
Broad Beam and Gamma Spectrometric Parameters of Some Granites

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Abstract: Using a γ -ray spectrometer with 3"x3" NaI (Tl) detector the linear and mass attenuation coefficients (μ/ρ) and (μ_b/ρ) from narrow and broad beam experimental arrangements have been measured and compared with the theoretical values for the granites Double Black, DB, from India, Rose Al-Howdy, RH, from Aswan, south Egypt and Bianco Halayeb, BK, from Halayeb, south Egypt. The photon energies lie in the range 0.081-1.332 MeV from the radioisotopes ^{133}Ba , ^{137}Cs and ^{60}Co . The build-up factor B, the effective atomic number Z_{eff} , and the total atomic cross-section σ_t for the granites as a function of photon energy were determined and discussed. It is found that the experimental results are consistent, within the experimental errors, with the theoretical values. The effective atomic number Z_{eff} , the build-up factor B, and the total atomic cross-section σ_t were calculated and discussed as a function of photon energy. The B factor is large at low gamma energy and not sensitive for discrimination between the granites. The maximum Z_{eff} corresponds to minimum B factor at the photon energy 0.356 MeV. The broad beam geometry is more efficient than narrow beam geometry in characterizing the shielding properties of the studied granites.

Keywords: Gamma-ray Spectrometry, Radiation Protection, Mass Attenuation Coefficients, Build-up Factor, Effective Atomic Number, Total Atomic Cross-section

1. Introduction

Everything in our environment is exposed to ionizing radiation from different sources like radioactive materials and cosmic radiation. Efforts are undertaken to possibly reduce the resulting harms. Protection against hazards of gamma radiation is of absolute mandatory. Therefore, studies and investigations are conducted to measure and evaluate the gamma spectrometric quantities of materials used in many fields as industry, medicine, biology, dosimetry, shielding, ...etc. Granite and basalt are used as shielding and building materials owing to the massive nature and homogeneous grains. Granite is eminently adapted for monumental and architectural work as well as for massive masonries. The linear and mass attenuation coefficients from narrow and broad radiation beams, respectively (μ), (μ_b) and (μ/ρ), (μ_b/ρ), the build-up factors B, the effective atomic numbers Z_{eff} and the total atomic cross-section, σ_t , are proudly used parameters in this respect.[1-3] The trend of Z_{eff} with respect to the energy inverts from decrease to increase

and vice versa according to the ranges of photon energy and the atomic number of the material. [4-6] Organic nonlinear optical materials of Z_{eff} in the range 3-5 follow slight decrease with E_γ from 0.122 to 1.332 MeV. [6] Expressions for Z_{eff} in the photo-electric, the Compton and the pair production regions in terms of the atomic numbers in a composite material were proposed and applied. [7] Values of $Z_{\text{eff ph}}$, $Z_{\text{eff Compton}}$ and $Z_{\text{eff pair}}$, were reported for each material and each energy under study. The photon attenuation by matter at the energy range below 100 keV is prevailed by the photo-electric effect. The cross-section for this process is proportional to the atomic number of the attenuator and the gamma energy according to the relation (Z^n/E_γ^m) , n and m vary from 3 to 5. The Compton interaction prevails at the energy range 0.1-1 MeV this interaction is proportional to the atomic number of the material. At energies ≥ 1.022 MeV interaction between photons and the material atoms by pair production shares with the Compton scattering, furthermore its probability appreciably ascends with energy besides the square of the atomic number. If there is no good collimation

