Investigation of Attenuation Properties of Liquid Materials by Gamma Absorption-Scattering Method

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***Abstract*: In this work, a system for the characterization of materials using transmission and scattering of gamma rays is described and used to assess the attenuation properties of some liquid materials. The apparatus consists of a 45 mCi point source of ^{124}Am and thin NaI (Tl) detector. Measurements are presented for sucrose solutions with densities ranging from 1 to 1.86 g/cm^3. For the absorbance, the solution Z (0.66 g/cm^3) with the lowest density has higher absorption with chances to attenuate more than some higher density absorber solution like the sucrose (1.37 g/cm^3) while sucrose (1.86 g/cm^3) solution with the highest density possessing highest absorption and attenuation capabilities. This however did not fully accord to the conformity with the theory in low-density absorber which will give rise to less attenuation than a high-density absorber since the chances of an interaction between the radiation and the atoms of the absorber are relatively lower. Consequently, the variation of the ratio of scattered and transmitted intensity against the density of the solutions display some arbitrary dependence with energy of the photons interacting with the density of the absorber solution with some little deviation to the exact ideal scattering and transmission case. With gamma rays, most likely the scattering is in the forward direction and that the probability of scattering backwards or in larger angles is relatively constant as the angle approaches 90.**

I. INTRODUCTION

In effort to reduce personnel exposure to ionizing radiation, attenuation or shielding of gamma radiation is an important component of radiation safety programs. Information about shielding properties of commonly used shielding materials is available in many data resources bases. Selecting the most appropriate shielding material for a given source of ionizing radiation will require knowledge of the source of radiation, application of attenuation data from available resources, and understanding of the basic principles gamma ray interactions with matter [1, 2].

For the investigation of materials (solid or liquid) which can be used for shielding against radiation, study of interaction of nuclear radiations with matter is very important. These radiation-shielding materials have great importance for many scientific, engineering and medical applications. The data based on mass attenuation coefficient and half value layer is very useful for the purpose to identify the various radiation shielding materials [3]. Despite the advantages of the existing shielding materials (concrete for example) some limitation are also associated with them. A concrete is not transparent to visible light thus restricting one to see through it. Secondly, when it is exposed to the radiations for a longer period its mechanical strength is reduced. So it is desired to have materials which are transparent to visible light and have better shielding properties in terms of lesser volume requirement [4, 5].

Materials that are used to absorb radiation are highly needed to properly attenuate ionizing radiation. Long-period exposure of human to ionizing radiation can cause permanent tissue damage, acute radiation syndrome, cancer, and even death in high cases. To prevent these effects, radiation workers supposed to be provided with efficient radiation shields that will lower the levels of radiation to regulatory limit [6, 7].

The most important parameter characterizing the transmission and diffusion of gamma-radiation in extended matter is the attenuation coefficient (μ) which depends on the photon energy and (E) and atomic number (z) of the medium. Hence, we are primarily interested in evaluating and the side scattering of gamma-radiation for different various sample solutions with different densities in their chemical composition. Gamma-ray photon is uncharged and creates no direct ionization of the material through which it passes. The detection of gamma rays is therefore critically dependent on causing the gamma ray photon to undergo an interaction that transfers all or part of the photon energy to an electron in the absorbing material. Mono-energetic gamma rays can be collimated into a narrow beam and allowed to strike a detector after passing through an absorber and the result will be simple exponential attenuation of the gamma rays [8, 9].

Each interaction process removes the gamma ray photon from the beam either by absorption or by scattering away from the detector direction. This removal of gamma photon from the beam is characterized by fixed probabilities. Although numbers of possible interaction mechanisms in matter are known for gamma, three major types play an important role in radiation measurement: photoelectric absorption, Compton scattering and pair production.

Among the interaction mechanisms for gamma rays in matter only Compton scattering that may rightly be called scattering. Both photoelectric effects and pair productions involve absorption of the primary photon. In Compton scattering, the photon transfers a portion of its energy to the electron, which is then known as recoil electron. Because all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma ray energy [10].

When the density of material increases, the probabilities of gamma ray photons undergo Compton scattering will increase. When the interaction increase, more scattered photons will be produced. Therefore the scattered intensity increases when the density of material increases [11]. A specific name is given to the thickness at which half the radiation is either absorbed or scattered and the other half passes through the material, this thickness is called the half thickness. Thickness in terms of its absorption ability is not normally how one would perceive thickness.

