

Photon interaction studies using ^{241}Am γ -rays

N RAMACHANDRAN¹, K KARUNAKARAN NAIR², K K ABDULLAH³
and K M VARIER^{4,*}

¹Department of Physics, MPMMSN Trust College, Shoranur 679 523, India

²Department of Physics, MES College, Ponnani 679 586, India

³Department of Physics, Farook College, Feroke, Calicut 673 632, India

⁴Department of Physics, University of Calicut, Malappuram 673 635, India

*Corresponding author. E-mail: kmvarier@gmail.com

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Abstract. We have carried out some photon interaction measurements using 59.54 keV γ -rays from a ^{241}Am source. These include γ attenuation studies as well as photoelectric absorption studies in various samples. The attenuation studies have been made using leaf and wood samples, samples like sand, sugar etc., which contain particles of varying sizes as well as pellets and aqueous solutions of rare earth compounds. In the case of the leaf and wood samples, we have used the γ -ray attenuation technique for the determination of the water content in fresh and dried samples. The variation of the attenuation coefficient with particle size has been investigated for sand and sugar samples. The attenuation studies as well as the photoelectric studies in the case of rare earth elements have been carried out on samples containing such elements whose K-absorption edge energies lie below and close to the γ -energy used. Suitable compounds of the rare earth elements have been chosen as mixture absorbers in these investigations. A narrow beam good geometry set-up was used for the attenuation measurements. A well-shielded scattering geometry was used for the photoelectric measurements. The mixture rule was invoked to extract the values of the mass attenuation coefficients for the elements from those of the corresponding compounds. The results are consistent with theoretical values derived from the XCOM package.

Keywords. ^{241}Am ; γ -ray attenuation; fresh and dried leaf and wood samples; water content; photoelectric effect; mixture rule; rare earth elements; particles of varying size; sand; sugar.

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1. Introduction

Water is the most abundant constituent of plants and trees. The actual water content of plants and trees vary with the tissue type and depends on environmental and physiological conditions. The water content typically accounts for about 60 to 80% by weight in nonwoody parts and 30 to 50% in the woody parts. When leaves and wood dry up, they mainly lose their water content. Information about the water content is essential for purposes like understanding various biochemical

and metabolic processes in the plants, water diffusion, flow studies etc. Mortatti and Fillo [1] have used a method to study ten different samples using 662 keV and 59.54 keV γ -rays. Barros-Ferraz and Rezenda [2] used the method to study the density variability in two different samples of pine wood using ^{241}Am γ -rays, with a view to understand their productivity and climatic adaptation. Aguiar and Barros-Ferraz [3] developed a new method of water content gradation in wood based on low-energy γ -ray attenuation in pine wood samples. They showed that the method is quick, nondestructive and has reliably good sensitivities for moisture contents varying from about 30 to 90%. de Miranda *et al* [4] studied γ attenuation in natural wood, dry wood and dry leaves using ^{241}Am γ -rays. They found that the variation is small among different species. The woody parts have higher attenuation than leaves, both depending on the water content. In the present work, the γ -ray attenuation method has been used to estimate the water content of natural and dried samples of leaves and wood. The mixture rule (see eq. (1) below) [5] has been used for extracting the water content. ^{241}Am γ -rays of 59.54 keV energy have been used in these studies.

Compacted sand, clay and soil can be used for shielding radiation to within safety levels. The grain sizes of the particles in these materials vary with the sample location etc. The void spaces in between the grains depend on the particle size. Consequently, when γ -rays pass through such materials, the attenuation will depend on the extent of the void spaces and hence on the particle size. In earlier reported measurements, Singh *et al* [6] and Mudahar and Sahotas [7,8] had investigated the effect of the particle size on γ -ray attenuation. Appreciable variations have been seen in linear and mass attenuation coefficients with soil grain diameter d between 0.053 and 0.308 mm. The slope of the μ/ρ curve vs. d was found to decrease over an appreciable range from 1.54 to 0.23 as the γ energy increased from 81 keV to 1.33 MeV.

In the present work we have used sand samples collected from the Calicut beach, Neendakara beach and Areakad river (all locations situated in Kerala) and sugar samples of varying particle sizes. These have been subjected to attenuation studies using a ^{241}Am source, with a view to study the effect of grain size and voids on mass attenuation coefficients in the samples.