of beam-area exposure, significant dose will consequently be absorbed, where impact of single and multiply scattered photons is possible. Radiation absorption characteristics of rocks collected from Jeddah, Mecca, Mina, and Taif areas have been studied. Most of the rocks show higher radiation attenuation than standard concrete. Only granites were found to be equivalent to concrete. [8] The linear and mass attenuation coefficients of gamma rays transmitted through granites of different countries were studied in the energy range 0.081-1.332 MeV. [9] It was concluded that the linear attenuation coefficients are appropriately correlated with the material density. Moreover, the mass attenuation coefficients are larger for materials of large atomic numbers. Various Turkish granites and marble species were investigated via measuring (μ), (μ/ρ) the half value layer and the tenth value layer, at the energy region 80.99 keV to 1.332 MeV using HPGGe detector, the results were compared with literature. [10] The density of hydrous peridotite magma containing 5% wt. H₂O was measured at pressures and temperatures up to 4.3 GPa and 2073-degree K, respectively, using the X-ray absorption method. [11] The transmission of X-rays in the energy range 0.081-1.332 MeV was studied on alloys brass, bronze, steel, aluminum-silicon, and lead-antimony. The mass attenuation coefficients were measured, the atomic cross-sections and the effective atomic numbers were determined. [4] The shielding parameters of rocks and concrete were studied in the energy range 0.122 -1.332 MeV. [12] The results showed that feldspathic basalt, volcanic rock dolerite, and pink granite are more efficient than sandstone and concrete for gamma-ray shielding applications. The effect of scattered photons on the accuracy of measured (μ/ρ) for low Z-building materials was investigated. [13] It was concluded that good accuracy in (μ/ρ) measurement can be achieved if the absorber optical thickness does not exceed 0.5 the mean free path. The shielding properties of granites which are produced in Turkey were studied for linear and mass attenuation coefficients of gamma rays at the energies 0.611, 1.173 and 1.332 MeV using NaI (TI) detector. [14] The measurements were carried out in narrow and broad beam geometries. It was concluded that the highest linear attenuation coefficient belongs to Canakkale Grey, Giresun Vison and Akasari Pink at 0.662, 1.173 and 1.332 MeV respectively while Bergama Grey has the lowest values. The experimental results are close to the values computed by XCOM code. [15]

In the present study (μ) and (μ/ρ) were measured from narrow and broad beam geometries for the Egyptian granite types Bianco Halayeb, and Rose El-Howdy, Aswan, and Indian Double Black granite at the energies 0.081, 0.356, 0.662, 1.173 and 1.332 MeV. These types of granites are widely used as materials for building and decoration. The results were compared with theoretical values. Comparisons between the granites besides the narrow and broad beam geometries were also undertaken via evaluation of the build-up factor B, the effective atomic number Z_{eff} and the total atomic cross-section σ_t .

2. Theoretical

When the narrow (parallel) beam of γ or X-rays transmitted through a material, attenuation by absorption and/or scattering occurs. The relation between the incident and scattered photons is described by the relation,

$$I = I_0 e^{-(\mu/\rho)t} \quad (1)$$

I_0 and I are the un-attenuated and attenuated photon intensities. ρ and t are respectively the density and thickness of the material, see figure 1. By revealing the collimator between the source and the detector, the set-up is applied as broad beam (or open-angle) geometry. The build-up in scattered intensity can be expressed as

$$B = \frac{I_b}{I} = e^{[(\mu/\rho) - (\mu_b/\rho)]t} \quad (2)$$

I_b stands for the broad beam intensity measured at the same conditions. The B factor comprises the mutual effects originated from the experimental arrangement, the attenuating material, (density, atomic number, etc.) and the energy of the incident photons.

The effective atomic number Z_{eff} is the ratio between the atomic and electronic cross-sections. It is used to describe the properties of composite material in terms of (μ/ρ) and its constituents. It obeys the relation stated in [16].

$$Z_{\text{eff exp}} = \frac{(\mu/\rho)_{\text{Granite}} \sum_i f_i A_i}{\sum_i f_i (A_i/Z_i) (\mu_i/\rho)} \quad (3)$$

In this regard, $Z_{\text{eff th}}$ can be determined from the expression,

$$Z_{\text{eff th}} = \frac{(\mu/\rho)_{\text{th}} \sum_i f_i A_i}{\sum_i f_i (A_i/Z_i) (\mu_i/\rho)} \quad (4)$$

Where $f_i = n_i / \sum_j n_j$, and (μ_i/ρ) represent respectively the fractional abundance and mass attenuation coefficient of the i^{th} element in the attenuator. The effective atomic numbers Z_{eff} for the attenuators used have been calculated based on the XCOM results.

