Study of Gamma Radiation Attenuation and Build up through Aluminium, Graphite, Iron and Lead Absorbers

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Abstracts: Gamma radiation attenuationoccurs when gamma-ray interacts with matter, losing its energy via photoelectric absorption, Compton scattering or Pair production. In this paper, we study the attenuation properties of aluminium, graphite, iron and lead blocks for collimated and un-collimated beams of gamma rays emitted from a cobalt-60 source,using Sodium Iodide Scintillation detector. For the collimated beam, the linear attenuation coefficients were found to be equal to 0.097 ± 0.010cm-1for graphite, 0.136 ± 0.010cm-1for aluminium, 0.387 ± 0.023cm-1 for Iron and 0.597± 0.045cm-1 for lead absorbers, showing that the gamma rays penetrate least in lead absorbers than the other absorbers.Using both collimated and un-collimated beams, the values of the build-up factorB for each absorber was found. The results demonstrate that Bdecreases linearly with increasing thickness of the absorber material.

KEY WORDS: Gamma-rays, Attenuation, Collimated,Un-collimated, Cobalt-60, Absorbers.

Introduction

Ionizing radiations are very harmful, especially if not properly handled. It suffices to say that great efforts need to be made at minimizing the radiation doses received by radiation workers, patients and even the general public. According to International Commission on Radiological Protection (ICRP), taking into account both economic and social factors, the likelihood of radiation exposures, the number of people exposed and the radiation doses they receive should be kept as low as reasonably achievable-the so called ALARA principle**[1]**. Therefore, the total dose one receives in a given radiation field can be controlled by: minimizing the exposure time, maximizing the distance from the source and most effectively, by shielding. A shield is the thickness of a material that can effectively attenuate ionizing radiations. And the interactions which take place in the shielding material depend on the type of radiation, energy of the radiation and the atomic number of the absorber material**[2].**In this paper, we study the attenuation properties of some selected absorbers such as aluminium, graphite, iron and lead blocks when collimated and un-collimated beams of gamma rays emitted from a cobalt-60 source transverse the absorbers. Linear attenuation coefficients and the values of the build-up factor for each absorber were found.

Theoretical Treatment

Gamma rays are simply emitted whenever an excited nucleus returns to its ground state and such excited nuclide is said to be radioactive. A good example of this gamma rays emitting radioactive nuclide is an isotope of element of Cobalt, $^{60}_{27}$Co which is widely used for sterilization of medical equipments, cancer treatment in radiotherapy, gauging materials thickness in the industries etc. It is produced artificially by the neutron activation of the only naturally occurring stable isotope of Cobalt, the $^{59}_{27}$Co.With a half-life of about 5.26 years[3]$^{60}_{27}$Coproduces two gamma rays of energies 1.17Mev and 1.33Mev[4] and the equation of the reaction is described below:

$$^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{60m}_{27}Co \longrightarrow ^{60}_{27}Co \longrightarrow ^{60}_{28}Ni + ^{0}_{-1}e + \gamma \qquad 1$$

ISSN 2229-5518

Gamma Ray attenuation

Gamma rays are attenuated either by photoelectric absorption, pair production or Compton scattering interaction with the material absorber. And thus the intensity of the incident beam decreases as it traverses the absorber.The gamma rays which reach the detector did not undergo interactions with the shielding material. Hence, interaction is what causes attenuation. The degree of attenuation by the materials can be explained using Beer-Lamberts lawas [5]:

$$I = I_0 e^{-\mu x} \quad 2$$

Where Iis the intensity of the beam of gamma ray after interaction, I0 is the initial gamma intensity when no absorber is present, x is the thickness of the material absorber and μ is the linear attenuation coefficient which is the fraction of gamma ray that interacts per cm of the absorber. It is dependent on the energy of the photons and type of absorber material involved.

Collimated and Un-collimated beam attenuation geometry

Fig.1.0 shows collimated beam with the absorber material placed between the source and the detector. In this circumstance, any scattered photon (even the photon scattered by a small angle) will not hit the surface of the detector. Therefore, the detector will just be able to detect the primary photons, which traverse the absorber material without undergoing any interaction.For the collimated beam (good geometry), we can write the expression for linear attenuation as:

$$I_g = I_0 e^{-\mu x} \quad 3$$

Where I_g is the intensity of the collimated beam after attenuation, and all other symbols have their usual meanings.

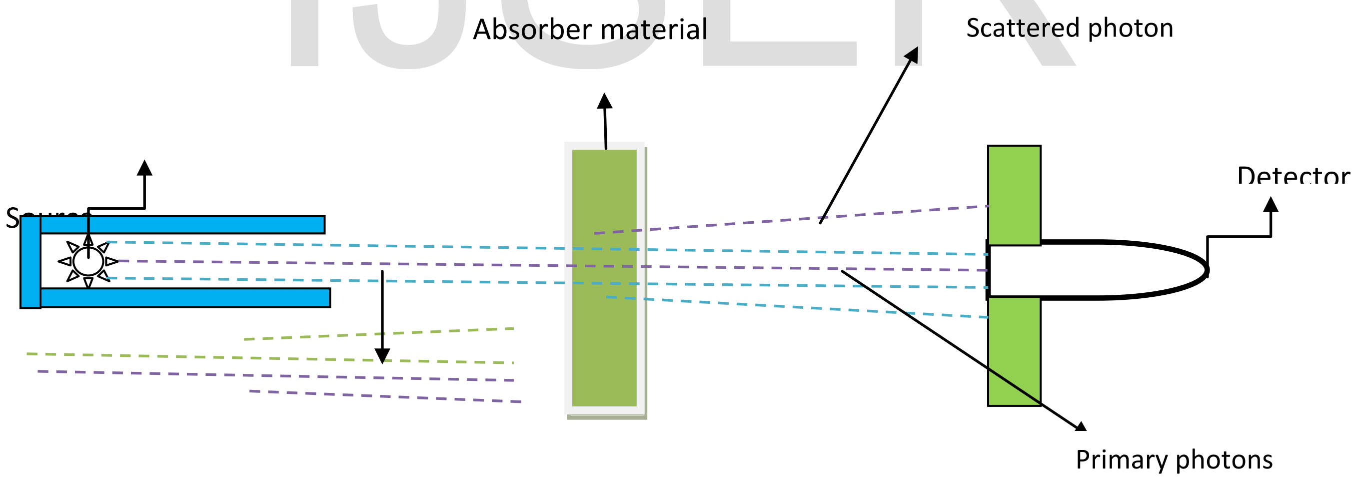


Fig.1.0: good geometry (collimated beam)

