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Factors Affecting Gamma Ray Transmission

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Abstract: Gamma ray transmission and the parameters which affect this process; attenuation coefficients, cross-sections, effective atomic numbers and electron densities, were studied for brass, Fe, Al, PVC and Perspex, using gamma spectroscopy. The comparison between experimental and theoretical values is made; these are found to be in good agreement. The inverse relations between energy and attenuation coefficients, as well as cross-sections were emphasized. In the energy range (661.6 keV-1332.5 keV), the effective atomic numbers showed a constant behavior with energy. Brass shows up as a good attenuating material, while other samples are relatively weak attenuators. The effect of the composition of the compound appears obviously in this study.

Keywords: Attenuation coefficients (linear and mass); Cross-sections; Effective atomic number; Electron density.

Introduction

Increasing the use of gamma active isotopes in support of application, makes the study of the absorption and interaction of gamma radiation in materials an important research field. The photon attenuation coefficients (linear and mass attenuation coefficients), effective atomic number and electron density are basic quantities required in determining the attenuation of X-rays and gamma photons in matter.

The purpose of this research is studying the factors which affect gamma ray transmission in different methods. The comparison between different methods and between experimental and theoretical values for each factor is made.

The importance of the attenuation of photons has prompted many investigators to measure the attenuation coefficients, effective atomic number and electron density by employing different methods. Some of these factors are determined for alloys [1-3], amino-acids [4-5], thermo-luminescent dosimetrics (TLD) [6], superconductors [7] and building materials [8]. Other used X-ray to determine the effective atomic numbers of materials of dosimetric interest at energies 1-20 keV [9]. Another paper reports a comprehensive set of formulae for calculating the effective atomic numbers and electron densities for all types of materials and for energies above 1 keV [10]. Some investigators defined the previous parameters, and further they found a quantity called effective atomic weight which they defined as the ratio of the molecular weight of a sample to the total number of atoms of all types composing it. A new effective atomic number relation has been evolved [11]. Also, variation method and Compton scattering are two different methods used to calculate the effective atomic number [12].

In this work, the transmission factors; linear and mass attenuation coefficients, effective atomic numbers, cross-sections and electron densities are studied for five different kinds of samples, which are pure elements (Al, Fe), thermoplastic (Perspex, PVC) and alloy (Brass), by using gamma ray spectroscopy.

The linear attenuation coefficients of the samples are determined by the transmission

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experiments as a Non-destructive testing method, under a good geometry condition (collimated gamma ray transmission method).

As a photon makes its path through a matter, there is a probability that it makes an interaction with the material such as absorption (photoelectric effect), scattering (Rayleigh or Compton scattering) or splitting (pair production). Therefore, part of the incident beam of intensity (I_o) will be partially or completely removed from the beam as a result of interaction(s) within the absorber of thickness x. This reduces the transmitted intensity that reaches the detector to (I), where, introducing μ, the linear attenuation coefficient, the transmitted intensity is given by;

$$I(x) = I_o \exp(-\mu x) \tag{1}$$

This is called the Beer-Lambert law, where μ measured in units of length^{-1} describes the probability of absorption or scattering occurring per unit length within the absorber material [13]. The exponential means that equal thickness of the absorber attenuates the photon beam by an equal fraction or percentage [14].

μ is also called the total attenuation coefficient due to the contribution of different effects in the attenuation process. Hence, the total attenuation coefficients may be expanded as:

$$\mu = \omega + \tau + \sigma + \kappa + \pi \tag{2}$$

where, ω: the probability of coherent scattering, τ: the probability of photoelectric absorption, σ: the probability of Compton scattering, κ: the probability of pair production and π: the probability of photodisintegration.

Therefore:

$$\left.\begin{aligned}\exp(-\mu x) = \exp(-\omega x) + \exp(-\tau x) \\ + \exp(-\sigma x) + \exp(-\kappa x) \\ + \exp(-\pi x)\end{aligned}\right\} \tag{3}$$

To overcome the dependence of the linear attenuation coefficient on the absorber density (ρ), it is normalized by the absorber density. Hence, the mass attenuation coefficient is defined as;

$$\mu_m = \mu / \rho \tag{4}$$

Using μ_m instead of μ, equation (1) becomes:

$$I(x) = I_o \exp(-\mu/\rho)\rho x \tag{5}$$

In the case of a compound of various elements, it is assumed that the contribution of each element of the compound to the total photon interaction is additive, obeying the well-known mixture rule and it is also called Bragg law. Therefore, the mass attenuation coefficient for the compound can be written as:

$$(\frac{\mu}{\rho})_{mix} = \sum_i w_i (\frac{\mu}{\rho})_i \tag{6}$$

where w_i is the weight fraction of the element i ($w_i = a_i A_i / \sum a_j A_j$; here A_i is the atomic mass of the ith element, and a_i is the number of atoms of this element in the compound), $(\mu/\rho)_i$ is the mass attenuation coefficient for element i.

Berger and Hubbell developed XCOM, for calculating mass attenuation coefficients or photon interaction cross-sections for any element, compound or mixture, at energies from 1 keV to 100 GeV [1].

The cross-section can be defined as the probability of an interaction to occur, it has the dimension of area in units of barn abbreviated $b = 10^{-28}\,m^2 = 10^{-24}\,cm^2 = 100 fm^2$.

There are different kinds of cross-sections; atomic, molecular and electronic cross-sections, the atomic cross-section for an element of atomic weight A is given by:

$$\sigma_a = \frac{\mu}{\rho}\frac{A}{N_{av}} \tag{7}$$

N_{av} represents the Avogadro's number.