A number of techniques based on the transmission and scattering of gamma rays have been developed for the characterization of materials. Several different systems, particularly for the measurement of bone density, using both the transmitted and Compton scattered beams have been developed [12]. The technique of obtaining the ratio of coherent to Compton scattering intensities has been applied to the determination of bone density and also to the characterization of industrial and biological materials [13]. There have been written reviews on bone density measurements which employ X-ray and gamma ray absorption and scattering. A new technique which considers the use of coherent scattering alone as a means of characterization has been developed [14].

In this work, a comparison of the liquids' absorption ability is intended to be made and therefore, gamma-ray shielding behavior of the liquids can be investigated. The prominent variations in their energy-absorption parameters (such as mass attenuation coefficients, mass energy absorption coefficients and corresponding atomic number and electron densities) with gamma-ray photon energy will as well be observed due to the dominations of various absorption and scattering phenomena.

II. THEORETICAL CONSIDERATIONS

2.1 Transmitted intensity versus material density

Interaction process between the beam of gamma photon and the bulk of the material removes the gamma ray photon from the beam either by absorption or by scattering.

Linear attenuation coefficient, (photoelectric) (Compton) κ (Pair) ……………………..…….(1)

2.2 Interaction of Gamma Rays

Although a large number of possible interaction mechanisms are known for gamma in matter, only three major types play an important role in radiation measurement: photoelectric absorption, Compton scattering and pair production.

Among the interaction mechanisms for gamma rays in matter, only Compton scattering that may rightly be called scattering. Both photoelectric effects and pair production involve absorption of the primary photon. In Compton scattering, the incoming gamma ray photon (*hv)* is deflected through an angle, with respect to its original direction. The photon transfers a portion of its energy to the electron (assumes to be initially at rest) which is then known as recoil electron. Because all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma ray energy. The scattered photon,

$$hv' = \frac{hv}{1+\alpha(1-cos\theta)} \qquad ……………………………..(2)$$

where $\alpha = \frac{hv}{m_0c^2}$ and m_0c^2 is the rest mass energy of the electron ($0.511\ MeV$)

The number of transmitted photons I is given in terms of the number without an absorber I_0 as

$$\frac{1}{10} = e^{-(\mu t)\rho t} \qquad …………...…..(3)$$

where ρ is the density of the medium.

For a given gamma energy, the mass attenuation coefficient ($^{\mu}/_{\rho}$) does not change with physical state of a given absorber. In this experiment, the gamma rays before entering the material (I_0) and the thickness of material (t) are fizzed. Therefore, the equation 3 becomes

$$-\ln I\ \alpha\ \rho \qquad …………………………………..(4)$$

If a graph *-ln I* versus ρ is plotted, a straight line can be obtained. By measuring the transmitted intensity, *I* from other material, the density ρ can be determined using that graph. The transmitted intensity decreases when the density of the material increases.

From the equation mentioned above, *I* will decrease when ρ is increased. This is because when the density increases, the probabilities of gamma ray photon undergo photoelectric absorption and pair production will increase. When the interaction increase, more energy will be absorbed in the absorber and transmitted intensity will be less.

When the density of material increases, the probabilities of gamma ray photons undergo Compton scattering will increase. When the interaction increase, more scattered photons will be produced. Therefore, the scattered intensity increases when the density of material increases. If a graph of ratio of scattered density to transmitted intensity versus density is plotted, a straight line can be obtained. By measuring the scattered intensity from other material, the density can be determined using that graph.

III. MATERIALS AND METHOD

To study low energy gamma ray transmission and scattering techniques in order to characterize liquid materials using transmission and scattering of gamma rays, facilities used were: multichannel analyzer (MCA); computer with Maestro Program; gamma sources Am-241 (45 mCi)**;** NaI (TI) detector; amplifier and voltage supply**;** Electronic balance and cylinder. While the liquids materials assessed are tabulated in Table 1 with their densities.

Table 1: Density of liquids materials assessed

Materials	Density (g/cm^3)
Water	1.01
Petrolatum	0.83
Honey	1.40
Palm Oil	0.97
Sucrose	1.00, 1.20, 1.37
Solution	0.30
Solution	0.06

The detector system, MCA and computer were turned on and the detector system was at 0.9 kV high voltage, with amplifier coarse gain of 1 K and fine gain of 2. Maestro program counting time was set at 20 s (live time), while initial scattering angle of 0° platform was set. Cover in front of Am-241 source was removed. Spectrum displayed on the PC screen was observed. The cross gain and fine gain were changed to set the peak at channel . An empty cylindrical plastic vial was placed in the center of platform. The transmitted peak area for at incidence angle was measured. Each material was filled into vial peak area was measured in certain counting time and scattering angle. The arrangement to measure scattered intensity is shown in Figure 1.