For the un-collimated beam attenuation shown in fig2.0, the distance between the source and the detector is increased to allow for gamma rays to reach the detector after interactions. The figure demonstrates that some gamma rays reach the detector with reduced intensities after interactions, while others are completely absorbed. Hence, by introducing a multiplicative factor B into the equation for the un-collimated beam condition, the contributions to interaction via photo electric absorption, Compton scattering, pair-production and even Bremsstrahlung X-rays are therefore taken into account. The equation governing this type of attenuation can therefore be written as:

$$I_b = BI_0 e^{-\mu x} \quad 4$$

Where B and I_b denote the build-up factor and un-collimated beam intensity after interaction

By comparing equ 2 and 3, we have:

$$B = \frac{I_b}{I_g} \quad 5$$

Thus generally, the build-up factor B can be defined as:

$$\text{Build-up factor } B = \frac{total\ \ intensity}{primary\ \ intensity}\ or\ \frac{(primary\ +scatter\ )intensity}{primary\ \ intensity}$$

Where I_b represents the number of counts under the condition of poor geometry (collimated beam), and I_g represent the number of counts under the condition of good geometry (un-collimated beam) [6].

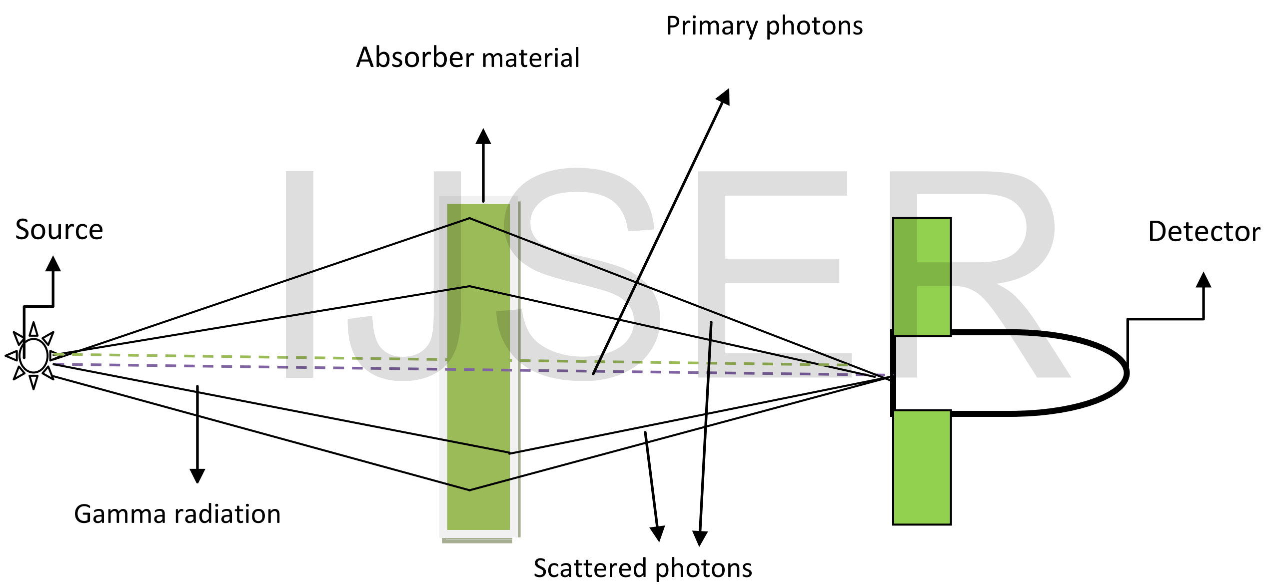


Fig.2.0: bad geometry (un-collimated beam)

Sodium Iodide Scintillation Detector, NaI(Tl)

This is a scintillation detector made with an inorganic sodium iodide crystal doped with thallium. When gamma ray interacts with the crystal in this detector, it excites the electrons from valence band to conduction band. . The presence of an impurity called thallium ensures that an emitted visible light is not lost due to further excitation within the crystal lattice. These excited electrons tend to return back to the valence band by emission of visible light which is picked up by a photomultiplier tube in the detector and converted to electrons which carry the signal. The part of photomultiplier tube that produces electrons when visible light quanta interact with it is the so called photocathode. When a positive voltage is applied, the electrons are drifted towards a sequence of plates called the dynodes, and as the electrons interact with each dynode, there is a multiplication of electron towards the next dynode. This sequence of multiplication continues until the last dynode which produces an avalanche of electron which is detected by Multi-Channel Analyzer, as an electronic pulse.

Results and discussion

As we discussed before, a narrow beam of gamma-ray with initial incident beam I_0 can penetrate a layer of different material with dependent on intensity ϱ and thickness x of the material. Therefore the intensity of the incident beam I_0 is reduced due to a various thickness of the absorber material, and the reduced of gamma intensity I can be measured by an exponential attenuation law, recall equation number (15)

$$I = I_0\, e^{-\mu x}$$

Hence we can put a natural logarithm and rearrange this equation to be able to calculate the value of

$$Ln\left(\frac{I}{I_0}\right) = -\mu x$$

So

$$\mu = -\frac{Ln\left(\frac{I}{I_0}\right)}{x}$$

Where μ is a linear attenuation coefficient which is exactly deepened on energy of incident beam, density and atomic number of the absorber material, thus we can calculate the value of μ for all four materials in this experiment which were (Al, Fe, C and Pb). Hence from our recorded date, it is clear that, if we plot between Ln $\left(\frac{I}{I_0}\right)$ on the (y-axis) and thickness (x) on the (x-axis), we can calculate the value of μ of the given materials.

