

•研究论文•

ATTENUATION AND SCATTERING OF GAMMA-RAY THROUGH ANDESITE AND FELSITE

MAHMOUD H M, ARMIA E

(*Department of physics, Faculty of Science, South Vally University, Qena, Egypt.*)

ABSTRACT The study of gamma-ray interactions with matter is increasingly important primarily due to new applications of gamma-emitting isotopes in agriculture, medicine and industry. Two igneous rocks, andesite and felsite, are investigated for radiation shields. The effects of particle size (grain diameter) d mm and sample density ρ on the linear μ , mass μ/ρ attenuation coefficients and side scattering coefficients ϕ_s of compressed and natural rocks has been studied with gamma radiation energy E ranging from 0.36 to 1.33 MeV. Flux distribution in samples and the halfvalue layers $X_{1/2}$ were determined. The results showed an inverse proportionality between the linear attenuation coefficient μ and both d and E . It was also found that μ has a direct proportionality with the sample density ρ . The side scattering coefficient ϕ_s is directly proportional to both d and E , but at the same time ϕ_s has an inverse proportionality with the sample density ρ .

KEYWORDS Gamma-ray attenuation and side scattering coefficients, Igneous rock sample

CLC O571.33

1 Introduction

Because of the intense production of neutrons as well as gamma and other radiation, and also due to the wide variety of reactor types that have been built and are being built, it has been a must to look for locally available and cheap materials to be used as shields from radiation hazards. Materials to be used should have certain specifications to remove these hazards or at least to minimize it to the permissible dose. The most important character for such materials is to have high density and to be free or almost free from radioactive elements.

The three processes contributing to photon attenuation are the photoelectric effects, Compton scattering and pair production. Each process causes some or all of the energy of the incident photon to be deposited at the site of the interaction. Thus the total microscopic cross section per atom of atomic number Z for the photon attenuation is given by^[1]

$$\sigma = \sigma_{ph} + \sigma_c + \sigma_{pP} \quad (1)$$

where σ_{ph} is the cross section per atom for the photoelectric effect, the cross section per atom for the Compton scattering σ_c is in proportion with Z and σ_{pP} is the cross section per atom for pair production.

Recived: 1999-06-02, Accepted: 7 August 2000

The macroscopic cross section computed from the total microscopic cross section of Eq.(1) is more commonly called attenuation coefficient thus:

$$\mu_l = N\sigma$$

where N is the atomic density and μ_l is linear attenuation coefficient which depends on the photon energy E and the atomic number Z of the medium, and may be defined as the probability per unit path length of a photon to interact with the medium.

2 Experimental

In this experiment, andesite and felsite materials have been used as shielding, silicon is the predominant essential element in their compositions. Andesite is characterized by its relatively small SiO_2 (54.20%) content^[2]. In addition, it contains other oxides: Al_2O_3 (17.17%), Fe_2O_3 (3.48%), FeO (5.49%), MnO (4.36%), CaO (7.92%), Na_2O (3.67%), K_2O (1.11%), TiO_2 (1.31%), H_2O (0.86%) and P_2O_5 (0.28%). On the other hand, felsite is composed of a higher amount of SiO_2 (74.57%) with the remaining constituents being Al_2O_3 (12.58%), TiO_2 (0.17%), Fe_2O_3 (1.3%), FeO (1.02%), MnO (0.05%), MgO (0.11%), CaO (0.61%), Na_2O (4.13%), K_2O (4.73%), H_2O (0.66%) and P_2O_5 (0.07%). The powdered andesite and felsite samples are sieved to separate samples into different grain sizes : 0.17, 0.13, 0.095, 0.085 and 0.0635 mm. The separated samples are pressed under 35 t/cm^2 into the form of discs 3 cm in diameter.

Three gamma sources were used in this experiment:⁶⁰Co in the form of cobaltous chloride which emits two gammas of energies 1.33MeV and 1.17MeV, ¹³⁷Cs in the form of cesium chloride which emits a 0.661 MeV

gamma ray and ¹³³Ba in the form of barium chloride which emits 0.36 MeV gamma rays. A scintillation counter was used in this experiment as detector. Our collimator has a hole 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 7mm diameter. 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 is enough for the absorption of radiation scattered from the beam inside the collimator so that the dose of scattered radiation is reducing much in the room.