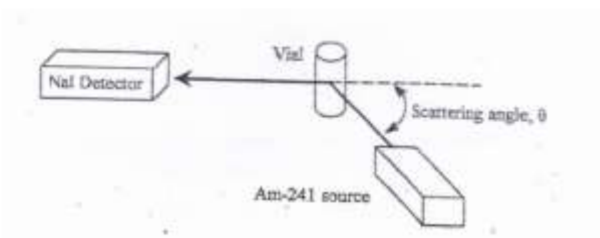

Figure 1: Arrangement to measure scattered intensity.

Measure The transmitted peak area for incidence angle for water and the other materials (Sucrose, honey….) was measured. The scattered peak area for incidence angle for water and the other materials (Sucrose, honey…...) was measured. One of the Sucrose solutions was taken and measured the scattered peak area for incidence (Scattering) angles of and. Weight and volume of solution and solution were measured using the electronic balance and cylinder measurement. Density was calculated, densities of the sucrose solutions and other materials were given. Three graphs were plotted

a) Absorbance versus density of water and sucrose solutions
b) Scattering peak data versus scattering peak angle for the chosen sucrose angle solution
c) Ratio of scattered to transmittance versus density of water and sucrose solution

IV. RESULTS AND DISCUSSION

The result of the background intensity I_o when the gamma source (Am-241) is open without any absorber solution placed in front of the source is shown in Table 2 below.

Table 2: Background intensity

Peak Intensity	FWHM	Net count	Net Area
456.13	61.40	7348.41	4409045 ± 13800

From the peak displayed and analyzed by the MCA, the FWHM is 61.40 and it gives the background intensity as 7348.41. While for the measurement of the transmitted intensity, the various solutions were individually placed in front of the gamma source at 0° incidence angle for 600 s each. The table below presents the data of the experiment.

Table 3: Peak intensity at 0° incidence angle for various solutions with different densities

Vial solution	Density, $\rho\ (\frac{g}{cm^3})$	Peak Intensity	FWHM	Transmitted Intensity	I_{tr}/I_0	$-ln(I_{tr}/I_0) \times 10^{-2}$	Net Area
Empty	0.00	444.55	60.91	7412.32	1.01	-0.86	444739313416
Honey	1.40	471.41	62.16	4972.53	0.68	39.06	298351611654
Palm oil	0.97	473.98	61.44	5201.63	0.71	34.55	312097712104
Petrolatum	0.83	468.33	61.98	5672.45	0.77	25.89	340347212382
Sucrose	1.37	484.07	63.56	6141.38	0.84	17.94	368482813151
Sucrose	1.20	477.22	61.87	4892.95	0.67	40.67	293576911638
Sucrose	1.00	472.98	62.03	6335.56	0.86	14.83	380133513030
Water	1.01	463.60	61.83	5303.82	0.72	32.61	318229412073
Solution Y	1.86	479.04	62.50	4650.98	0.63	45.74	279058811349
Solution Z	0.66	478.65	62.27	5039.97	0.69	37.71	302397912200

For the scattered intensity measurement, the various solutions were also placed in front of the gamma source at 20° scatter angle of incidence for 600 s lifetime each.

Table 4: Peak intensity at scatter angle for various solutions with different densities

Vial solution	Density, $\rho\ (\frac{g}{cm^3})$	Peak Intensity	FWHM	Scattered Intensity	$I_{sc}/I_{tr} \times 10^{-3}$	Net Area
Honey	1.40	174.84	52.44	20.43	4.11	12258543
Palm oil	0.97	174.84	52.44	14.35	2.76	8608495
Petrolatum	0.83	174.45	48.53	13.34	2.35	8002490
Sucrose	1.37	186.38	48.73	23.98	3.90	14391621
Sucrose	1.20	177.92	49.43	15.16	3.09	9097511
Sucrose	1.00	185.97	48.72	19.91	3.14	11947533
Water	1.01	176.67	49.22	15.92	3.00	9550499
Solution Y	1.86	181.14	50.15	20.23	4.35	12140521
Solution Z	0.66	181.27	41.54	15.10	2.99	9058469

Table 5: The sucrose (1.20 g/cm^3) scattered peak intensity at different scattering angles of 20°, 30°, 45°, 60°, 70° and 90° for 600 s lifetime.