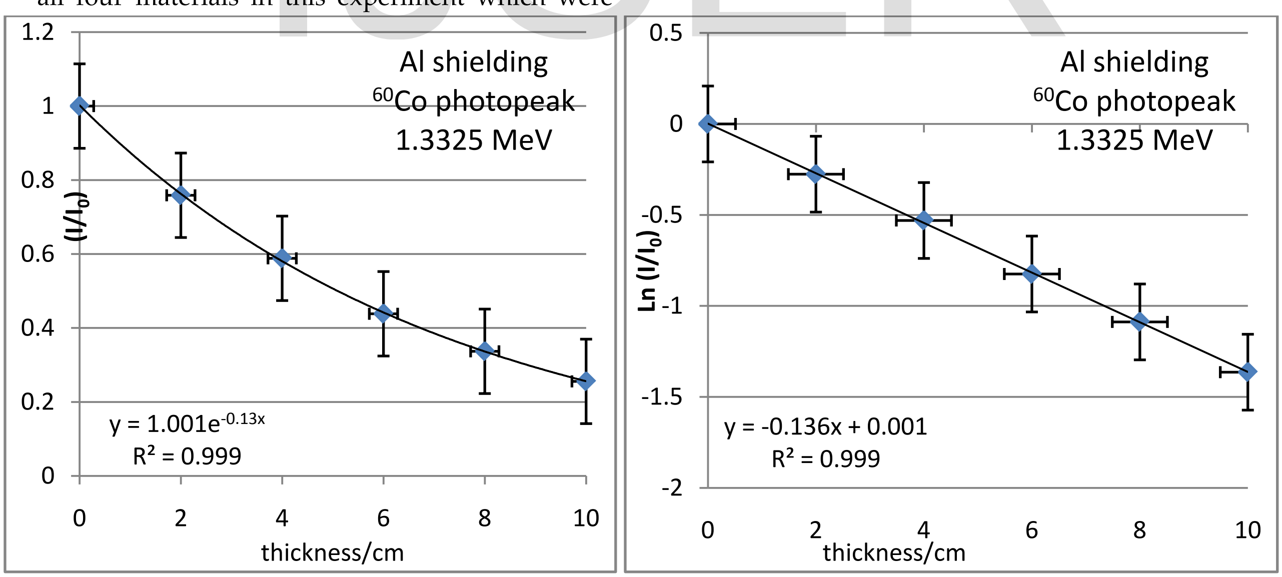


Figure (2A) standard exponential of 60Co gamma-ray MeV) intensity as a function of Al thickness (x). Figure (2B): Natural logarithm of 60Co gamma-ray (1.3325 MeV) intensity as a function of Al thickness,
And the experimental value of μ for Al is 0.136 cm-1

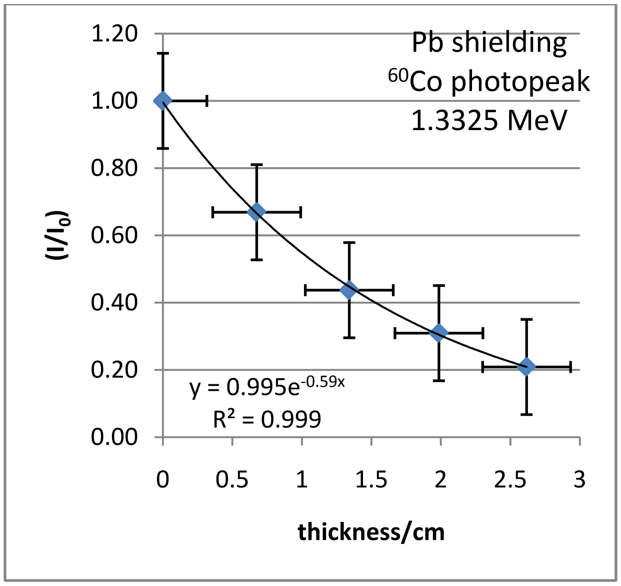


Figure (3A) standard exponential of 60Co gamma-ray MeV) intensity as a function of Pb thickness (x).

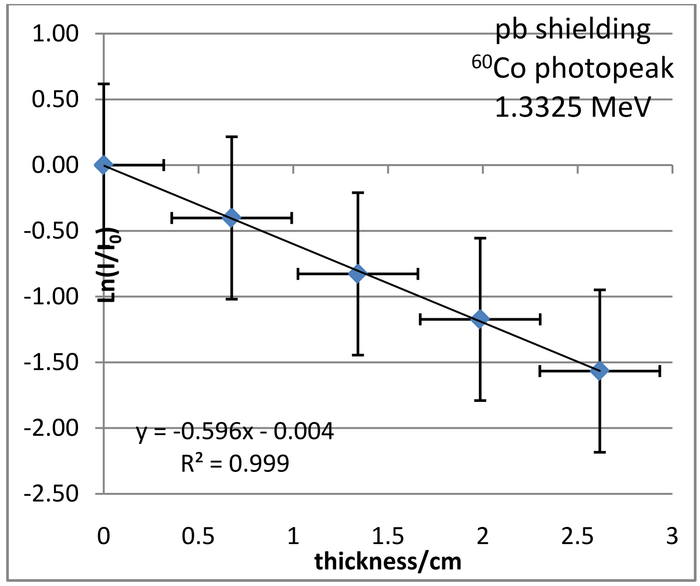


Figure (3B): Natural logarithm of 60Co gamma-ray (1.3325 (1.3325 MeV) intensity as a function of Pb thickness,

And the experimental value of μ for Al is 0.596 cm-1

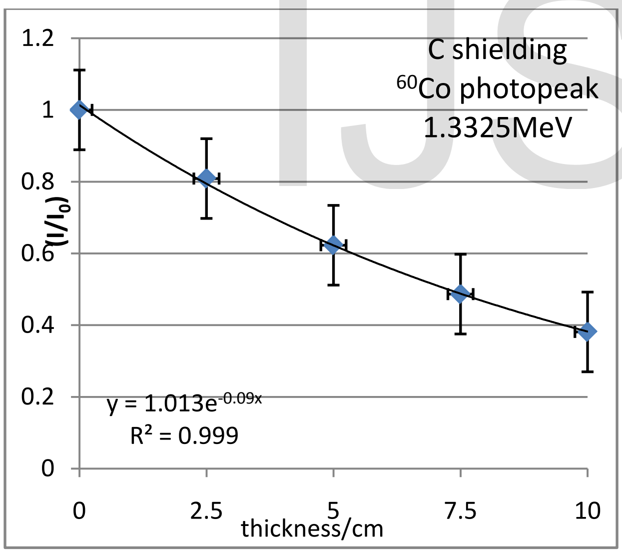


Figure (4A) standard exponential of 60Co gamma-ray MeV) intensity as a function of C thickness (x).