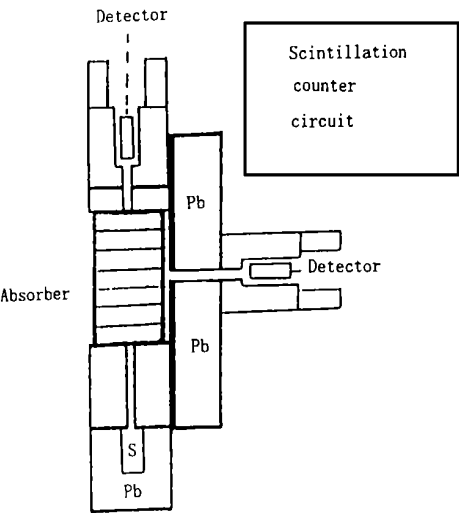


Fig.1 A schematic diagram for good geometry absorption and side scattering arrangement

The scale used in this experiment is a BAIRO-ATOMIC scaler, model, 1966-160, Bedford series. The output voltage ranges from zero to 10^4 volts. Fig.1 is a schematic diagram

for good geometry absorption and side scattering arrangement.

Besides, the evaluation of the relaxation lengths and the mass attenuation coefficients, the scattered radiation leakage from absorber side, and the distribution of radiation inside the sample and half value layer $X_{1/2}$ are studied.

3 Results and discussion

3.1 Evaluation of the attenuation coefficients and relaxation lengths

We follow the recent nomenclature of ICRU report^[3] using the “term attenuation coefficient”, for absorption coefficient. This quantity depends on the photon energy E and the atomic number Z of the medium. Both the linear μ and mass μ_ρ attenuation coefficients of the compressed powdered felsite and andesite for gamma rays of three radioactive sources : ^{60}Co , ^{137}Cs and ^{133}Ba were graphically evaluated from attenuation curves as well as by the least square method.

Figs.2,3 show the variation of μ_ρ and relaxation length. λ as a function of grain diameter, d , for andesite and felsite. It is possible to see that μ_ρ varies linearly with d according to the equation

$$\mu_\rho = ad + k \quad \text{for } 0.0635 \leq d \leq 0.17 \text{ mm} \quad (2)$$

where a represents the rate of change of μ_ρ with d , k is a constant depending on the kind of absorber. These figures also show that the relaxation, λ , increases linearly with d . Since the density, ρ , of the compressed powder is inversely proportional to the grain diameter d the variations of μ_ρ and λ were studied with the variation of ρ . The obtained values are plotted in Figs 4,5 for andesite and felsite. It is seen that μ_ρ increases linearly with ρ in the energy range of interest according to the following formula

$$\mu_\rho = b\rho + c \quad \text{for } 0.0635 \leq d \leq 0.17 \text{ mm} \quad (3)$$

where b represents the rate of change of μ_ρ with ρ and c is a constant depending on the kind of absorber, also from Figs.4,5 we see that the relaxation length λ varies linearly with density ρ .

As the powder gets finer (i.e d gets smaller) the density, ρ , increases, the number of scattering centers increases causing more elimination of photons from the incident beam, hence more attenuation.

Attenuation coefficients show a small difference between andesite and felsite due to small differences in their compositions. However, the small differences in these coefficients could be attributed to the excess of iron compounds, TiO_2 , Al_2O_3 , MnO , MgO , CaO , Na_2O , P_2O_5 and water in the composition of andesite than that of felsite. Besides the density of andesite is greater than that of felsite therefore andesite has attenuation

coefficients higher by small values than felsite; see Table 1,2.

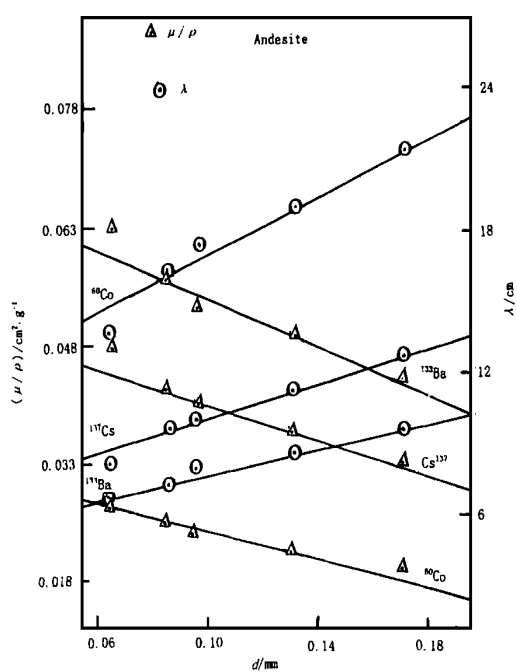


Fig.2 The relation between grain diameter d (mm) of the compressed samples of andesite and both mass attenuation coefficient μ/ρ (cm^2/g) and relaxation length λ (cm)