For a compound the molecules of which have n_i atoms for the i-th element, the atomic or molecular cross-sections are given by:

$$\sigma_a = \frac{\mu}{\rho}\sum_i \frac{n_i A_i}{\sum n_i}\frac{1}{N_{av}} \tag{8}$$

The electronic cross-section for an element is given by:

$$\sigma_e = \frac{\sigma_a}{Z} \tag{9}$$

Hence, for the compound, the electronic cross-section is:

$$\sigma_e = \frac{1}{N_{av}}\sum_i (\frac{f_i A_i}{Z_i})(\frac{\mu}{\rho})_i \tag{10}$$

where f_i (= $n_i/\sum n_j$) is the fractional abundance of element i, with respect to the total number of atoms. Z_i is the atomic number of the element.

The effective atomic number (Z_{eff}) is a property for a compound, it describes the properties of the composite materials in terms of equivalent elements, it represents the weighted average atomic number of the compound composed of different materials, the average is weighted according to the relative number of each type of atom, Z_{eff} value of a material varies within a range with lowest and highest atomic numbers of its constituent elements [7].

The effective atomic number is equal to:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} = \frac{\sum_i n_i \sigma_i}{\sum_i n_i \frac{\sigma_i}{Z_i}} = \frac{\sum_i f_i A_i (\frac{\mu}{\rho})_i}{\sum f_i \frac{A_i}{Z_i} (\frac{\mu}{\rho})_i} \quad (11)$$

The electron density can be defined as the number of electrons per unit mass, and it can be mathematically written as:

$$N_{el} = \frac{(\frac{\mu}{\rho})_c}{\sigma_e} \quad (12)$$

where N_{el} represents the electron density in unit of electron/gram, $(\mu/\rho)_c$ is the compound mass attenuation coefficient and σ_e is the electronic cross-section.

Experimental Procedure:

Transmission experiments with the narrow beam (good-geometry) setup were used for measuring the incident and transmitted intensities, and hence calculating the attenuation coefficient. Further calculations of the cross sections (atomic, electronic and molecular), effective atomic numbers and electron densities were performed.

Two gamma sources were used in these experiments so that the above parameters were studied at three different energies. Table 1 displays the properties of the gamma sources used in this experiment.

The five sample materials were shaped each in five square slices, for measuring the attenuation, these five slices are stacked one by one on the detector, the intensities of the transmitted photons were determined by choosing the counting time as 100 minutes, counts were recorded under the photo peaks, ad statistical uncertainty was kept as low as possible, Henceforth, different thickness is achieved each time. The dimensions of the samples were measured with a vernier caliper. Then the samples were weighted with a digital balance, and the density was calculated.

TABLE 1. The gamma source description.

Gamma-ray source	Half-life (days)	Activity (μCi) (Production date 1999)	Energy (MeV)	Count rate at aperture (count/sec)
^{137}Cs	11012	0.9508	0.6616	12.2
^{60}Co	1923	1.016	1.173	9.0
^{60}Co	1923	1.016	1.332	9.0

TABLE 2. The sample description.

Sample	Chemical composition	Dimensions (cm) Length ×Width ×Thickness	Average mass (g)	Average density (g/cm^3)
Aluminum	Al	3.95 × 5.69 × 0.51	30.75	2.68 ± 0.016
Perspex	$C_5H_8O_2$	5.17 × 5.07 × 0.45	13.31	1.12 ± 0.022
PVC (Poly-Vinyl Chloride)	C_2H_3Cl	5.08 × 5.03 × 0.51	17.61	1.34 ± 0.014
Iron	Fe	5.00 × 5.00 × 0.20	37.45	7.49 ± 0.34
Brass	Cu_3Zn_2	5.10 × 5.11 × 0.21	43.73	7.85 ± 0.36

The experiment was performed at the Radiation Measurement Laboratory at Al- Balqa Applied University. The gamma rays are well collimated using two collimators; one at the source and the other at the detector. Each of the collimators has a cylindrical shape and a circular aperture. The signal is detected by NaI (Tl) scintillation detector of a (3×3 inch) crystal and a high bias voltage of 1000 volts. A lead shield surrounds the detector to reduce the undesired external radiation. Fig. 1 below shows the system setup, the source collimator and the lead shield in which the detector is embedded.

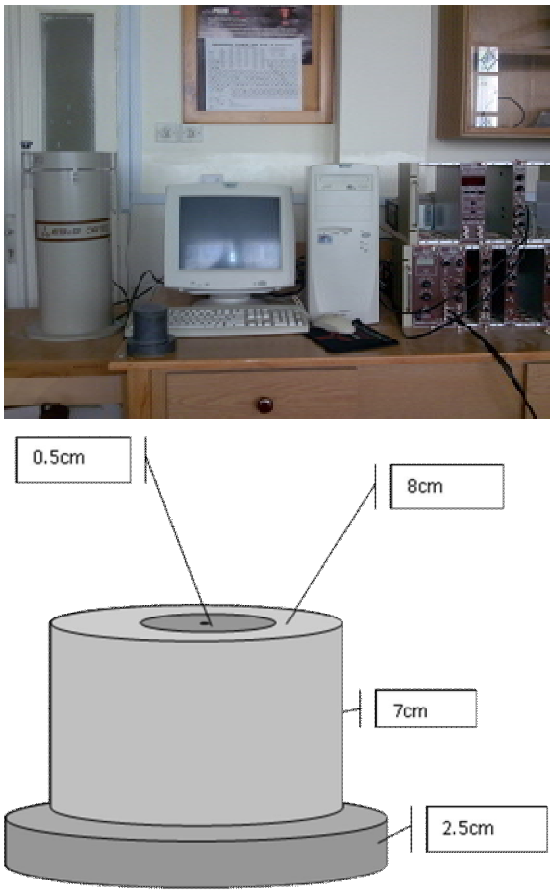


FIG. 1. The experimental setup and the source collimator dimensions.