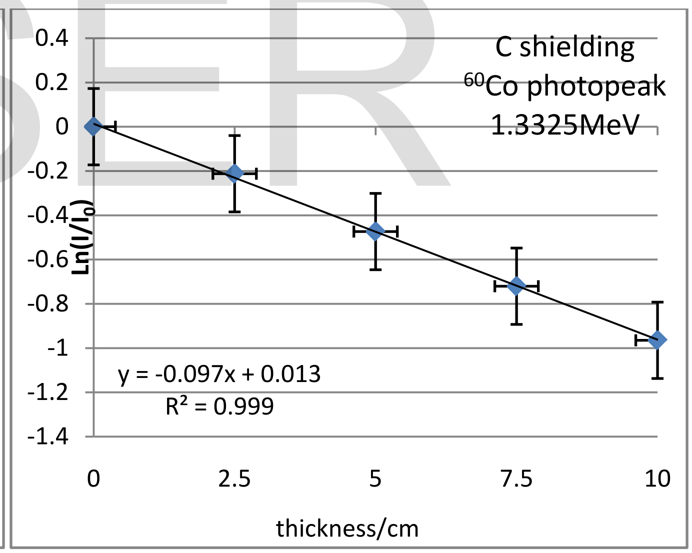
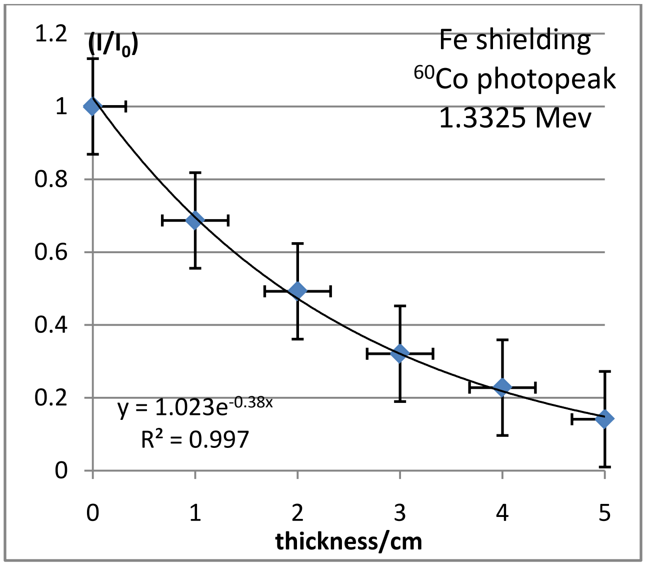


Figure (4B): Natural logarithm of 60Co gamma-ray (1.3325 (1.3325 MeV) intensity as a function of C thickness,

And the experimental value of μ for C is 0.097 cm-1



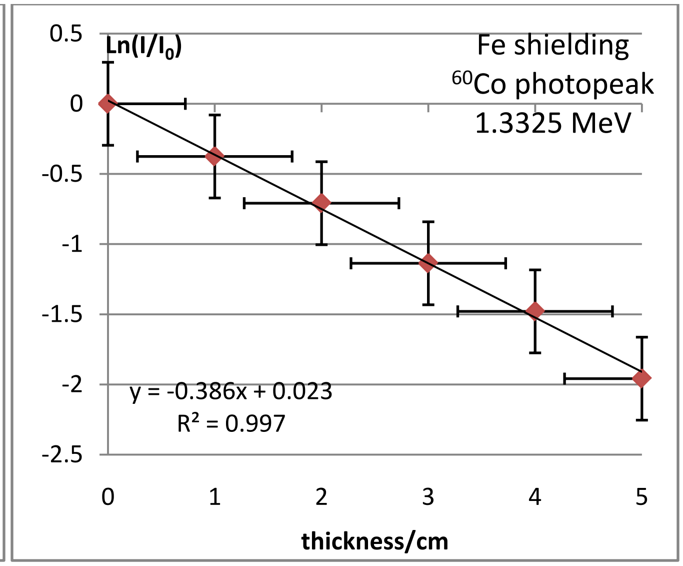


Figure (5A) standard exponential of 60Co gamma-ray MeV) intensity as a function of Fe thickness (x).

Figure (5B): Natural logarithm of 60Co gamma-ray (1.3325 (1.3325 MeV) intensity as a function of Fe thickness, And the experimental value of μ for Fe is 0.386 cm-1

For each absorber material a table was made to record the thickness (x) of the attenuated material and the number of net rate counts per second. The uncertainty of the measurement thickness was determined from the accuracy of ruler provided an accuracy of ruler ± 0.1 including x=0, whereas the uncertainty of the net rate counts per second was determined by considering on the standard division, again including I_0 which is the number of counts per second without any absorber material. Table (1) shows the value of μ/ cm-1 for a different absorber material

Material	Atomic number	Density (g/cm^2)	Linear attenuation μ/cm	R^2	Maximum thickness/cm
C	6	2.25	0.097	0.999	10
Al	13	2.74	0.136	0.999	10
Fe	26	7.86	0.386	0.977	5
Pb	82	11.35	0.596	0.999	2.62

Table (1) shows some information of different absorber material, if we consider the value of μ which can be seen either on the table or on the figure number (2B, 3B, 4B and 5B), it is clear the Pb has the highest value of μ. In contrast C is one of the poorer materials to attenuate gamma-ray. As we mentioned the attenuation graph depends on the type of radiation and the thickness of the absorber material. And the exponential attenuation is applied particularly for photons (x and gamma-ray) and a little thin sheet thickness. Therefore, the graph number (2A, 3A, 4A and 5A) show how the intensity of the incident beam of 60Co is exponentially attenuated as a function of thickness (x)