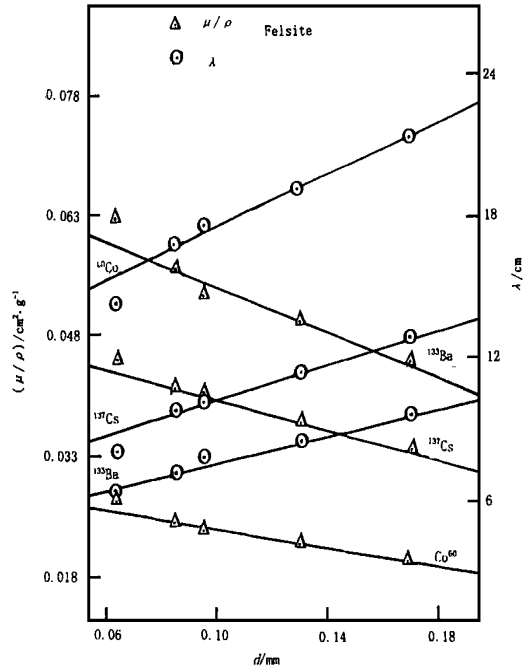


Fig.3 The relation between grain diameter d (mm) of the compressed samples of felsite and both mass attenuation coefficient μ/ρ (cm^2/g) and relaxation length λ (cm)

Tab.1 Measured values of mass attenuation coefficients and relaxation lengths
for andesite with different radiation sources

Grain diameter	Density	^{60}Co 1.33 MeV, 1.17 MeV		^{137}Cs 0.661 MeV		^{133}Ba 0.36 MeV	
/mm	/ $\text{g}\cdot\text{cm}^{-3}$	$(\mu:\rho)/\text{cm}^2\cdot\text{g}^{-1}$	λ/cm	$(\mu:\rho)/\text{cm}^2\cdot\text{g}^{-1}$	λ/cm	$(\mu:\rho)/\text{cm}^2\cdot\text{g}^{-1}$	λ/cm
0.17	2.359	0.01996	21.24	0.03357	12.63	0.04455	9.52
0.13	2.410	0.02204	18.83	0.03707	11.19	0.04920	8.43
0.095	2.432	0.02362	17.41	0.03972	10.35	0.05271	7.80
0.085	2.474	0.02525	16.01	0.04247	9.52	0.05638	7.17
0.063	2.602	0.02828	13.59	0.04760	8.07	0.06316	6.08

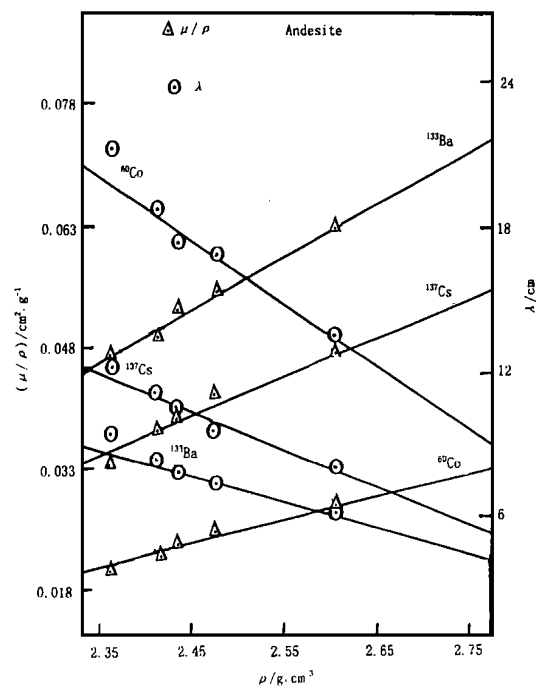


Fig.4 The relation between density $\rho(\text{g}/\text{cm}^3)$ of the compressed samples of andesite and both mass attenuation coefficient μ/ρ (cm^2/g) and relaxation length λ (cm)