Gamma ray interaction studies at energies near the photoelectric absorption edges have been of interest to investigators in the field for quite some time now [9,10]. One reason for such an interest is the validity of the mixture rule at energies very close to the absorption edges [11]. Kerur *et al* [12] have shown that there is a possibility of the mixture rule breaking down at photon energies ranging from about 100 eV below to about 1500 eV above the K-edge. There have been very few measurements for testing the validity of the mixture rule within such energy ranges [13,14]. Jackson [15] pointed out that the range of validity of the mixture rule has not been adequately established close to the absorption edges. Nagel [16] has also stressed that the tabulated values of the attenuation coefficients can be in error near the absorption edges by as much as 50% and by 10% upto 400 eV above the edge. ^{241}Am presents a very suitable γ -ray source for measurements around the K-edge absorption threshold region. Its γ energy, 59.54 keV, lies in between the K-edges of the rare earth elements thulium (59.39 keV) and ytterbium (61.332 keV). Keeping this fact in mind, we have chosen ^{241}Am source also for the present

γ -ray measurements on attenuation and photoelectric effects, on several rare earth elements from Ce ($Z = 58$) to Yb ($Z = 70$).

2. Experimental details

The ^{241}Am source for the present measurements has been procured from Bhabha Atomic Research Centre, Mumbai. A vertical narrow beam geometry was used in order to reduce the effect of in-scattering on the measured γ -ray attenuation coefficients.

The γ -rays transmitted through the absorbing samples during the attenuation measurements and the X-rays emitted from the rare earth samples in the photoelectric studies were detected by a $2'' \times 1\frac{1}{4}''$ NaI(Tl) detector, coupled to a RCA 6810A photomultiplier tube, pre-amplifier and an ORTEC 571 amplifier. The amplifier output pulses were then fed to a CAMAC-based data acquisition and analysis system, consisting of a kinetic CAMAC crate, crate controller, a 4k Quad ADC, supplied by the Electronics Division, BARC and connected to a personal computer through a suitable interface card. A Linux-based package, FREEDOM [17], was used for the data collection and analysis. This Linux software had been developed at the Inter University Accelerator Centre, New Delhi for online data acquisition for accelerator-based experiments using CAMAC data acquisition hardware and also for online as well as offline data analysis. It has event-by-event data recording capabilities utilizing coincident detector signals. There is provision for spectrum fitting involving Gaussian peaks (with or without tailing) and polynomial background. The software presents a very user friendly graphical user interface (GUI) which is completely menu-driven.

A schematic diagram of the experimental set-up for the attenuation studies is given in figure 1. Suitable absorbers were prepared from the leaf and wood samples. For this, the leaf samples were cut in the form of rectangular pieces of dimensions $5\text{ cm} \times 5\text{ cm}$. Sets of three to ten such sheets were packed together in between two cardboard frames with a $2\text{ cm} \times 2\text{ cm}$ central hole, and secured intact to avoid corrugation of the leaves during drying. In order to increase the thickness of the leaf sample, another set of leaves was arranged in the same manner and placed over the first one and so on. In the case of wood, the absorbers were in the form of rectangular sheets of dimensions $5\text{ cm} \times 5\text{ cm} \times 1\text{ cm}$. After the measurement with each species of leaf/wood sample, the samples were kept in an oven at a temperature of 60°C for a period of four days. This ensures that all the water in the samples have been evaporated. Care was taken to ensure that the leaf samples did not develop wrinkles. The attenuation measurements were then repeated on the dried samples. Combining the measurements using the fresh samples and the dried samples the fractional weight of water in the fresh samples will be evaluated using the mixture rule as follows:

$$(\mu/\rho)_{\text{fresh}} = (1 - f_0)(\mu/\rho)_{\text{dried}} + f_0(\mu/\rho)_{\text{water}}, \quad (1)$$

where f_0 is the fractional water content and μ/ρ are the mass attenuation coefficients. The mass of the absorbers was taken on a precision electronic balance both