The mass attenuation coefficient is another important parameter, as we gave an example for liquid water, vapor water and frozen water, which they have a different value of linear attenuation coefficient, because of their difference value of density. But when we consider on their mass attenuation coefficient they get the same value. Therefore we can also calculate the mass attenuation coefficient of each material, which have studied in this experiment. As it has discussed before the simple definition of mass attenuation is the value of linear attenuation coefficient μ for each material divide by its density ϱ , thus the equation number (15) can be given as:

$$I = I_0\, e^{(\frac{\mu}{\rho})\rho x}$$

Where $\frac{\mu}{\rho}$ is the value of mass attenuation coefficient which is measured by unit of (cm2.g-1) Andρx is called mass thickness measured by unit of (g.cm-2). Therefore from our date if we plot Ln(I/I0) on the (y-axis) as a function of ρx on the (x-axis) we can obtain the value of $\frac{\mu}{\rho}$

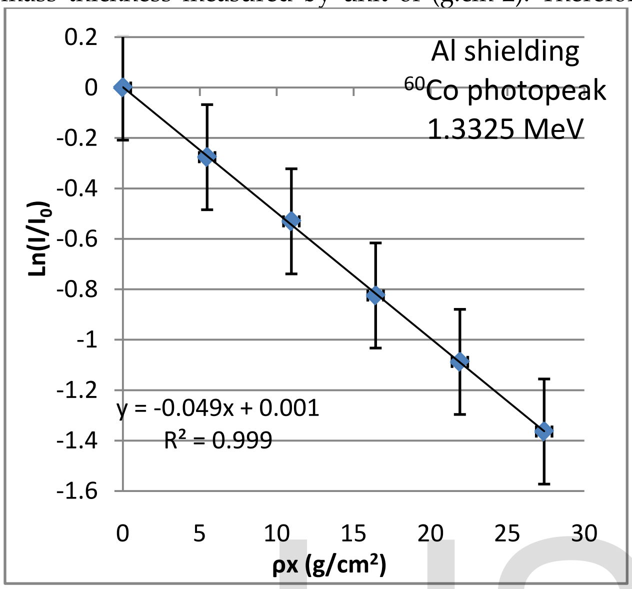


Figure (6A) natural logarithm of 60Co gamma-ray intensity as a function of Al mass thickness (ϱx), the experimental value of μ/ϱ for Al is 0.049 cm2/g

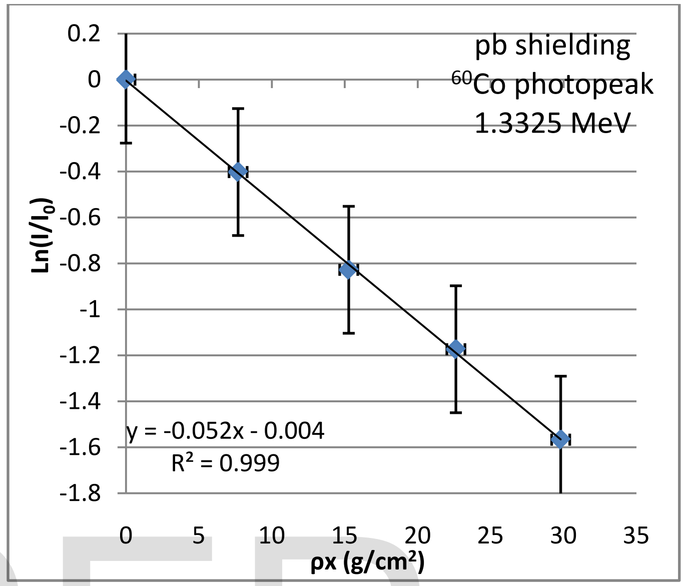


Figure (6B): Natural logarithm of 60Co gamma-ray (1.3325 MeV) intensity as a function of (ϱx) for Pb, the experimental value of μ/p for Pb is 0.052 cm2/g

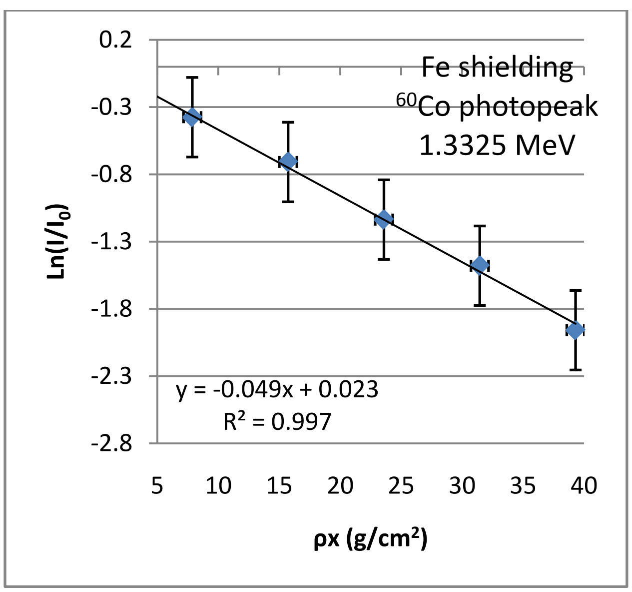


Figure (6C) natural logarithm of 60Co gamma-ray intensity as a function of Fe mass thickness (ϱx), the experimental value of μ/ϱ for Fe is 0.049 cm2/g