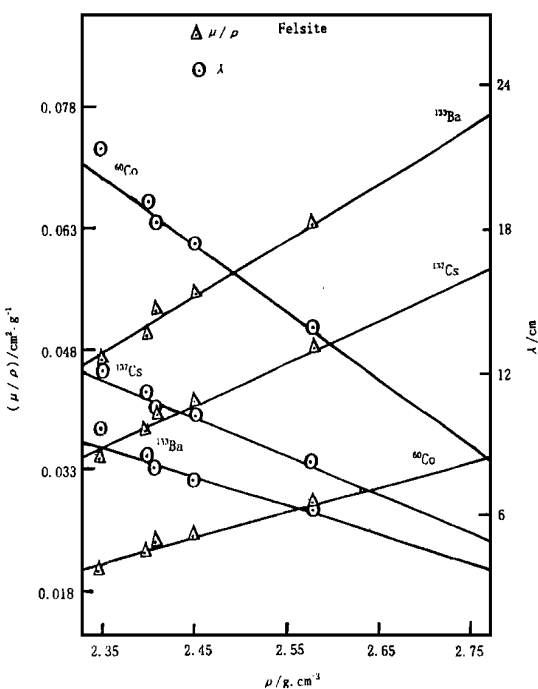


Fig.5 The relation between density $\rho(\text{g}/\text{cm}^3)$ of the compressed samples of felsite and both mass attenuation coefficient μ/ρ (cm^2/g) and relaxation length λ (cm)

Tab.2 Measured values of mass attenuation coefficients and relaxation lengths for felsite with different radiation sources

Grain diameter /mm	Density /g·cm ⁻³	⁶⁰ Co 1.33 MeV, 1.17 MeV		¹³⁷ Cs 0.661 MeV		¹³³ Ba 0.36 MeV	
		(μ/ρ)/cm ² ·g ⁻¹	λ /cm	(μ/ρ)/cm ² ·g ⁻¹	λ /cm	(μ/ρ)/cm ² ·g ⁻¹	λ /cm
0.17	2.345	0.01995	21.38	0.03356	12.71	0.04454	9.57
0.13	2.396	0.02200	18.97	0.03706	11.26	0.04921	8.48
0.095	2.406	0.02360	17.61	0.03970	10.47	0.05269	7.89
0.085	2.447	0.02443	16.73	0.04152	9.84	0.05637	7.25
0.063	2.575	0.02820	13.77	0.04757	8.16	0.06313	6.15

3.2 Half value layer

If a beam of gamma-rays impinges on a sheet of absorbing material, some of the radiation will pass through while others will be absorbed or scattered. As the thickness of the absorber increases, the fraction of radiation passing through will decreases. When exactly half of radiation passes through the absorber (The other half being absorbed or scattered), the thickness of the absorber is called the half value layer HVL or the half thickness $X_{1/2}$.

Since the intensity of radiation is reduced by 50% by passing through one HVL it will be reduced by another 50% or the only 25% of the original intensity in passing through a second HVL of absorber^[4].

From the plotted curves between radiation intensity and absorber thickness, the half value layer $X_{1/2}$, is determined. The relationship between the half value layer and the linear attenuation coefficient is as following

$$X_{1/2} = \frac{0.693}{\mu}$$

(4)

Tables 3,4 represent the Half value layers for andesite and felsite

Tab.3 Half value layers for powdered andesite

Grain diameter/mm	HVL/cm		
	⁶⁰ Co 1.33 MeV, 1.17 MeV	¹³⁷ Cs 0.661 MeV	¹³³ Ba 0.36 MeV
0.17	14.72	8.75	6.59
0.13	13.04	7.75	5.84
0.095	12.12	7.17	5.40
0.085	11.09	6.59	4.96
0.063	9.42	5.59	4.21

Tab.4 Half value layers for powdered felsite

Grain diameter/mm	HVL/cm		
	⁶⁰ Co 1.33 MeV, 1.17 MeV	¹³⁷ Cs 0.661 MeV	¹³³ Ba 0.36 MeV
0.17	14.81	8.80	6.63
0.13	13.14	7.80	5.87
0.095	12.20	7.25	5.46
0.085	11.59	6.82	5.02
0.063	9.54	5.65	4.26

3.3 Dependance of $X_{1/2}$ on grain size and photon energy

The half value layers $X_{1/2}$ for all samples were calculated from the relation ($X_{1/2} = 0.693/\mu$) and was determined from the curves ($\log I_o/I$, thickness X relation). The obtained values of $X_{1/2}$ were plotted versus the grain diameter d for all samples under investigation as in Fig.6.