The total atomic cross-section σ_t obeys the formula, [17]

$$\sigma_t = \frac{(\mu_n/\rho)_{\text{Granite}}}{N_A \sum_i (w_i/A_i)} \quad (5)$$

N_A is the Avogadro's number,

w_i and A_i are respectively the weight fraction and the mass number of the element i .

Error calculation

The errors in (μ/ρ) and Z_{eff} in terms of the measured values are calculated according to the following expressions

$$\left(\Delta \mu/\rho\right) = (1/t) \left\{ \left(\Delta I_0/I_0\right)^2 + \left(\Delta I/I\right)^2 + \left[\ln\left(I_0/I\right)\right]^2 \left(\Delta t/t\right)^2 \right\}^{1/2} \quad (6)$$

ΔI_0 and ΔI are the standard deviations of the number of counts without and with the material. [18] The errors are less than 6%.

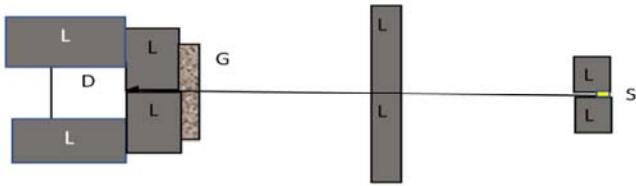
The error in the σ_t obeys the relation, [4]

$$\Delta\sigma_t = \frac{(\Delta\mu_n/\rho)_{Granite}}{N_A \sum_i W_i/A_i} \quad (7)$$

$$\Delta Z_{eff} = \frac{(\Delta\mu/\rho)_{Granite} \sum_i f_i A_i}{\sum_i f_i (A_i/Z_i) (\mu/\rho)_i} \quad (8)$$

3. Materials and Methods

The γ -ray spectrometer consists of 3"x3" NaI (Tl) detector attached to 1024 channel analyzer. The experimental set-up is illustrated in figure 1. The gamma line 1.463 MeV from ^{40}K was employed as a natural monitor to ensure detection stability. The linear and mass attenuation coefficients (μ) and (μ/ρ) are measured at the energies 0.081, 0.356 from ^{133}Ba , 0.662 MeV from ^{137}Cs and 1.173, 1.332 MeV from ^{60}Co . The granites studied are basalt- peridotite granite, (double black, DB) from India, alkali feldspar (Rose Al-Howdy, RH) from Aswan and Tonalite from Halayeb (Bianco Halayeb, BH). Halayeb and Aswan exist in the southern province of Egypt. The densities and thicknesses of the DB, RH, and BH sheets are respectively, (3.1 gcm^{-3} , 1.9 cm), (2.56 gcm^{-3} , 1.8 cm) and (2.66 gcm^{-3} , 1.85 cm). The activities of the γ -sources ^{137}Cs and ^{60}Co are 580 and 180 μ Ci respectively. The source-detector distance is 50 cm. In the case of ^{133}Ba this distance was reduced to 13 cm. The broad beam measurements were performed with only the collimators around the source and the detector.



S, Source, D, Detector, G, granite, L, Lead Shield.

Figure 1. The experimental set-up.

The results of the mass attenuation coefficients were measured in narrow and broad beam geometries and indicated as (μ/ρ) and (μ_b/ρ) respectively. The results were compared with the values obtained from the theoretical XCOM program [15] according to a worldwide average of the chemical composition of 2485 granites, see table 1. [19] Other references do not show significant differences from this chemical composition. i), [20, 21].

Table 1. The Chemical composition of granites.