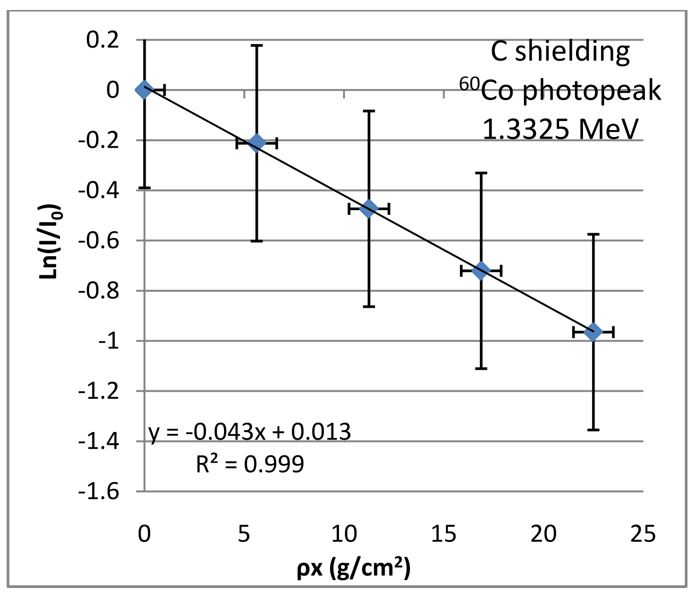


Figure (6D): Natural logarithm of 60Co gamma-ray (1.3325 MeV) intensity as a function of (ϱx) for C, the experimental value of μ/p for C is 0.043 cm2/

Material	Atomic number	Density (g/cm^{3})	μ (cm^{-1})	μ/ρ (g^{-1}.cm^{2})	R^2	Maximum thickness/cm
C	6	2.25	0.097	0.043	0.999	10
Al	13	2.74	0.136	0.049	0.999	10
Fe	26	7.86	0.386	0.049	0.997	5
Pb	82	11.35	0.596	0.052	0.999	2.62

Table (2) shows the experimental value of mass attenuation coefficient for all four materials

We can also look a half-thickness for each material has studied. The simple definition of the half-thickness is that the intensity of the beam I reduces into half of its original intensity I_0 when the thickness of the absorber material reaches half of its maximum thickness (X1/2). Take Al as an example which is plotted below.

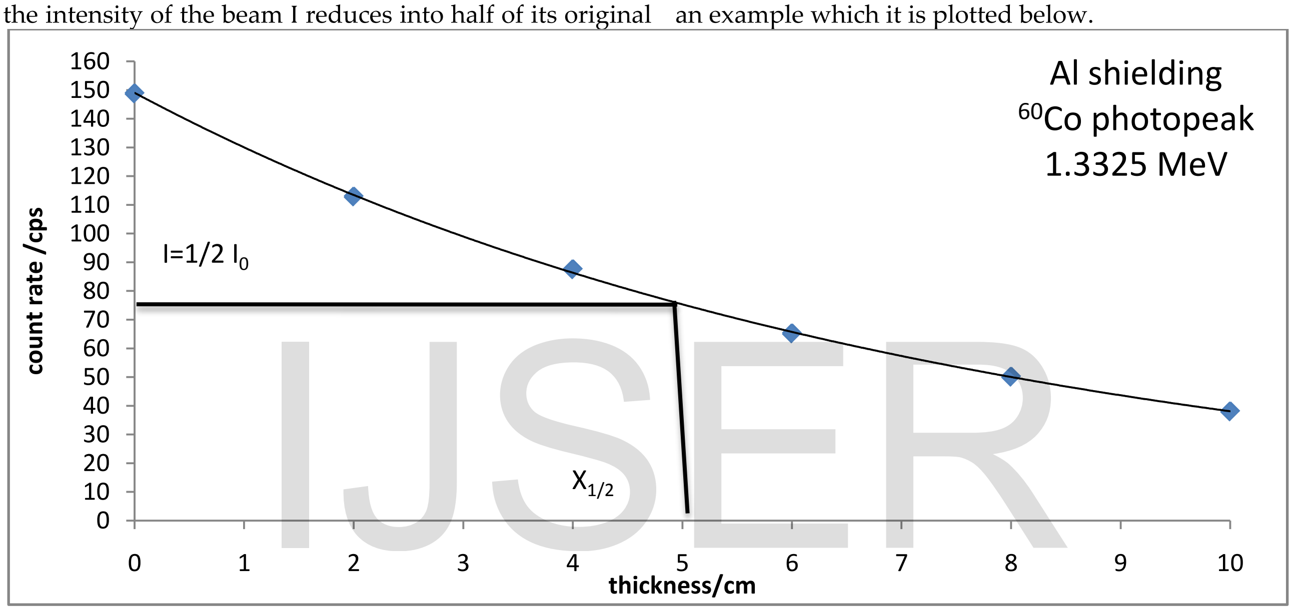


Figure (7) shows the relationship of number of net rate counts per second as a function of thickness per unit cm, at X1/2 of Al absorber shielding.

Again as we discribed before when the gamma-ray interacts with matter, it may loss some of its energy either by absorption or scattering which is caused by deacrising the intensity of the beam. And the intensity of the beam Imay reduce into half of its original intensity of the beam I_0 at X1/2. Therefor we can drive equation number (15) to find the value of X1/2

$$I = I_0\, e^{-\mu x}$$

$$I/I_0 = e^{-\mu x}$$

Note at a half-thickness the intensity of radiation halved, thus $I = \frac{1}{2} I_0$ plugging into equation above

$$\frac{1}{2} = e^{-\mu x}$$

Take natural logarithm for both sides: $\text{Ln}(1/2) = \mu\, x_{1/2}$

Where Ln(1/2) = 0.6931 $x_{1/2} = \frac{0.6931}{\mu}$

ISSN 2229-5518

And in out experiment the value of μ is equal to 0.136 cm-1

Hence $x_{1/2} = \dfrac{0.6931}{0.136} = 5.09$ cm

As we discussed before the geometry has a huge impact to attenuate radiation intensity. Because under the condition of good geometry (collimated bean). The number of scattered photons is lower than the number of absorbed photons. Thus the lower number of photos can reach the detector because more of them have already absorbed by the absorber material. Whereas under the condition of poorer geometry when the bean is un-collimated. The larger number of scattered photos can also reach the detector. Therefore, from out data we can calculate the value of Build-up factor B, which is the ratio between net count rate per second of the broad-beam (un-collimated beam) and the net count rate per second of the narrow-beam (collimated beam). Recalled equation number (21,22 and 23) from the theory

$$I_b e^{+\mu x} = I_g e^{+\mu x}\ \mathrm{B}(\mu x)$$

$$\mathrm{B}(\mu x) = \frac{I_b e^{+\mu x}}{I_g e^{+\mu x}}$$

Hence we can cancel the term of $e^{+\mu x}$ because the value of x and μ are the same in each case.

$$\mathrm{B}(\mu x) = \frac{I_b}{I_g}$$

From this equation above if we plot the net count rate where the beam is un-collimate I_b against of the net cout rate when the beam is collimate I_g, we can obtain the value of B(μx) for eache material.