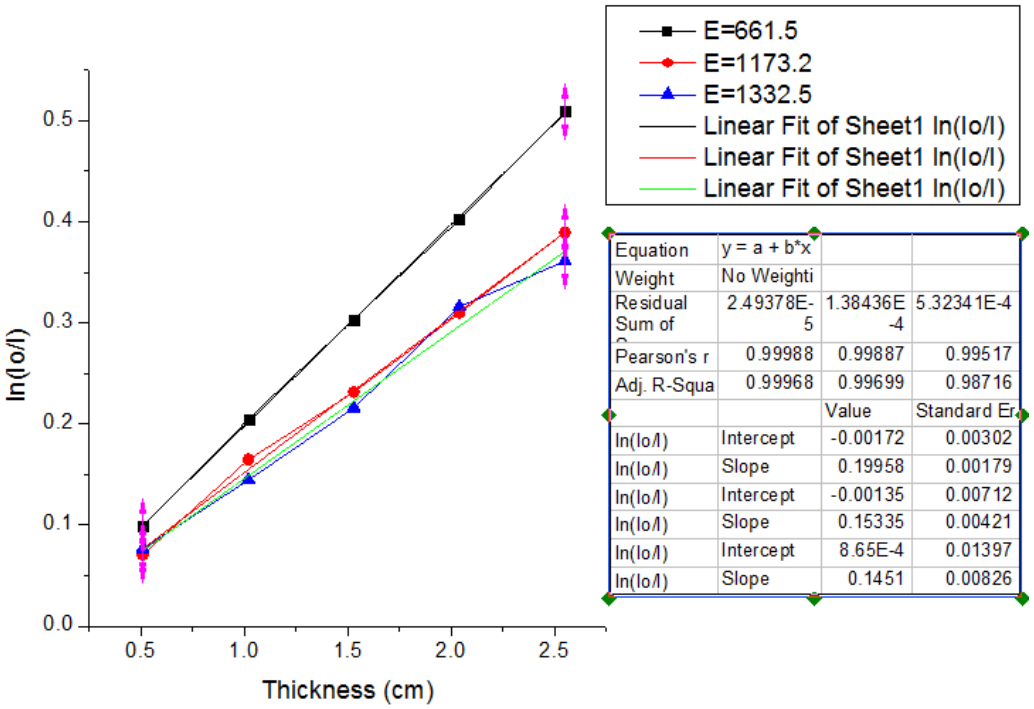
The weak detector pulse enters the preamplifier (or preamp.). The pulse then enters the linear amplifier which has two main functions; pulse shaping and amplitude gain, for which the multi-channel analyzer has been designed. The amplified pulse is then fed to the Multi-Channel Analyzer (MCA), which converts the analog signal into a digital number through an analog to digital converter (ADC), in this case the software is used to control the MCA functions and other settings, in this experiment Senti-vision was used to analyze the spectrum. The energy and the efficiency of the system were calibrated using a certified standard source from the International Atomic Energy Agency (IAEA).

Results and Discussion

The linear attenuation coefficient quantity (μ) is determined by measuring the incident photons intensity (I_0) and the intensity (I) of the photons after passing through samples with thickness (x), a graph of $\ln(I_0/I)$ versus thickness (x) is drawn, a linear relation appears, each linear graph is fitted by linear fit method, the slope of the linear fit equation represents the value of the linear attenuation coefficient.

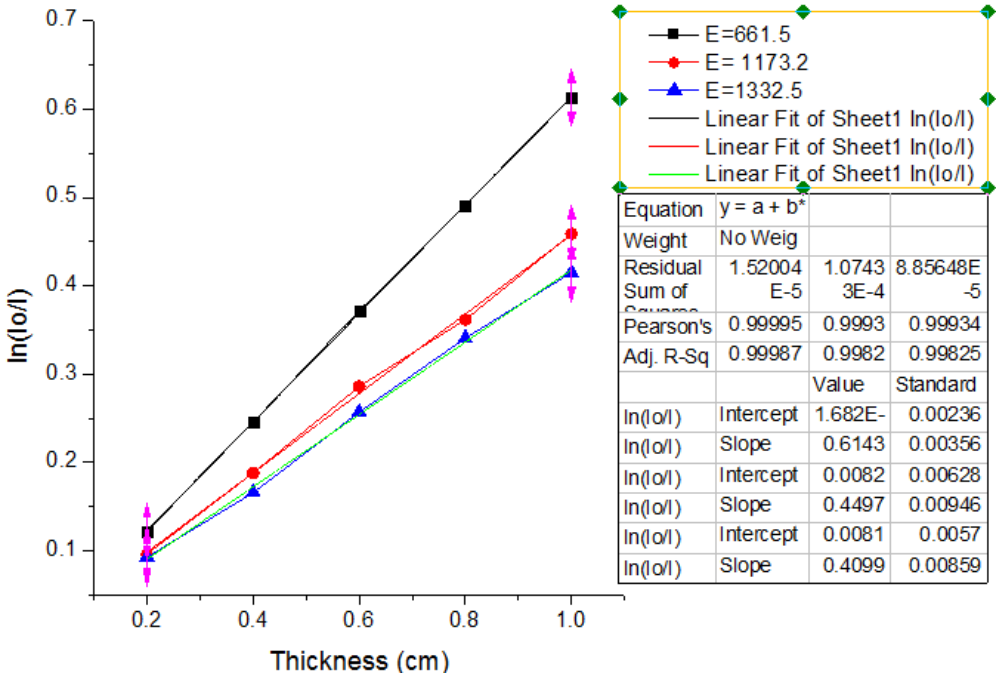
From the graphs, it is clear that the linear attenuation coefficient is inversely proportional to energy, and that's related to the dependency of the linear attenuation coefficient on the interaction between photons and matter, when the photons energy increases, the transmitted photons increase and the absorbed photons decrease, as a result the linear attenuation coefficient decreases.