Vial solution	Scattering angles (θ)	Peak Intensity	FWHM	Scattered Intensity	Net Area	Scattering Peak, ($I_{sc} \times 10^{-3}$)
Sucrose	0°	227.06	65.12	1198.51	4812	1000
Sucrose	20°	177.92	49.43	15.16	9097511	2.06
Sucrose	30°	176.06	55.91	24.84	14905601	3.38
Sucrose	45°	174.52	56.62	52.06	31234743	7.08
Sucrose	60°	181.45	52.96	51.41	30845803	6.99
Sucrose	70°	179.38	57.62	45.95	27569762	6.25
Sucrose	90°	173.93	54.23	36.95	22168689	5.03

Table 6: Transmission of the absorbance intensity ratio of solutions at 0° incident angle for 600s lifetime.

Vial solution	Density, $\rho\ (\frac{g}{cm^3})$	Transmitted Intensity	Net Area	$-ln(I_{tr}/I_0) \times 10^{-1}$	$I_{sc}/I_{tr} \times 10^{-3}$
Honey	1.40	5303.82	318229412073	3.26	4.11
Palm oil	0.97	5201.63	312097712104	3.46	2.76
Petrolatum	0.83	5672.45	340347212382	2.59	2.35
Sucrose	1.37	6141.38	368482813151	1.79	3.90
Sucrose	1.20	4892.95	293576911638	4.07	3.09
Sucrose	1.00	6335.56	380133513030	1.48	3.14
Water	1.01	5303.82	318229412073	3.26	3.00
Solution Y	1.86	4650.98	279058811349	4.57	4.35
Solution Z	0.66	5039.97	302397912200	3.77	2.99

The absorption of a beam of gamma rays in a given material is described by the exponential law:

$$I = I_0 e^{-\mu\rho l}$$

then, $$-ln(I_{tr}/I_0) = \mu\rho l$$

Where I_0 is the beam intensity at the point of observation in the absence of the absorbing material, ρ is the density of the medium in g/cm^3 and l is the thickness of the medium traversed by the beam in cm. In order to observe the disparity of the absorbance with density, we first find the linear attenuation coefficients by plotting a graph of $-ln(I_{tr}/I_0)$ vs the density of the solutions.

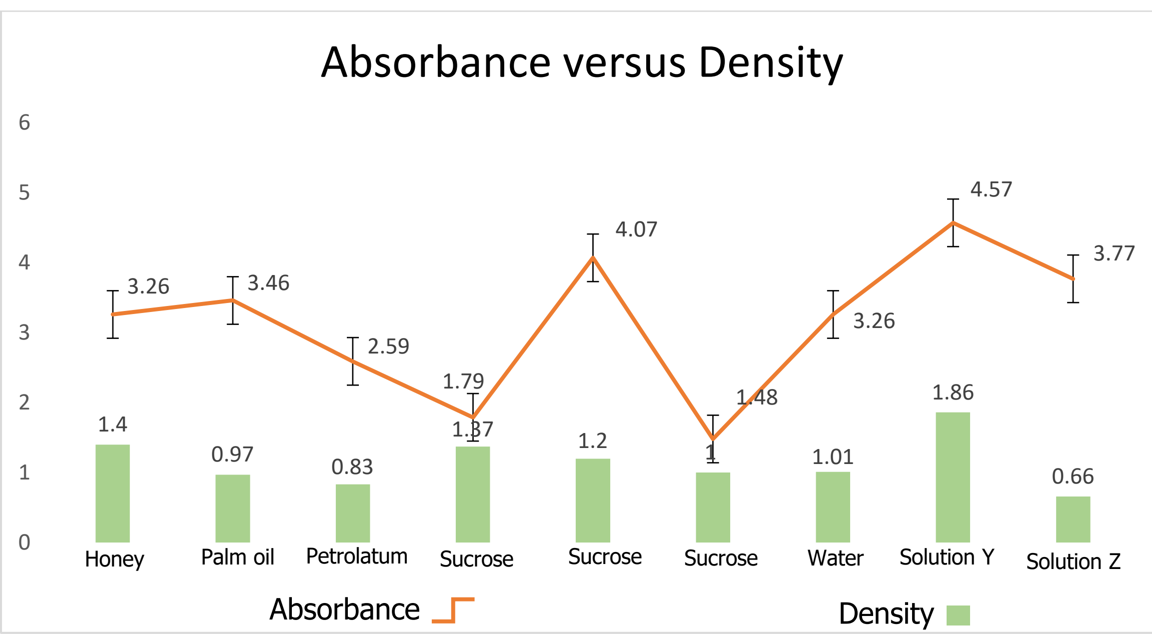

Figure 2: Absorbance $-ln(I_{tr}/I_0)$ versus density of water and sucrose solutions + other solutions.