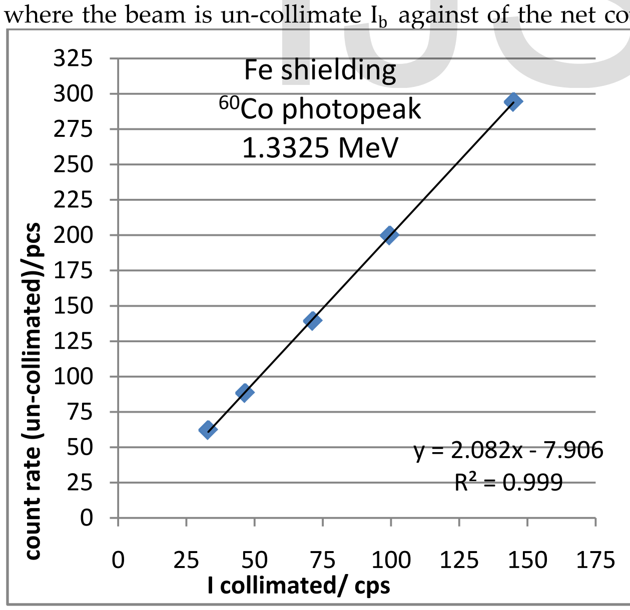
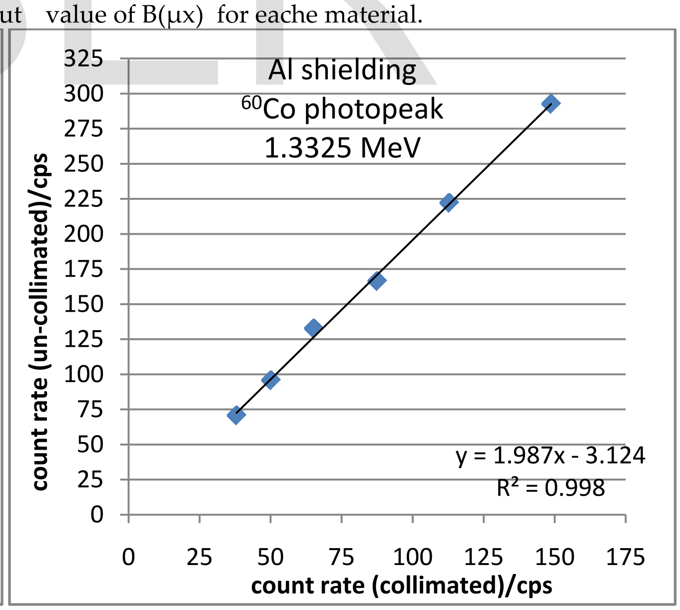
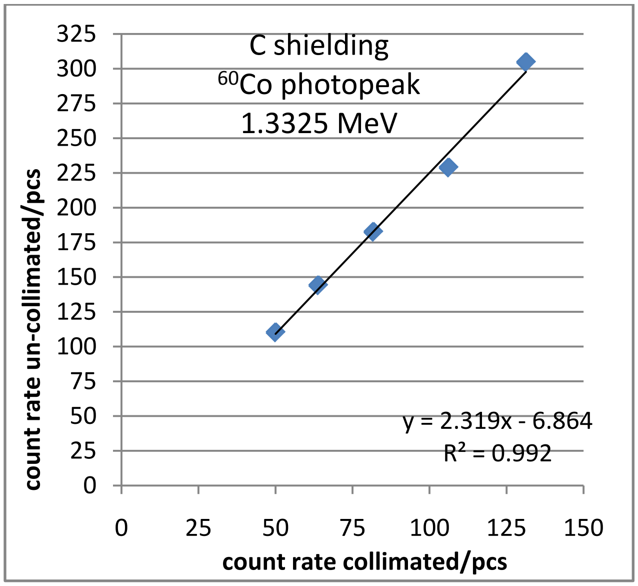


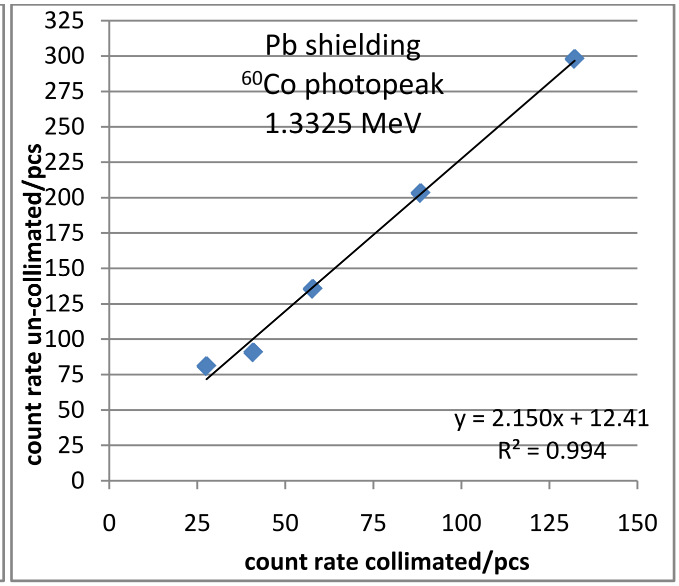
Figure (8A) shows the relationship between the number Of counts under condition of un-collimated and the Number of counts under condition of collimated Of 60Co photopeak 1.3325 MeV for Fe shielding



Figure(8B) shows the relationship between the number Of counts under condition of un-collimated and th3 Number of counts under condition of collimated Of 60Co photopeak 1.3325 MeV for Alshielding



Figure(8C) shows the relationship between the number Of counts under condition of un-collimated and the Number of counts under condition of collimated Of 60Co photopeak 1.3325 MeV for C shielding



Figure(8D) shows the relationship between the number Of counts under condition of un-collimated and th3 Number of counts under condition of collimated Of 60Co photopeak 1.3325 MeV for Pb shielding