SiO ₂	72.04% (silica)
Al ₂ O ₃	14.42% (alumina)
K ₂ O	4.12%
Na ₂ O	3.69%
CaO	1.82%
FeO	1.68%
Fe ₂ O ₃	1.22%
MgO	0.71%
TiO ₂	0.30%
P ₂ O ₅	0.12%

The corresponding elemental composition according to XCOM program is given in Table 2.

Table 2. The elemental analysis of granite.

Element	Fraction by Weight
Z=8	0.484913
Z=11	0.027454
Z=12	0.004294
Z=13	0.076540
Z=14	0.337720
Z=19	0.034302
Z=20	0.013045
Z=26	0.021733

4. Results and Discussion

4.1. The Linear and Mass Attenuation Coefficients

The values of (μ_b), (μ) as a function of E_γ for all granites are plotted in figure 2. Figures 3-5 show (μ_b), (μ) (μ_b/ρ) (μ/ρ) and (μ_{th}/ρ) as a function of energy for all granites. It is obvious from the figures that the attenuation coefficients decrease with increasing photon energies. Generally, there is good agreement between the experimental and theoretical values of the mass attenuation coefficients. It is clear that μ_b and μ at DB >BH>RH for all photon energies. The high density of BD let its (μ_b/ρ) becomes less than (μ_b/ρ) for each of BH and RH. The (μ/ρ) values are comparable for the three granites. Consequently, (μ) can provide clearer discrimination between granites, as a shielding material, than (μ/ρ), see also [9] and [14]. This can be correlated with the atomic numbers of the constituting atoms and the experimental set-up. The photo-electric effect is proportional to $Z^n/E_{\gamma^{3.5}}$, $n=4-5$. The Compton interaction is proportional to Z and the pair production is proportional to $Z^2 f(E_\gamma, Z)$.

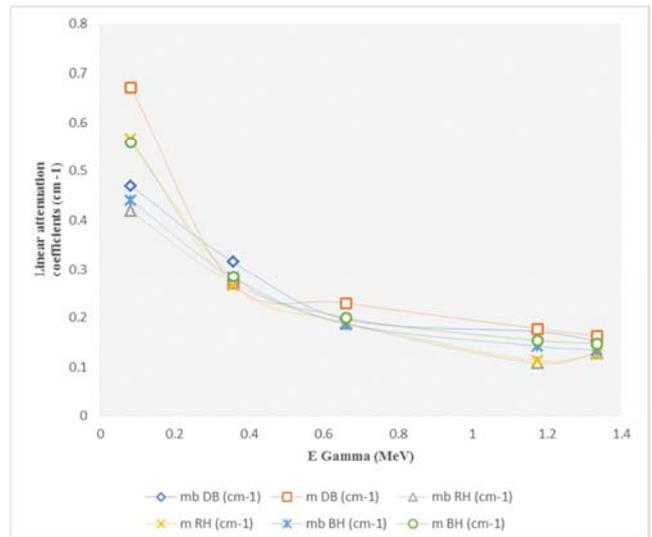


Figure 2. Linear narrow and broad beam attenuation coefficients for Double Black, Rose Al-Howdy and Bianco Halayeb granites.

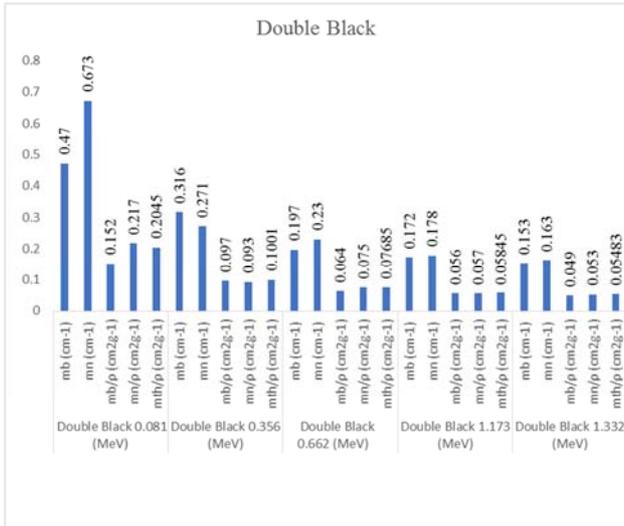


Figure 3. Linear and mass attenuation coefficients for broad and narrow beam geometries for Double Black granite.