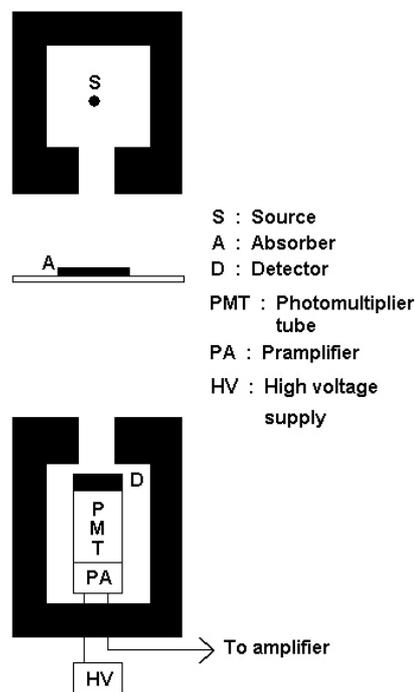


Figure 1. Schematic diagram of the experimental set-up for narrow beam geometry γ -attenuation measurements.

for the fresh and dried samples. Thus the water content of the samples can be evaluated separately and compared with the results from the attenuation studies.

The sand samples were prepared by sieving the oven-dried sand through a set of standard sieves with mesh sizes between $50 \mu\text{m}$ and 2mm . Equal quantities of the sand was taken in a weighed plastic sheet and weighed on an electronic balance. Ten such measured samples of the same grain size were used as the absorbers to calculate μ/ρ , ρ being the density. In order to prepare sugar samples of varying particle sizes, commercially available sugar of particle size 2mm was ground in a mixer-grinder and sieved in sieves of different mesh sizes.

First of all, the weighed quantity of sand of grain size of $50 \mu\text{m}$ is taken in a small beaker. By means of a suitable piston, the thickness of sand in the beaker is made uniform. The beaker containing the given amount of sand was kept between the detector and the source. For this thickness of the absorber, transmitted γ -ray spectrum was collected for sufficient time to ensure reasonable statistical accuracy. The background spectra were also collected in between these runs. Net absorption spectra were calculated by subtracting background from the actual spectrum. The mass attenuation coefficient was extracted from the data for different thicknesses of the absorbers for different grain sizes up to 2mm .

The absorbers and targets for the photon interaction studies in rare earth elements were prepared using oxides of rare earth elements Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Tm, Yb and Lu. The purity of the materials was better than 99%.

Two sets of targets have been prepared for each compound. One set was in the form of pellets of 1.2 cm diameter prepared using a pelletizer at a pressure of 10–12 t. In preparing the pellets, KBr has been added as a binding agent. The other set was in the form of aqueous solutions. For attenuation measurements both types of absorbers have been used. The solution was taken in a small beaker and kept at a convenient distance from the detector in the narrow beam good geometry set-up. The levels of the solution absorbers were measured using a sensitive travelling microscope. The thickness of the absorber is increased by adding more and more drops of the liquid. Each set of measurements using one aqueous solution absorber lasted typically for about 100 min. It was ensured that loss of water from the surface due to evaporation was negligible. The solution in the beaker as well as the stock solution were stirred well after each measurement. This ensured uniformity and homogeneity of the absorber.

The pellet absorbers were kept at a suitable distance from the source on a platform and the absorber thickness was varied by adding more pellets. For each absorber thickness, transmitted γ spectrum was collected for sufficient time periods to ensure reasonable statistical accuracy of better than about 2%. The background spectra were also collected in between these runs. Net absorption spectra were obtained by subtracting the background. For various thicknesses of the absorbers, the area under the photopeak of the transmitted spectrum was extracted and taken as a measure of the transmitted counts. The logarithms of the counts were plotted against the absorber thickness, and a linear plot was obtained. The mass attenuation coefficient was calculated in units of cm^2/g from the slope of the straight line plot. The experiment was repeated for various concentrations of the rare earth compounds.

The mass attenuation coefficients measured as above correspond to the mixtures of the rare earth oxides with water in the case of aqueous solutions and with potassium bromide in the case of the pellet absorbers. In order to extract the mass attenuation coefficients of the rare earth elements, it is first necessary to know the coefficients for water and KBr as the case may be. The values of the mass attenuation coefficients were separately measured for these compounds. The coefficient for KBr was also measured using pure KBr pellets. Using these additional data, the mixture rule was used to extract the mass attenuation coefficients of the rare earth oxides. Theoretical values of the coefficients for oxygen required for extracting the values of the coefficients for the rare earth elements were obtained from the XCOM package [18,19]. This package is a computer program and data base, developed by Berger and Hubbell. It can be used to calculate theoretical photon cross-sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, in any element, compound, or mixture, at energies from 1 keV to 100 GeV. It utilizes a vast data base for all elements from hydrogen to fermium.