Another definition which is associated with linear attenuation coefficient is the mean free path, it represents the distance between successive interactions. Mathematically, it is the inverse of the linear attenuation coefficient, the direct relation between it and energy is found, and it explains why the number of interactions becomes higher when the distance between the interactions gets smaller.



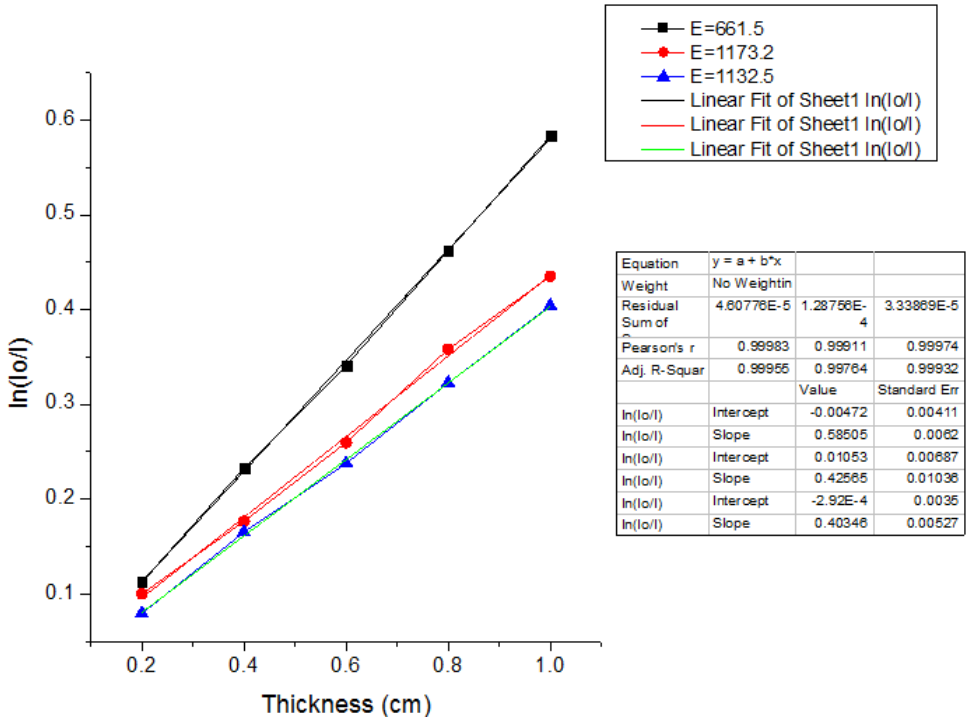
Equation	y = a + b*x		
Weight	No Weighti		
Residual Sum of	2.49378E-5	1.38436E-4	5.32341E-4
Pearson's r	0.99988	0.99887	0.99517
Adj. R-Squa	0.99968	0.99699	0.98716
		Value	Standard Er
ln(Io/I)	Intercept	-0.00172	0.00302
ln(Io/I)	Slope	0.19958	0.00179
ln(Io/I)	Intercept	-0.00135	0.00712
ln(Io/I)	Slope	0.15335	0.00421
ln(Io/I)	Intercept	8.65E-4	0.01397
ln(Io/I)	Slope	0.1451	0.00826

FIG. 2. Linear attenuation coefficient of Al at (a) 661.6 keV, (b) 1173.2 keV and (c) 1332.5 keV.



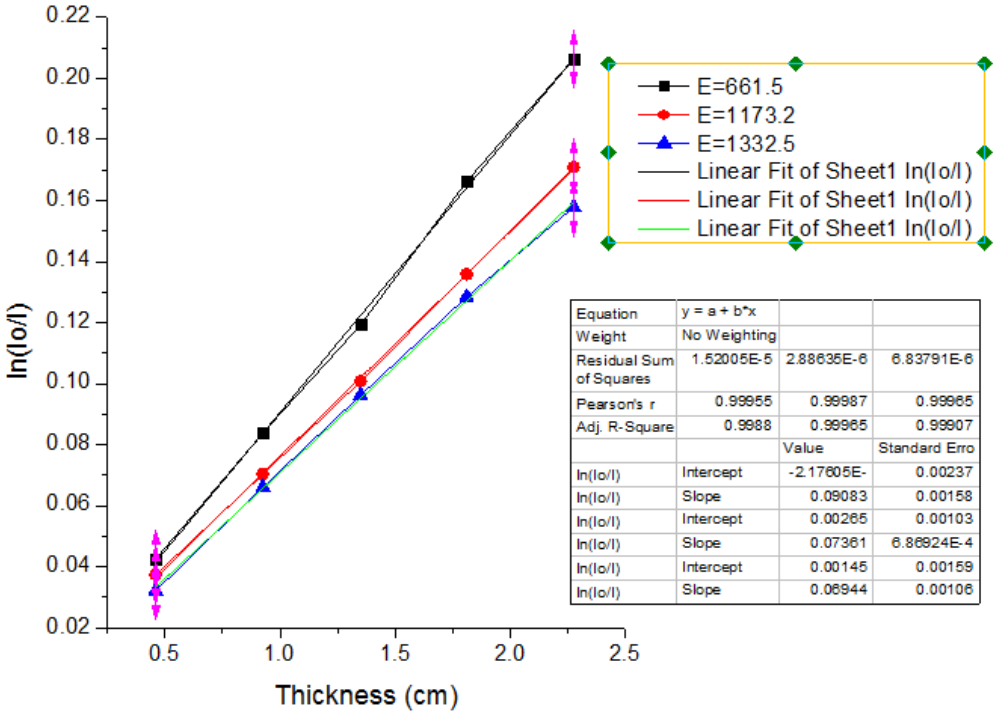
Equation	y = a + b*		
Weight	No Weig		
Residual Sum of	1.52004E-5	1.07433E-4	8.85648E-5
Pearson's	0.99995	0.9993	0.99934
Adj. R-Sq	0.99987	0.9982	0.99825
		Value	Standard
ln(Io/I)	Intercept	1.682E-	0.00236
ln(Io/I)	Slope	0.6143	0.00356
ln(Io/I)	Intercept	0.0082	0.00628
ln(Io/I)	Slope	0.4497	0.00946
ln(Io/I)	Intercept	0.0081	0.0057
ln(Io/I)	Slope	0.4099	0.00859

FIG. 3. Linear attenuation coefficient of brass at (a) 661.6 keV, (b) 1173.2 keV and (c) 1332.5 keV.



