed to Compton scattering. Hence, the scattered intensity is

Table 5—Half-value layers for diorite rock

Sample No	Density ρ g/cm^3	H.V.L ($X_{1/2}$) cm		
		Co^{60} (1.33 and 1.17)MeV	Cs^{137} (0.661)MeV	Ba^{133} (0.36)MeV
1	2.7298	7.75	4.61	3.46
2	2.7268	7.77	4.62	3.46
3	2.6496	7.99	4.75	3.56
4	2.5985	8.15	4.84	3.63
5	2.5589	8.28	4.92	3.69
6	2.5563	8.28	4.92	3.69
7	2.5531	8.30	4.93	3.69
8	2.5403	8.34	4.95	3.71
9	2.5055	8.45	5.02	3.76
10	2.4997	8.47	5.03	3.77
11	2.4949	8.49	5.05	3.78
12	2.4943	8.49	5.05	3.78
13	2.4760	8.55	5.08	3.81
14	2.4588	8.61	5.11	3.84
15	2.4074	8.79	5.23	3.92

Table 6—Half-value layers for andsite rock

Sample No	Density ρ g/cm^3	H.V.L ($X_{1/2}$) cm		
		Co^{60} (1.33 and 1.17)MeV	Cs^{137} (0.661)MeV	Ba^{133} (0.36)MeV
1	2.5947	8.16	4.85	3.64
2	2.5726	8.23	4.89	3.67
3	2.5506	8.30	4.93	3.70
4	2.5394	8.34	4.96	3.71
5	2.5169	8.41	5.00	3.75
6	2.5022	8.46	5.03	3.77
7	2.4900	8.50	5.05	3.79
8	2.4786	8.54	5.08	3.81
9	2.4705	8.57	5.09	3.82
10	2.4699	8.57	5.09	3.82
11	2.4664	8.59	5.10	3.84
12	2.4573	8.62	5.12	3.84
13	2.4546	8.63	5.13	3.84
14	2.4514	8.64	5.13	3.85
15	2.4304	8.71	5.18	3.88

Table 7—Measured values of side scattering coefficients for diorite with different radiation sources energies

Sample No	Density ρ g/cm^3	Co^{60}(1.33 and 1.17MeV)		Cs^{137}(0.661MeV)		Ba^{133}(0.36MeV)	
		ϕ_s cm^{-1}	$\phi^{-1}{}_s$ cm	ϕ_s cm^{-1}	$\phi^{-1}{}_s$ cm	ϕ_s cm^{-1}	$\phi^{-1}{}_s$ cm
1	2.7298	0.04651	21.50	0.04178	23.93	0.03467	28.85
2	2.7268	0.04656	21.48	0.04183	23.91	0.03479	28.74
3	2.6496	0.04792	20.87	0.04305	23.23	0.03585	27.90
4	2.5985	0.04886	20.47	0.04389	22.78	0.03642	27.46
5	2.5589	0.04962	20.15	0.04457	22.44	0.03698	27.04
6	2.5563	0.04967	20.13	0.04462	22.41	0.03702	27.01
7	2.5531	0.04973	20.11	0.04467	22.38	0.03707	26.98
8	2.5403	0.04998	20.01	0.04490	22.27	0.03725	26.84
9	2.5055	0.05068	19.73	0.04552	21.97	0.03777	26.48
10	2.4997	0.05079	19.69	0.04563	21.92	0.03786	26.41
11	2.4949	0.05089	19.65	0.04572	21.87	0.03793	26.36
12	2.4943	0.05090	19.65	0.04573	21.87	0.03794	26.36
13	2.4760	0.05128	19.50	0.04606	21.71	0.03822	26.16
14	2.4588	0.05164	19.37	0.04639	21.56	0.03849	26.98
15	2.4074	0.05274	18.96	0.04738	21.11	0.03931	26.44

Table 8—Measured values of side scattering coefficients for andesite with different radiation sources energies

Sample No	Density ρ g/cm^3	Co^{60}(1.33 and 1.17MeV)		Cs^{137}(0.661MeV)		Ba^{133}(0.36MeV)	
		$\phi_s cm^{-1}$	$\phi_s^{-1} cm$	$\phi_s cm^{-1}$	$\phi_s^{-1} cm$	$\phi_s cm^{-1}$	$\phi_s^{-1} cm$
1	2.5947	0.04893	20.44	0.04396	22.75	0.03647	27.42
2	2.5726	0.04935	20.26	0.04433	22.56	0.03 679	27.18
3	2.5506	0.04978	20.09	0.04472	22.36	0.03710	26.95
4	2.5394	0.05000	20.00	0.04491	22.26	0.03727	26.83
5	2.5169	0.05045	19.82	0.04532	22.07	0.03760	26.60
6	2.5022	0.05074	19.71	0.04558	21.94	0.03782	26.44
7	2.4900	0.05099	19.61	0.04581	21.83	0.03801	26.31
8	2.4786	0.05123	19.52	0.04602	21.73	0.03818	26.19
9	2.4705	0.05139	19.46	0.04617	21.66	0.03831	26.11
10	2.4699	0.05141	19.45	0.04618	21.66	0.03831	26.10
11	2.4664	0.05148	19.43	0.04624	21.62	0.03837	26.01
12	2.4573	0.05167	19.35	0.04642	21.54	0.03851	25.97
13	2.4546	0.05173	19.33	0.04647	21.52	0.03855	25.94
14	2.4514	0.05179	19.31	0.04653	21.49	0.03860	25.90
15	2.4304	0.05224	19.14	0.04693	21.31	0.03894	25.68

expected to increase along the extension of the absorber, where the scattering angle decreases. However, it was found that the scattered intensity decreases along the absorber extension. This paradox finds an explanation in comparing relaxation lengths, λ with the distance travelled by the scattered radiation through the absorber. The distance is smaller than λ at the near end larger than λ at the far end of the absorber[6].

4 Conclusion

The results showed an inverse proportionality between μ and radiation energy (E) and μ has a direct proportionality with the sample density, ρ. However, the side scattering coefficient (ϕ) is directly proportional to E_γ, but at the same time ϕ has an inverse proportionality with the sample density ρ. The similarity of gamma-ray properties in diorite and andesite is due to similarities in their compositions, but there are small observed differences which attribute to higher content of iron and other higher-z (atomic number) elements in diorite.

References

1 Hubbel J H, Photon Cross-Sections, Attenuation Coefficients from 10 keV to 100 GeV, NSRDS (*National Standard Reference Data System*) NBS (*National Bureau of Standards*) 29 (1969) U S.

2 Goldstein H & Wilkins USAEC Report NYO, 3075 (NDA-15C-41) *Nuclear Development Associates*. (1954) US.

3 Mahmoud H M, Hok A, Armia E & El-Taher A, *Indian J Pure & Appl Phys*, 33 (1995) 332.

4 Mahmoud H M, Hok A, Armia E & El-Taher A, *Radiation Res, Radiation Proccess*, 14 (1996) 134.

5 Mudahar G S & Sahata H S, *Indian J Pure & Appl Phys*, 24 (1986) N7.

6 El-Taher A, M Sc.Thesis, (South Valley University, Qena, Egypt) 1996.