It is shown that $X_{1/2}$ increases linearly as the particle diameter d increased. This relation could be represented by an empirical formula^[5]

$$X_{1/2} = Ad + c \quad 0.0635 < d < 0.17\text{mm}$$

(5)

Where c is a constant and A represents the rate of change of $X_{1/2}$ with d . The change of $X_{1/2}$ with d can be explained by the fact that as the grain diameter d increases the boundary surface area decreases, and the multiple scattering decreases, this leads to decrease the attenuation of the incident radiation inside the absorber $\mu = 0.693/X_{1/2}$ consequently the half value layer increases. Fig.6 shows a directly proportionality between

half value layer $X_{1/2}$ and photon energy.

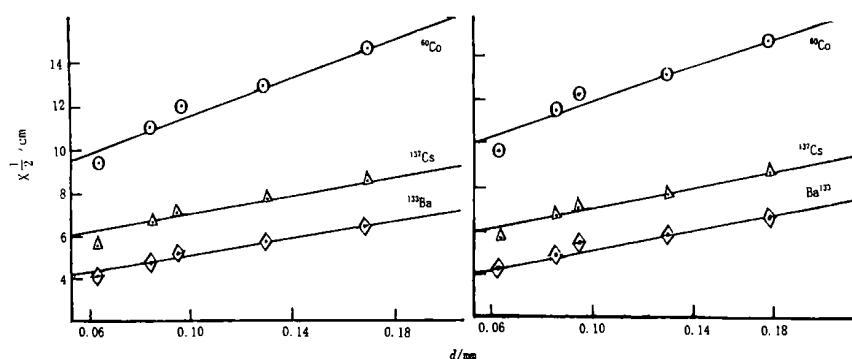


Fig.6 The relation between half value layer $X_{1/2}$ (cm) and grain diameter d (mm) of the compressed samples for both andesite and felsite

3.4 Flux distribution

All physical processes involving the emission of radiation sources and their subsequent transport through material are statistical; that is, one can not predict with certainty what will occur for every individual photon in the process. Nevertheless such random processes can be effectively characterized and predictions can be made by describing the average behavior of many particles. The gamma-ray flux distributions in andesite and felsite were measured along the beam direction. In addition, measurements were also performed to study the gamma-ray flux transmission in the perpendicular direction.

Assuming that the incident radiation was propagated along the x axis; the disc shaped samples would be in the $(Y-Z)$ plane. The intensity of penetrating radiation in the $(Y-Z)$ plane in high surface of samples is measured along the x axis at distances $x=$ zero (in the centre of samples), $x=0.75$ cm and $x=1.5$ cm. The relation between the side scattering radiation and the absorber thickness were plotted. To determine the suitable thickness and geometric shape of shields necessary to attenuate gamma-rays to certain required flux density, and to make the intensity of isoflux radiation in the $(Y-Z)$ plane in high surface of the absorber is equally in any point on its high surface equal I_0 , the intensity of radiation in the centre of sample.

The flux distribution function of radiation over the high surface of absorber is given by^[5]

$$\phi = \phi_0 e^{-\mu(E)x} \quad (6)$$

where $\phi_0 = S/(4\pi R^2)$ and ϕ is the radiation flux at any point on the $(Y-Z)$ plane of the absorber, ϕ_0 is the radiation flux in the centre of the absorber, μ is the linear attenuation coefficient of radiation for the absorber, x is the distance between the centre of sample and the point, where we want to determine the intensity of radiation flux.

From the Eq.(6) it is clear that ϕ depends on the position of the detector relative to the direction of incidence as well as on the energy of radiation. The flux distribution function of radiation is replaced by

$$Z = Z_0 e^{-\mu(E)x}$$

(7)

it is the function of curves in Fig.7 where ϕ and ϕ_0 are directly proportional to Z and Z_0 , respectively; Z is the suitable thickness of the absorber (at any point on the high surface) necessary to attenuate the intensity of gamma-ray to certain required flux density equal to the intensity of radiation in the centre of the absorber (I_0), Z_0 the suitable thickness of the absorber required to attenuate the intensity of radiation to I_0 and thus on the high surface of absorber at the centre ($x=0$). From the measured values of gamma-ray intensities at the high surface of absorber at $x=0$, $x=0.75$, $x=1.5$ cm and by using side scattering curves (which represent the relation between the scattered radiation and the absorber thickness), we can determined the values of Z at $x=0$, $x=0.75$, $x=1.5$ cm. The measured data for gamma-ray flux distribution in andesite and felsite are shown in Tables 5,6. This means that to attenuate gamma-radiation to a certain value, we must construct a shield with larger thickness in felsite than that in andesite.