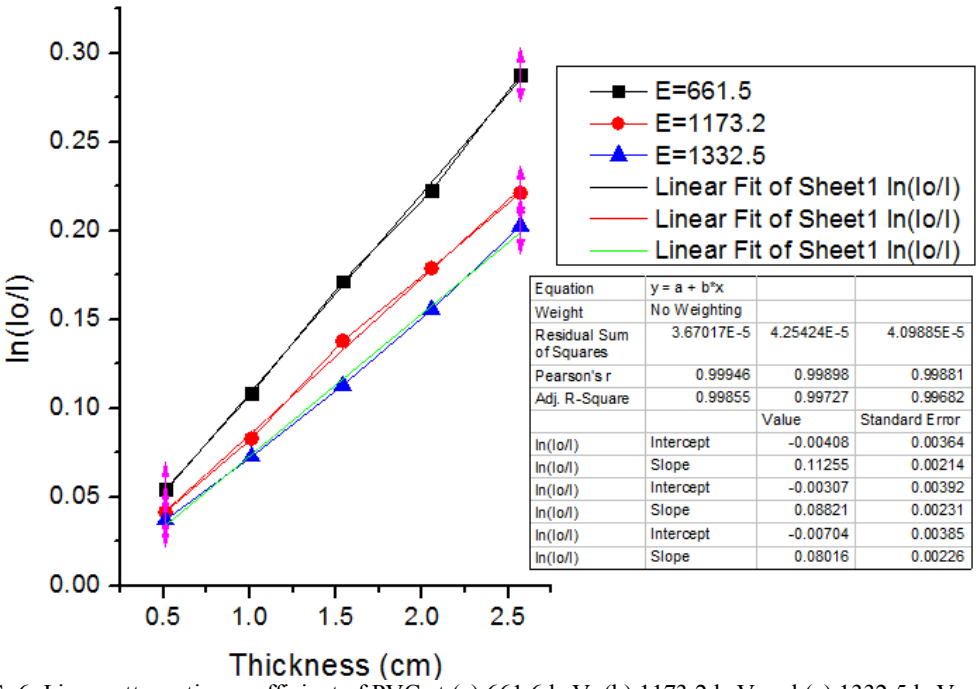
Equation	y = a + b*x		
Weight	No Weightin		
Residual Sum of	4.60776E-5	1.28756E-4	3.33869E-5
Pearson's r	0.99983	0.99911	0.99974
Adj. R-Squar	0.99955	0.99764	0.99932
		Value	Standard Err
ln(Io/I)	Intercept	-0.00472	0.00411
ln(Io/I)	Slope	0.58505	0.0062
ln(Io/I)	Intercept	0.01053	0.00687
ln(Io/I)	Slope	0.42565	0.01036
ln(Io/I)	Intercept	-2.92E-4	0.0035
ln(Io/I)	Slope	0.40346	0.00527

FIG. 4. Linear attenuation coefficient of Fe at (a) 661.6 keV, (b) 1173.2 keV and (c) 1332.5 keV.



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	1.52005E-5	2.88635E-6	6.83791E-6
Pearson's r	0.99955	0.99987	0.99965
Adj. R-Square	0.9988	0.99965	0.99907
		Value	Standard Erro
ln(Io/I)	Intercept	-2.17605E-	0.00237
ln(Io/I)	Slope	0.09083	0.00158
ln(Io/I)	Intercept	0.00265	0.00103
ln(Io/I)	Slope	0.07361	6.86924E-4
ln(Io/I)	Intercept	0.00145	0.00159
ln(Io/I)	Slope	0.06944	0.00106

FIG. 5. Linear attenuation coefficient of perspex at (a) 661.6 keV, (b) 1173.2 keV and (c) 1332.5 keV.



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.67017E-5	4.25424E-5	4.09885E-5
Pearson's r	0.99946	0.99898	0.99881
Adj. R-Square	0.99855	0.99727	0.99682
		Value	Standard Error
ln(Io/I)	Intercept	-0.00408	0.00364
ln(Io/I)	Slope	0.11255	0.00214
ln(Io/I)	Intercept	-0.00307	0.00392
ln(Io/I)	Slope	0.08821	0.00231
ln(Io/I)	Intercept	-0.00704	0.00385
ln(Io/I)	Slope	0.08016	0.00226

FIG. 6. Linear attenuation coefficient of PVC at (a) 661.6 keV, (b) 1173.2 keV and (c) 1332.5 keV.

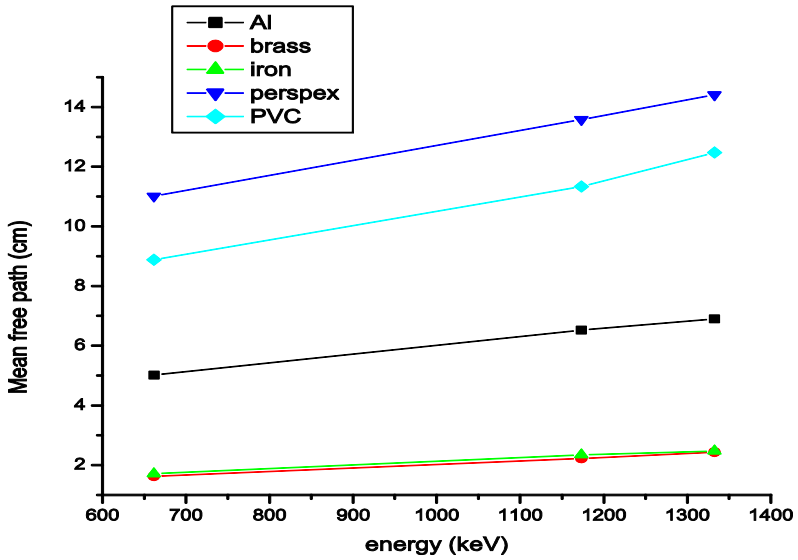


FIG. 7. The mean free path for all samples at different energies.