An approach to exploring the magnitude of absorption is to see what happens when the density of the absorber solutions is changed. We can see from Figure 2 that the solution Z (0.66 g/cm^3) is the lowest density solution but possessing high absorption and attenuation, while solution Y (1.86 g/cm^3) is the highest density solution with the highest absorption and more attenuation. Unlike the sucrose (1.37 g/cm^3) with density higher than solution Z showing low absorption and attenuation capabilities. Likewise in the other solutions' absorptions and attenuation, significant fluctuations can be observed which however fail to accord to the conformity with the theory in low-density absorber which will give rise to less attenuation than a high-density absorber since the chances of an interaction between the radiation and the atoms of the absorber are relatively lower. In addition, the density determines the transmission coefficient as it relates to the sample, since the lower the density, the higher the transmission coefficient due to the porous nature of the material. The ambiguous deviation can be due to some errors in the experimental set-up and preparation which in turn can lead to uncertainties in the entire measurement and calculation process.

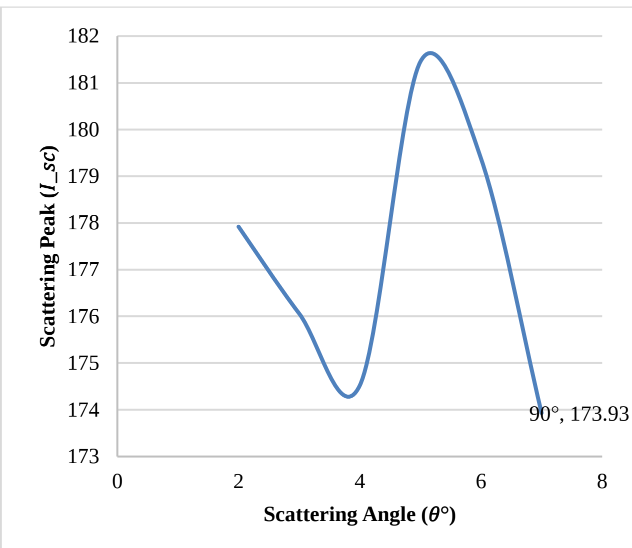

Figure 3: Scattering peak intensity (I_{sc}) versus scattering angle (θ°)

Scattering angles depends on the energy of the photon in the theoretical curve with E_r 0, representing variation with photons of less energy and E_r = 0.09 MeV E_r = 0.51 MeV representing those which are energetic. In our work the graph is more similar to the variation of E_r = 2.56 up to 90. According to this work, gamma rays from Am-241 have energy 0.00595409 MeV, we expect it to vary like E_r = 0.09 MeV but that was compromised because we stopped at 90. With our results and the theoretical curve, it is clearly shown that with gamma rays, most likely the scattering is in the forward direction and that the probability of scattering backwards or in larger angles is relatively constant as the angle approaches 90.

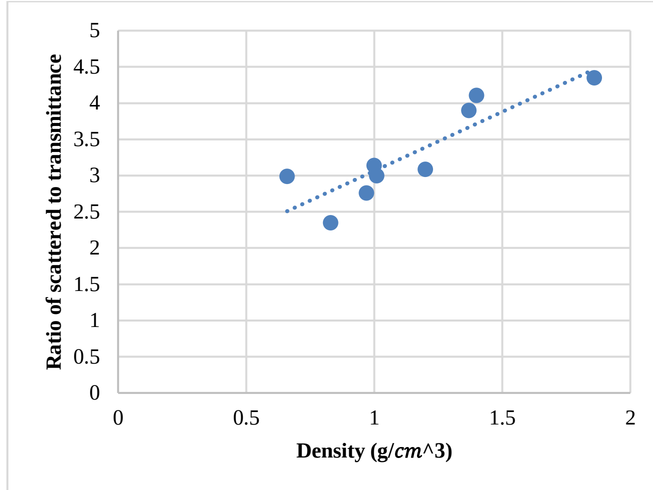

Figure 4: Variation of the ratio of scattered to transmitted intensity versus density of water and sucrose solutions + other solutions.

The variation of the ratio of scattered and transmitted intensity with the density of the solutions is also arbitrary to the theory in exploring the magnitude of the change in densities. The graph shows that Compton scattering is dependent on the density. Although variation of the ratio of scattered to transmitted intensities against the density display some deviations somewhat in few solutions as in the case of solution Y (0.66 g/cm^3) and sucrose (1.20 g/cm^3), but according to the theoretical graphs, there exist dependency with energy of the photons interacting with the density of the absorber material for an ideal scattering and transmission case.

V. CONCLUSION

The scattered intensity through solutions is more to the forward direction and it decreases rapidly with slight changes in the angles of incident radiation and becomes nearly close to zero as angles approach 90.

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