Tab.5 The flux distribution in andesite

x/cm	Grain diameter d/mm				
	0.17	0.13	0.095	0.085	0.063
Absorber thickness of ^{60}Co in andesite* Z/cm					
0	2.87	2.63	2.40	2.18	1.75
+0.75	1.80	1.62	1.40	1.27	0.95
+1.5	0.53	0.45	0.40	0.33	0.20
-0.75	1.80	1.62	1.40	1.27	0.95
-1.5	0.53	0.45	0.40	0.33	0.20

*At 485 counts/min

Tab.6 The flux distribution in felsite

x/cm	Grain diameter d/mm				
	0.17	0.13	0.095	0.085	0.063
Absorber thickness of ^{60}Co in andesite* Z/cm					
0	3.37	3.00	2.80	2.52	2.15
+0.75	2.32	1.90	1.65	1.50	1.18
+1.5	0.60	0.52	0.45	0.35	0.25
-0.75	2.32	1.90	1.65	1.50	1.18
-1.5	0.60	0.52	0.45	0.35	0.25

*At 485 counts/min

3.5 Study of side scattering and determination of its coefficients

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 interactions with transported medium. The second component is composed of the collided or scattered

photons. These have undergone one or more interaction resulting in changes of direction or energy or both.

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

Measurement was taken at equal steps 1 cm apart. The detector was moved in a circular plane around the sample discs at 45° intervals and the average value of measured side scattering was taken. Three different parameters were investigated:

(1) The effect of radiation energy on side scattering using three different sources (^{60}Co , ^{137}Cs , ^{133}Ba). (2) The density of the absorber. (3) The effect of sample material.

The scattered radiation on primary ratio (I_s/I_o) is found to decrease exponentially along the extension of the absorber, where $I_s/I_o = \exp(-\phi_s t)$ where I_o is the intensity of initial radiation when $t=0$ cm and I_s the intensity of radiation after crossing t cm from the absorber, and t is the thickness of the absorber, ϕ_s is the side scattering coefficient. By using linear equation

$$\log \frac{I_o}{I_s} = 0.4343 \phi_s t$$

and drawing the relation between $\log I_o/I_s$ and t (cm), we calculated the side scattering coefficients ϕ_s for all samples where slope of straight line equals $0.4343 \phi_s$.

3.6 The relation between side scattering, material density and energy of radiation

The results of the relation between side scattering coefficient and the absorber density are shown in tables 7, 8, from which we notice the variation of ϕ_s with ρ as follows.

(1) The side scattering coefficient decreases linearly as density increases and this can be explained as follow :

There is a change in the sample density due to difference in grain size. This increase in the density increases the attenuation coefficient, which leads to a decrease in side scattering coefficient. Thus the empirical formula can be proposed

$$\phi_s = A\rho + B \quad \text{for } 0.0635 \leq d \leq 0.17 \text{ mm} \quad (8)$$

where A represents the rate of change of ϕ_s with ρ and B is a constant and depends on the kind of absorber.

(2) The side scattering coefficient 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 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 radiation energy with density of the absorber.

3.7 Dependence of the scattering coefficient on grain diameter

Side scattering coefficients depend on the grain diameter of the absorber. Tables 7 and 8 also list the relation between the grain diameter (d/mm) and side scattering coefficient for andesite and felsite, we find that as grain diameter decreases, the side scattering coefficients decrease linearly for the same source of radiation.

It has been shown that the side scattering coefficient varies with grain diameter according to the following empirical formula

$$\phi_s = ed + F \quad \text{for } 0.0635 \leq d \leq 0.17 \text{ mm}$$

(9)

where ϕ_s is the side scattering coefficient for absorber, d is the grain diameter, e represents the rate of change of ϕ_s with d and F is a constant and depends on the kind of absorber.

The behavior of side scattering coefficients with grain diameter (d/mm) can be explained as follows:

- (1) As the powder gets finer, the boundary surface area increase giving rise to multiple scattering. This increases the path of incident radiation inside the absorber. Hence the probability that a photon will be removed from the beam increases^[6] and consequently the side scattering coefficient decreases.
- (2) The compressed powdered absorber can be considered as a material containing small random voids between the grains, the random voids between the grains increase and lead to increase the side scattering coefficient. The random voids between grains become bigger at large grain diameter, so that the side scattering coefficient is directly proportional to the grain diameter.