TABLE 3. The linear attenuation coefficients and mean free path for the samples.

Sample	Linear attenuation coefficient (cm^{-1})			Mean free path(cm)		
	661.6 keV	1173.2 keV	1332.5 keV	661.6 keV	1173.2 keV	1332.5 keV
Aluminum	0.1991	0.1530	0.1448	5.020	6.530	6.906
Iron	0.5850	0.4256	0.4034	1.709	2.349	2.478
Brass	0.6143	0.4497	0.4099	1.628	2.223	2.439
Perspex	0.0908	0.0736	0.0694	11.013	13.586	14.409
PVC	0.1125	0.0882	0.0801	8.884	11.336	12.475

In this experiment, the samples are chosen to make a comparison between pure elements (Al, Fe), thermoplastic materials (PVC, Perspex) and alloy which is represented by Brass. It's found that brass (the alloy) is a good absorber and then come pure elements but thermoplastic materials are not, from this arrangement the dependency of the linear attenuation on density is obvious, if we normalize the linear attenuation by the absorber density. Hence, the mass attenuation coefficient (μ_m) is defined.

From the tables, it is observed that, as the density increases the mass attenuation coefficient decreases; this confirms the contribution of the absorption process (photoelectric effect), scattering process (Compton, coherent) and pair production.

The experimental results for mass attenuation coefficients are compared with the XCOM data base and mixture rule, the results are close to each other, and Table (4) below clarifies that.

TABLE 4. The mass attenuation coefficients of the samples at different energies

Sample	^{137}Cs data (661.6 keV)				^{60}Co data(1173.2 keV)			
	$(\mu/\rho)_{XCOM}$ (cm^2/g)	$(\mu/\rho)_{exp}$ (cm^2/g)	$(\mu/\rho)_{mix}$ (cm^2/g)	error%	$(\mu/\rho)_{XCOM}$ (cm^2/g)	$(\mu/\rho)_{exp}$ (cm^2/g)	$(\mu/\rho)_{mix}$ (cm^2/g)	error%
PVC	0.079	0.082	0.079	2.8	0.060	0.063	0.060	6.0
Perspex	0.083	0.079	0.083	5.2	0.063	0.064	0.063	0.80
Aluminum	0.074	0.073	-	1.3	0.056	0.057	-	3.5×10^{-3}
Brass	0.072	0.073	0.072	0.2	0.054	0.053	0.054	1.8
Iron	0.073	0.074	-	1.0	0.055	0.054	-	2.3

Sample	^{60}Co data(1332.5 keV)			
	$(\mu/\rho)_{XCOM}$ (cm^2/g)	$(\mu/\rho)_{exp}$ (cm^2/g)	$(\mu/\rho)_{mix}$ (cm^2/g)	error%
PVC	0.056	0.058	0.056	2.8
Perspex	0.059	0.063	0.059	1.4
Aluminum	0.053	0.054	-	7.5×10^{-3}
Brass	0.051	0.048	0.051	4.5
Iron	0.051	0.051	-	1.2

Trials are made to make a relation between mass attenuation coefficient and energy. First, suppose that the mass attenuation coefficient can be written as [15]:

$$\mu_m = AE^{-B} \tag{13}$$

Take the logarithm for both sides:

$$\ln \mu_m = \ln A - B \ln E \tag{14}$$

This relation represents a straight line with slope ($-B$) and intercepts ln (A).

The linear attenuation coefficient can be written as:

$$\mu = \rho A E^{-B} \tag{15}$$

The equations that represent the relations between linear attenuation coefficient and energy for samples can be known after finding the constants which are:

$$\left.\begin{array}{l} \text{For Al } \mu = 3.86181E^{-0.4567} \\ \text{For Fe } \mu = 19.42989E^{-0.5396}. \\ \text{For Brass } \mu = 24.4989E^{-0.5673}. \\ \text{For PVC } \mu = 2.350692E^{-0.4673} \\ \text{For Perspex } \mu = 1.23073E^{-0.3802} \end{array}\right\} \tag{16}$$

The previous relations represent a generalization of the samples to find the linear attenuation coefficient at any energy.

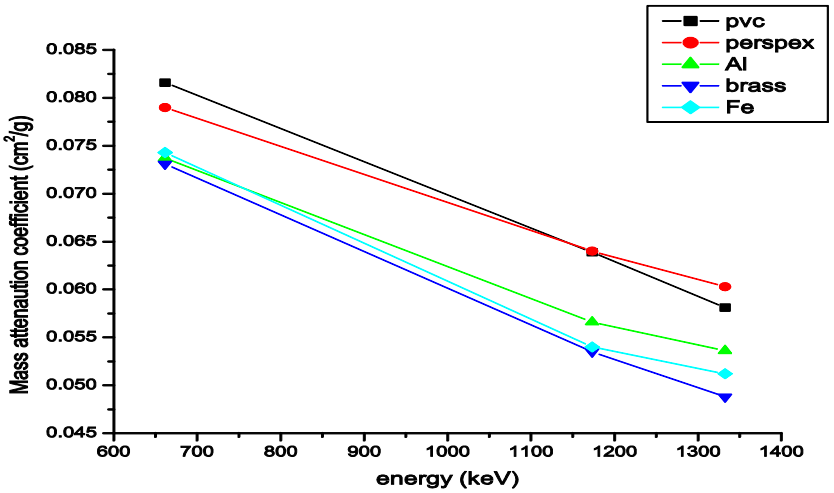


FIG. 8. Mass attenuation coefficient versus energy for all samples.