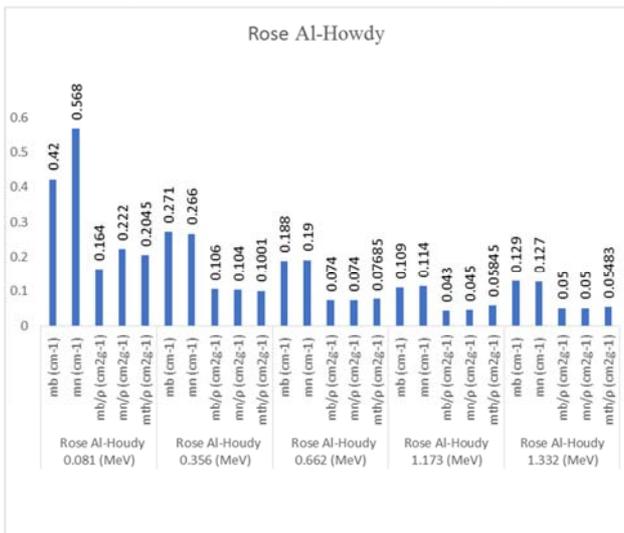


Figure 4. Linear and mass attenuation coefficients for broad and narrow beam geometries for Rose Al-Howdy granite.

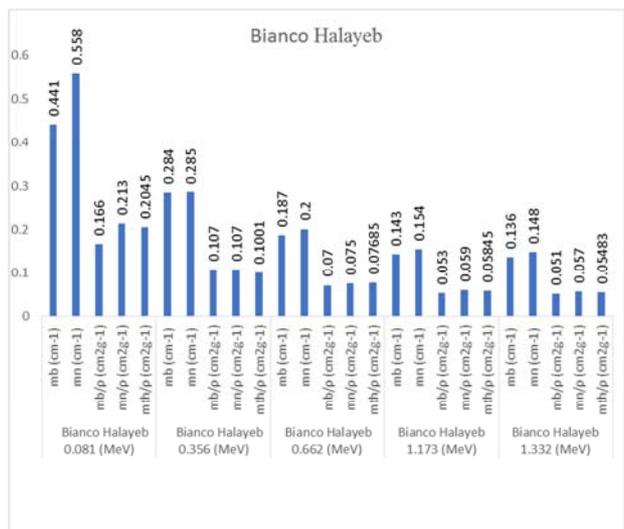


Figure 5. Linear and mass attenuation coefficients for broad and narrow beam geometries for Bianco Halayeb granite.

At the photon energies 0.081 and 0.662 MeV the linear attenuation coefficients (μ) for DB=0.673 and 0.23 cm⁻¹ respectively. These values are comparable with (μ) of metabasalt (density=2.98 gcm⁻³) which are respectively 0.7513 and 0.216 cm⁻¹ at these two energies. [8] Furthermore, the metabasalt and the DB in the present study have the largest values of (μ) in the rocks and granites studied. According to the values of (μ) and (μ/ρ), the DB granite is suggested as the best shielding material, at $E_\gamma < 0.3$ (MeV), while the RH and BH granites have nearby shielding properties. It might be of benefit to indicate that the values of (μ) at photon energies 0.662, 1.173 and 1.332 MeV for Turkey granites lei in the ranges 0.148-0.341, 0.133-0.168, 0.129-0.158 cm⁻¹ respectively. [14] To interpret for the large decrease of the attenuation coefficients from 0.081 to 0.356 MeV and smaller decrease at larger energies the ratio of attenuation by photo-electric effect to Compton scattering at $E_\gamma=0.81, 0.356, 0.662, 1.173$ and 1.332 MeV is respectively $\approx 3.86 \times 10^{-1}, 3.96 \times 10^{-3}, 9.8 \times 10^{-4}, 3.69 \times 10^{-4}$ and 3.16×10^{-4} and the ratio of attenuation by pair production to Compton scattering at 1.332 MeV is also $\approx 10^{-3}$. [15, 19] It is obvious that the contribution of the photo-electric effect to the total mass attenuation coefficient is significant at the energy 0.081 MeV and appreciably decreases at larger energies. This can also be employed to interpret the changes of the total atomic cross-sections σ_t , see section 4, from the energy 0.081 MeV to the larger energies. The mean atomic number $\langle Z \rangle$ for the studied granites according to table 1 is 11.452.