Tab.7 Measured values of side scattering coefficients of andesite for different radiation sources

Grain diameter/mm	Density/g·cm ⁻³	ϕ_s/cm^{-1}		
		⁶⁰ Co	¹³⁷ Cs	¹³³ Ba
0.17	2.359	0.05395	0.04849	0.04021
0.13	2.410	0.05281	0.04746	0.03935
0.095	2.432	0.05233	0.04703	0.03900
0.085	2.474	0.05144	0.04632	0.03834
0.063	2.602	0.04891	0.04395	0.03645

Tab.8 Measured values of side scattering coefficients of felsite for different radiation sources

Grain diameter/mm	Density/g·cm ⁻³	ϕ_s/cm^{-1}		
		⁶⁰ Co	¹³⁷ Cs	¹³³ Ba
0.17	2.345	0.05428	0.04878	0.04046
0.13	2.396	0.05314	0.04760	0.03960
0.095	2.406	0.05290	0.04754	0.03943
0.085	2.447	0.05201	0.04674	0.03877
0.063	2.575	0.04944	0.04443	0.03685

4 Conclusion

Our main purpose of the present work is to construct a new type of shield to screen the major part of gamma-rays. We used for this ground samples from some igneous rocks, namely andesite and felsite with different grain sizes as 0.17, 0.13, 0.095, 0.085 and 0.063 mm. All our rock samples were pressed at 35ton/cm², to form tablets 3 cm in diameter, thickness ranging 0.85 to 1.95 cm, the used gamma sources were of energies ranging between 0.36 and 1.33 MeV (⁶⁰Co; ¹³⁷Cs and ¹³³Ba).

The similarities of gamma-ray propagation properties in andesite and felsite are due to similarities in their compositions. The observed differences were attributed to higher content of iron and other higher Z (atomic number) elements in andesite. Side scattering is shown to depend on the absorber density and on the energy of the radiation. Attenuation and scattering coefficients for the two natural rocks are close to the results for the compressed samples which have the smallest grain size used in this investigation. Half value layers $X_{1/2}$ were determined having a direct proportionality with both grain diameter " d " and photon energy " E ".

References

- 1 Schaeffer N M. Reactor Shielding for Nuclear Engineers, U.S Atomic Energy Commission, 1978, 455
- 2 Harwood H F, Hume W F. Bull Geol Soc Am, 1954, 65
- 3 Gameel Y H, Belal A A, El-Kamel A H. Indian J Pure Appl Phys, 1978, 16:62
- 4 CHASE, Rituper Sulcoski. In: Alpha ed. Experiments in Nuclear Science. Burgess Publishing Company, 1971
- 5 Hussein M M, M Sci thesis. Assiut University, Egypt, 1984
- 6 Abd El-Baset A M, M Sci thesis. Assiut University Egypt, 1983

γ 射线通过两类火成岩石材的衰减和散射

马赫茂德 阿尔米亚

(埃及庆纳,南谷大学理学院物理系)

摘要 由于发射 γ 射线的同位素在工业、农业和医学上许多新的应用,研究 γ 射线与物质相互作用变得日趋重要。定量研究了两类火成岩石材料:安山岩和霏细岩对 γ 射线的屏蔽效果。分别对天然的(整块割制)和(碎粒经)人工压制的石材样品,采用能量在 0.36—1.33MeV 范围的 γ 射线,测量了样品的岩粒粗细(石英颗粒直径)、石材厚度 $d(\text{mm})$ 和密度 ρ 诸因素对石材材料吸收 γ 射线的线性衰减系数 μ 、质量衰减系数 μ/ρ ,以及边缘散射系数 ϕ_s 3 个主要参数的影响。确定了在石材样品中射线的通量分布和半吸收层厚度 $X_{1/2}$ 。结果发现:石材的线性衰减系数 μ 对厚度 d 和 γ 射线能量 E 都有反比关系,而 μ 与样品密度 ρ 有正比关系;另一方面,石材样品的边缘散射系数 ϕ_s 却正比于 d 和 E ,而 ϕ_s 反比于 ρ 。

关键词 γ 射线(在吸收材料中)的衰减与边缘散射系数,火成岩石材;安山岩与霏细岩
中图分类号 O571.33