Another important parameter that affects the transmission photons is cross-section (atomic, molecular and electronic cross-section), which has an inverse relation with energy and is associated with the mean free path definition.

Atomic cross-section which is represented by Al and Fe in this experiment, has linear relationships with atomic weight and mass attenuation coefficient, the atomic weight for Al is 26.98 while for Fe is 55.8 with a difference equal to 28.82, for this reason iron has a higher value of atomic cross-section than Al, although Al has a higher mass attenuation coefficient.

Turning to the compounds, the molecular cross-section plays an important role in the interaction between photons and matter, if we assume that the molecular cross-section is related to the molecular weight and energy by the expression:

$$\sigma_m = kAE^b \qquad (17)$$

where k and b are constants, then we have:

$$\ln(\sigma_m/A) = b \ln(E) + \ln(k) \qquad (18)$$

This is a straight line of slope b and intercepts ln (k). The numerical values of k and b are given under the assumption that the energy is expressed in units of keV, the atomic weight in gmol^{-1} and the molecular cross-section in barn/molecule. The straight line fitting yields the values of b, ln (k), the equation of the molecular cross-section is;

$\sigma_m = 3.62879 \times 62.4967\ E^{-0.51}$

$\sigma_m = 1.21191 \times 100.1112\ E^{-0.3418}$

$\sigma_m = 3.14842 \times 321.398\ E^{-0.5009}$

Brass molecules have the highest probability of interaction, then Perspex, but PVC molecules have low interaction probability, the explanation of this result is related to the large difference of the molecular weight, for brass it equals 321.398 comparing with Perspex which has a molecular weight of 100.1112, but for PVC the molecular weight is only 62.4967.

Due to the size of the atoms which compose the compounds, Cu and Zn of brass are sufficiently large so the electrons in the last shell are fewer bands to the nucleus; this point increases the interaction probabilities, comparing with H-atom, C-atom, O-atom and Cl- atom in Perspex and PVC, which seem small relative to Cu and Zn.

Molecular cross-section is also found by using Eq. 8, the comparison between the results of the two methods is made, and the results are almost compatible.

The last definition in cross-sections is electronic cross-section, for the compounds brass has the largest value. However, PVC and Perspex are approximately close to each other, with a small difference between them; PVC has a greater value than Perspex; attributed to the existence of chlorine (Z = 17, A = 35.45) in PVC which is a little greater than Oxygen (Z = 8, A = 17) in Perspex, although oxygen has a higher value of mass attenuation coefficient.

TABLE 5. The atomic and electronic cross-sections of the pure elements.

Sample	661.6 keV		1173.2 keV		1332.5 keV	
	$\sigma_a \times 10^{-24}$	$\sigma_e \times 10^{-25}$	$\sigma_a \times 10^{-24}$	$\sigma_e \times 10^{-25}$	$\sigma_a \times 10^{-24}$	$\sigma_e \times 10^{-25}$
Al	3.282 ± 0.02090	2.525 ± 0.01869	2.509 ± 0.3849	1.930 ± 0.04606	2.414 ± 0.05086	1.863 ± 0.03643
Fe	6.770 ± 0.04413	2.639 ± 0.02471	5.318 ± 0.1481	2.045 ± 0.05696	4.742 ± 0.03508	1.824 ± 0.01348

TABLE 6. The molecular and electronic cross-sections of the samples.

Sample	σ_m from fitting equation (barn/molecule)			σ_m from equation(8) $\times(10^{-23})$ (cm^2/molecule)			$\sigma_e \times 10^{-25}$		
	661.6 keV	1173.2 keV	1332.5 keV	661.6 keV	1173.2 keV	1332.5 keV	661.6 keV	1173.2 keV	1332.5 keV
Brass	8.263	6.169	5.781	3.902 ± 0.01183	2.969 ± 0.03301	2.72712 ± 0.05688	2.644	2.563	2.566
Perspex	13.18	10.84	10.37	1.313 ± 0.009970	1.105 ± 0.04710	1.021 ± 0.005850	1.977	1.956	1.957
PVC	39.11	29.36	27.54	0.8204 ± 0.08318	0.6411 ± 0.11566	0.5602 ± 0.09432	1.856	1.827	1.828

Note: σ_a has a unit of (cm^2/atom), σ_m is in barn/molecule and σ_e is in (cm^2/electron).

Table 7. The effective atomic number and electron density of the samples.

Sample	$Z_{effective}$ from constituents			$Z_{effective}$ from equation (11)			Electron density		
	661.6 keV	1173.2 keV	1332.5 keV	661.6 keV	1173.2 keV	1332.5 keV	661.6 keV	1173.2 keV	1332.5 keV
Brass	29.49± 0.08426	29.99 ± 0.3222	29.39± 0.5959	29.50 ± 0.09154	30.04 ± 0.3351	29.39 ± 0.6129	2.763± 0.007890	2.809± 0.03018	2.754 ± 0.05582
Perspex	3.414 ± 0.02716	3.783 ± 0.06115	3.715 ± 0.02128	3.415 ± 0.02718	3.766 ± 0.06077	3.724 ± 0.02133	3.080 ± 0.02451	3.413± 0.05518	3.352 ± 0.01921
PVC	5.311 ± 0.05371	5.470 ± 0.09854	5.083 ± 0.08546	5.329 ± 0.05403	5.387 ± 0.1139	5.109 ± 0.08519	3.070 ± 0.03104	3.162± 0.05696	2.939 ± 0.04942

After finding the cross-section of the samples, the calculation of effective atomic number $Z_{effective}$ and electron density becomes possible, by using Eq. 11, the results are arranged in the table above.