4.2. Build-up Factor

The values of (μ/ρ) and (μ_b/ρ) are employed to determine the build-up factor B according to equation (2), Table 2 where the values of the mass attenuation coefficients are the measured broad beam value and the theoretical value from XCOM, [15, 19]. Table 3 lists the obtained values of B.

Table 3. The build-up factor for Double Black, Rose Al-Howdy and Bianco Halayeb granites.

E_γ (MeV)	B DB	B RH	B BH
0.081	1.105	1.076	1.074
0.356	1.008	0.989	0.987
0.662	1.004	1.006	1.012
1.173	1.005	1.009	1.010
1.332	1.011	1.007	1.007

General trends for the build-up factor B show that B has largest values at $E_\gamma=0.081$ MeV, drops to get no scattering build-up ($B \approx 1$) at $E_\gamma=0.356$ MeV then B is recovered to slightly exceed unity at larger energies. As mentioned above, the granites studied have thicknesses in the range 1.8-1.9 cm, which corresponds to ≈ 0.2 mean free path, mfp of the 0.356 MeV photons. This thickness can, consequently, be considered as the depth of maximum absorbed dose for this photon energy. At $E_\gamma=0.081$ and 0.356 MeV the B factor is relatively large at DB with comparison to RH and BH. The experimental errors at $E_\gamma > 0.356$ MeV inhibit showing accurate dependence of B on the elemental composition of the granites. In this

regard the (μ/ρ) was studied for low Z-building materials in the energy range 0.661- 1.332 MeV. [13] It was concluded that the sample thickness can be kept below 0.5 mfp to achieve accurate (μ/ρ) . The minimum of B at the energy 0.356 MeV means that (μ_b/ρ) is maximum in this case. This might lead to the conclusion that the photon energy absorbed in the 1.8-1.9 cm thickness granites fm 0.356 MeV photons is maximum.

4.3. Effective Atomic Number

Table 4 lists experimental and theoretical values of Z_{eff} as a function of gamma energy for the studied granites, according to the experimental results and equations (3) and (4).

Table 4. Effective atomic numbers for Double Black, Rose Al-Howdy and Bianco Halayeb granites and the Compilation from [19].

E_γ (MeV)	Z eff exp DB	Z eff exp RH	Z eff exp BH	Z eff th
0.081	12.00	12.276	11.779	11.284
0.356	10.951	12.207	12.558	11.749
0.662	11.2056	11.071	10.489	11.466
1.173	11.247	10.757	11.502	11.472
1.332	11.004	10.377	11.841	11.471

It is found that $Z_{\text{eff exp}}$ is maximum at $E_\gamma=0.081$ and 0.356 MeV. Generally, except a slight decrease with increase in photon energy, the effective atomic numbers Z_{eff} for the three granites has no significant change with respect to energy and show consistency with the theoretical values. At the other energies Compton photon interaction dominates, therefore (μ/ρ) and Z_{eff} remains almost constant. These results agree with [5], where the variation of Z_{eff} for eight alloys, over wide ranges of atomic numbers and photon energy, was studied. It was concluded that in all alloys Z_{eff} increases in the low energy region to a maximum value and becomes independent of energy. Bronze aluminum (90% copper and 10% aluminum) has maximum $Z_{\text{eff}} \cong 27.6$ at $E_\gamma \cong 0.7$ MeV. In present results, Z_{eff} has maxima $\cong 12$ at $E_\gamma \cong 0.081$.