Material	Atomic number	Density g/cm^3	Build-up factor	R^2	Max.thickness
C	6	2.25	2.32	0.992	10
Al	13	2.74	1.98	0.999	10
Fe	26	7.86	2.08	0.998	5
Pb	82	11.35	2.15	0.994	2.62

Table (3) shows the experimenat value of build-up factor for all four materials

From table numder (3), if we look the value of build-up factor, it is clear that the value of build-up factoer is eaxctly depend on the density of the material and the thickness of shielding. Therefore unitl the density of the material decrease the value of B(μx) increases. Because for those materilas, which have less density, cannot absorbe the energy of the beam sufficiently, and then reduce the intensity of the beam, therefore a larger number of photons can reach the detector. Take graphid as an example which has a lower density and higher value of build-up factor is larger enough. But the reader may be counfused about the value of B(μx) for lead absorber. Although this absorber materail has a larger density or atomic number, still has a larger value of B(μx). But the problem here is that just a little thickness was considered for this material absorber, which was 2.62 cm at maximum value. Because later on we will look the relationship between the value of B(μx) and the thickness of the absorber material.a and it will illustrate how the value of B(μx) decrease by increasing the thickness of the absorber material. We can also consider on the relationship between the buil-up facter and the thickness of the absorber materaila, take Fe absorber material as an example as plotted below

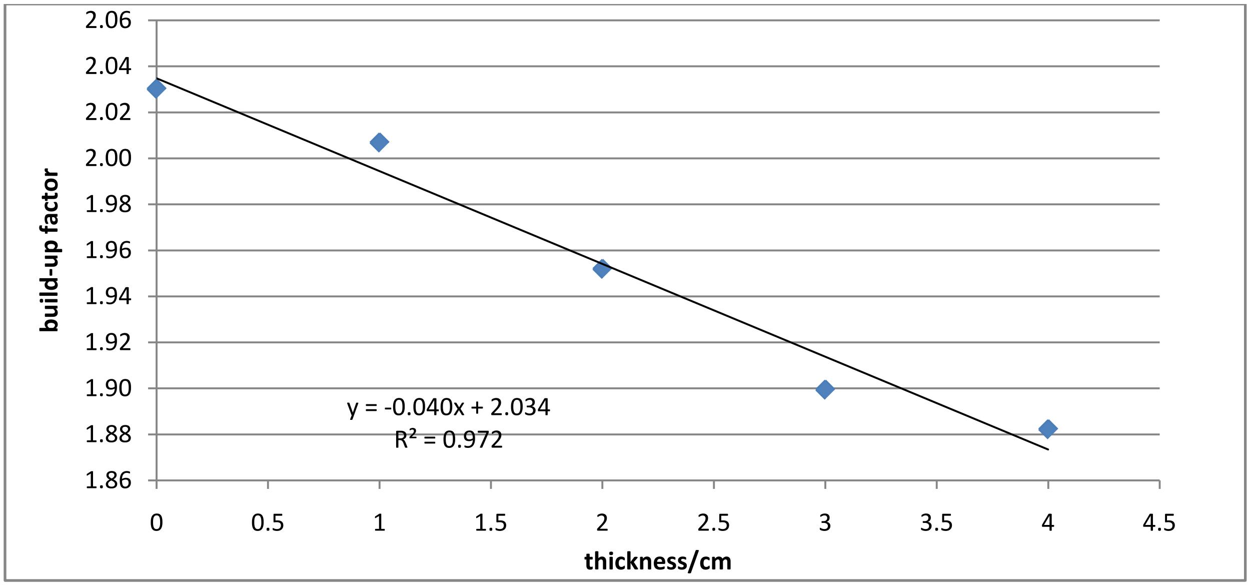


Figure (9) shows the relationship between the build-up factor as a function of thickness for Fe shielding of 1.3325 MeV 60Co

As we can see from figure (8), by increasing the thickness of the absorber material the value of build-up factor decreases, therefore it tells us at the maximum thickness the larger amount of radiation intensity is absorbed instead of scattered and then reach the detector. That is why at maximum thickness just a lower number of counts can pass through the absorber material and reach the detector

Conclusion

At the first part of the experiment, the attenuation of 60Co 1332.5 KeVgamma-ray by using different material shielding such as C, Al. Fe and Pb were studied as a function of thickness and mass thickness. It was found that for all absorber materials, which have studied, the gamma-ray attenuation is exactly described by an exponential decay, which can be seen from figure (2A, 3A, 4A and 5A). the reason for this is that, as we discussed from different types of attenuation the third type of attenuation, which was exponential attenuation is particularly applied for a photon radiation (X and gamma-ray), and a reasonable thickness (should not be too much thick). The value of linear attenuation coefficient μ was found for all four absorber materials. In this section the highlight point is that, the Pb absorber had the highest value of linear attenuation coefficient. In contrast, the C absorber had the lowest value of μ. Therefore this point tells us, at a higher atomic number material the probability of gamma-ray interaction with matter much higher than due to other lower atomic number materials. That is why when the gamma-ray interacts with high atomic number materials, it loses its energy either by absorption or scattering, thus just a lower number of photos, which have high energy level, can reach the detector. The value of mass attenuation coefficient μ/ϱ was also found for each material, again the Pb absorber had the highest value of mass attenuation coefficient and C absorber had the lowest value. But the confused point was about other two materials (Al and Fe). Although each of them has a different density, they have nearly the same value of mass attenuation coefficient. In the second part of this experiment we considered on the broad beam, when the beam is un-collimated. Figure (8A, 8B, 8C and 8D) show the relationship between the number of counts per second under condition of poor geometry and the number of counts per second under the condition of good geometry for each material. Generally if we look the graphs we can see that the number of un-collimated counts are twice time greater than the number of collimated counts. The reason for this is that, when the beam is quite broad more number of photons can actually be scattered and then reach the detector. Last but not least, the build-up factor, which is the ratio the number of counts under condition of bad geometry to the number of photons under the condition of bad geometry, was found for all four materials. From table () it can be seen that graphed has a larger value of build-up factor (B). Because this material has a lower atomic number, thus it is easy for the photons to scatter and pass through this material.

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