There is another method for determining effective atomic numbers and electron densities. These have been determined by matching the atomic cross-section with the corresponding values of the elements of the compound at a given energy. In other words, the effective atomic number for each sample was determined by using the atomic cross-section for the compound constituents.

Since the mass attenuation coefficients for each individual element in the compound for the energies 661.6, 1173.2 and 1332.5 keV are not available experimentally, these attenuations were taken from the XCOM data base, assuming that the elemental cross-section can be written as [6]:

$$\sigma = A(Z)E^{B(Z)} \tag{19}$$

Since this cross-section shows a non-linear relation with energy E and atomic number Z; $A(Z)$ and $B(Z)$ are constant with respect to energy. Taking the logarithm for both sides of the previous equation gives:

$$\ln \sigma = \ln A(Z) + B \ln E \quad (20)$$

This equation represents a straight line with slope $B(Z)$ and intercepts ln ($A(Z)$). The linear fit is taken to determine the values of $B(Z)$ and ln ($A(Z)$). Since ln ($A(Z)$) and $B(Z)$ are simple functions of the atomic number, it is assumed that it can be written as [6]:

$$\ln A(Z) = \ln A_1 + B_1 \ln Z$$

and

$$B(Z) = \ln A_2 + B_2 \ln Z \quad (21)$$

These equations also represent straight lines with slopes B_1 and B_2 and intercept ln (A_1) and ln (A_2), respectively. All of the previous coefficients are constants and can be determined using the linear fit method.

The formula that can be used to determine the effective atomic number in this case is:

$$Z_{eff} = [\frac{\sigma_{compound}}{A_1 E^{\ln A_2}}]^{1/d} \quad (22)$$

where

$$d = B_1 + B_2 \ln E \quad (23)$$

The electron density can also be calculated using the formula:

$$N_{el} = N_{av} Z_{eff} \frac{\sum_i n_i}{\sum_i n_i A_i} \quad (24)$$

Theoretically, the variation of energy makes a difference in the effective atomic number. In general, that is not clear here in this experiment, where the effective atomic numbers for different energies are very close to each other. This is attributed to the Compton scattering which is dominant in this range of energy. Although we take the net area under the photo peak, Compton scattering cross-section has a Z-dependence, where it is proportional to Z^1 as $\sigma_{compton} \propto Z$. Therefore, the effective atomic number is constant in this energy range.

Comparing the three compounds in terms of the effective atomic number, we find that Brass has the highest value, then PVC, and Perspex is the last one. The reason of this order is the kind of atoms in each compound, the atomic numbers of the constituents affect the atomic number of the compound, Cu (Z = 29) and Zn (Z = 30) in Brass, have atomic numbers higher than carbon (Z = 6), hydrogen (Z = 1) and oxygen (Z = 8) in Perspex. In PVC, in addition to carbon and hydrogen, there is chlorine (Z = 17), so there is a large difference between the constituents of Perspex and PVC relative to those of Brass. However, a reverse order is found for electron density because of the big difference in the atomic weight of the compounds.

Conclusion

Attenuation coefficients of the samples have been measured, using collimated gamma ray transmission method, the other factors; cross-sections, effective atomic numbers and electron densities; have been calculated with respect to the mass attenuation coefficients.

From the analysis, brass appears as a good attenuator, and the inverse relation between energy and gamma attenuation clearly appears. The cross-sections for the ^{60}Co lines 1173.2 keV and 1332.5 keV are very close to each other, which means the probability of interaction is approximately the same. On the other hand, the effective atomic numbers for the samples are found to be constant; also the effective atomic number and electron density of composite material give an indication of their atomic composition.

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References

[1] Kaewkhao, J., Laopaiboon, J. and Chewpraditkul, W., J. Quant. Spectrosc. Ra. 109 (2008) 1260.

[2] Murty, V., Rad. Phy. and Chorn. 21 (2004) 667.

[3] Sabriye, S., Karahan, H. and Őmer, F., J. Quant. Spectrosc. Ra. 83 (2004) 237.

[4] Manohara, S.R. and Hanagodimath, S.M., Nucl. Instrum. Methods. B, 258 (2007) 321.

[5] Shivalinge, G., Krishnaveni, S. and Ramakrishna, G., Nucl. Instrum. Methods B, 239 (2005) 369.

[6] Shivalinge, G., Skrishnaveni, Y., Umesh, T.K. and Ramakrimshna, G., Pramana –J. Phys. 63 (2004) 529.

[7] Baltas, H. and Cevik, U., Nucl. Instrum. Methods B, 266 (2008) 1127.

[8] Awadallah, M.I. and Imran, M.M., J. Environ. Radioactiv. 94 (2007) 129.

[9] Kiran, K. and Venkata, K.R., Radiat. Phys. Chem. 50 (1997) 545.

[10] Manohara, S.R., Hanagodimath, S.M. and Gerward, L., Phys. Med. Biol. 53 (2008) 377.

[11] Manjunathaguru, V. and Umesh, T., J. Phys. B- At. Mol. Opt. 39 (2006) 3969.

[12] Kaliman, Z., Orlic, N. and Jelovica, I., Nucl. Instrum. Methods A, 580 (2007) 40.

[13] Hendee, R. and Ritenour, E.R., Medical Imaging Physics, 4th Ed. (John Wiley and Sons, New York, 2005).

[14] Morgan, C.L., Basic Principles of Computed Tomography, (University Park Press, Baltimore, 1983), Chapter 2.

[15] Awadallah, M.I., Ph.D. Thesis, University of Jordan, (2003), Amman, Jordan (Unpublished).