4.4. Total Atomic Cross-section

Table 5 and figure 6 display the experimental and theoretical values of σ_t for DB, RH and BH in the energy range 0.081- 1.332 MeV. Generally, σ_t tends to decrease with the increase of photon energy. The rate is rapid at $E_\gamma=0.081-0.356$ MeV. This result is correlated with the predomination of the photo-electric effect at low values of E_γ . Consequently, the contribution of the photo-electric cross-section, σ_{photo} to σ_t increases at low photon energy. From the XCOM analysis [15], the photo-elctric effect is comparable to Compton contribution at $E_\gamma=0.081$ MeV for all granites. At $E_\gamma>0.081$ MeV, the Compton interaction between the photons and granite atoms prevails. At $E_\gamma>0.356$ MeV σ_t continues decreasing but with smaller rate. Furthermore, the differences between granites become smaller.

Table 5. Total atomic cross-sections (in barns/atom) for Double Black, Rose Al-Howdy and Bianco Halayeb granites.

E_γ (MeV)	$\sigma_{t \text{ exp DB}}$	$\sigma_{t \text{ exp RH}}$	$\sigma_{t \text{ exp BH}}$	$\sigma_{t \text{ th}}$
0.081	7.479	7.651	7.341	7.048
0.356	3.215	3.5847	3.687	3.449
0.662	2.588	2.558	2.423	2.650
1.173	1.975	1.889	2.019	2.015
1.332	1.813	1.709	1.959	1.897

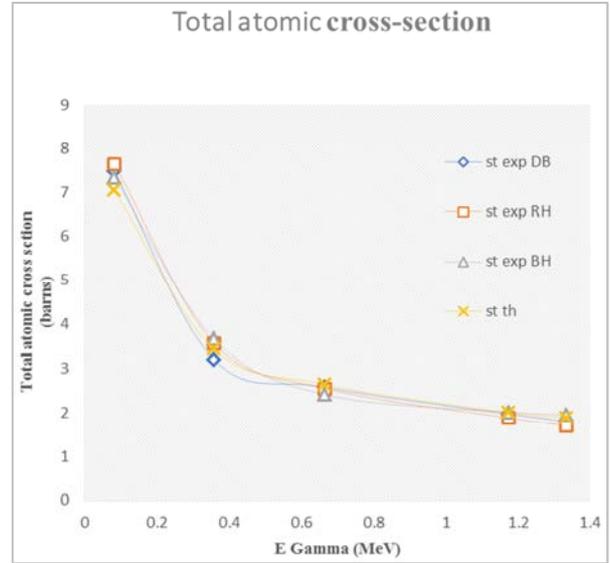


Figure 6. The total atomic cross-section.

5. Conclusions

Gamma spectrometric parameters of DB, RH and BH granites have been determined from narrow and broad beam geometries. The theoretical mass attenuation coefficients (μ_{th}/ρ) were calculated using the XCOM program based on chemical analysis for granites. The attenuation coefficients decrease with increase in photon energy. The broad beam geometry is more efficient than narrow beam geometry in characterizing the shielding properties of the studied granites. The experimental values of (μ/ρ) agree, within the experimental errors, with the theoretical values. The B factor has maximum values at $E_\gamma=0.081$ and minimum values ($\cong 1$) at $E_\gamma=0.356$ MeV then increases slightly over 1 in the studied energy region. The B factor can't discriminate between the granites. The maximum Z_{eff} corresponds to minimum B at photon energy 0.356 MeV. The enhancement of the photo-electric effect on shielding properties exists in B and σ_t , especially at $E_\gamma=0.081$ MeV. The total atomic cross-section decreases with increase in photon energy, at the energy region 0.081-0.356 MeV.

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