A schematic diagram of the experimental set-up for the photoelectric studies is given in figure 2. A suitable aluminium frame is made for mounting the pellet target with its plane making an angle at 45° to the direction of incident γ -rays. The target is kept within a hole of 1.2 cm diameter in the aluminium strip. The ^{241}Am source is placed at a distance of about 10 cm from the target. Hence γ -rays will be incident on the target at an angle of 45° with respect to its plane. The targets were in the form of pellets, prepared as explained earlier. The strength of

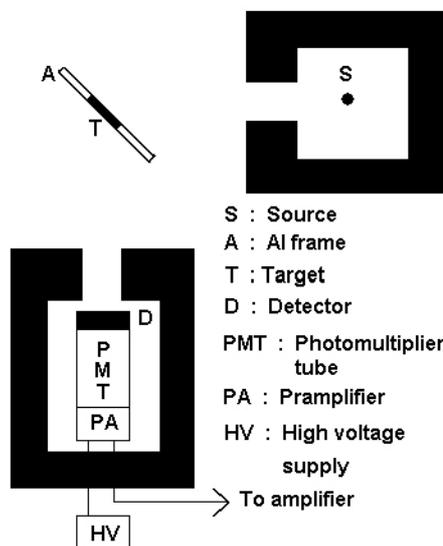


Figure 2. Schematic diagram of the experimental set-up for photoelectric measurements in rare earth compounds.

Table 1. Percentage water content in various plant leaves and corresponding attenuation coefficients.

Name	% Loss of water (theory)	% Loss of water (expt)	$(\mu/\rho)_{\text{fresh}}$ (cm ² /g)	$(\mu/\rho)_{\text{dried}}$ (cm ² /g)
<i>Musa paradisiaca</i>				
Nenthran	84.7	83.6	0.201	0.370
<i>Musa paradisiaca</i>				
Malavazha	67.2	68.8	0.185	0.297
<i>Musa paradisiaca</i>				
Kallanvazha	70.5	70.9	0.169	0.250
<i>Heliconia</i>	71.1	62.3	0.166	0.215
<i>Ficus elastica</i>	78.9	79.3	0.155	0.227
<i>Cocos nucifera</i>	60.0	56.6	0.149	0.166

the source has been eliminated from the calculations by measuring the direct count rates in the detector for the 59.54 keV peak with the source placed at the target position. The required efficiencies have been calculated theoretically.

3. Results

Tables 1 and 2 give the results of the present measurements for the leaf and wood samples respectively. The attenuation coefficients for the fresh and dried samples as well as the percentage of the water contents derived from the attenuation

Table 2. Percentage water content in various wood samples and corresponding attenuation coefficients.

Name	% Loss of water (theory)	% Loss of water (expt)	$(\mu/\rho)_{\text{fresh}}$ (cm^2/g)	$(\mu/\rho)_{\text{dried}}$ (cm^2/g)
<i>Psidium gujava</i>	52.7	49.0	0.173	0.208
<i>Samania saman</i>	48.3	34.0	0.149	0.154
<i>Artocarpus heterophyllus</i>	44.5	32.5	0.159	0.169
<i>Emblica officinalis</i>	38.4	41.4	0.159	0.176
<i>Briddia setusa</i>	42.1	35.7	0.158	0.170

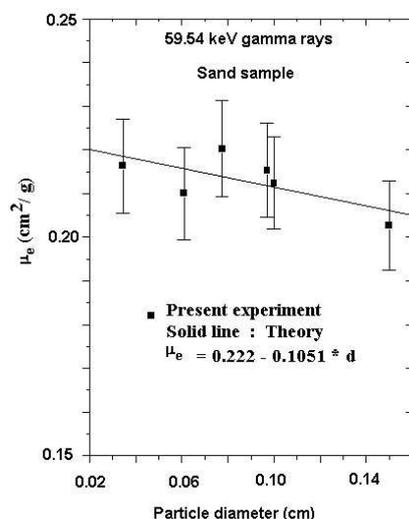


Figure 3. Variation of the attenuation coefficients with grain size at 59.54 keV for sand sample.

measurements and from direct mass measurements are given in these tables. It is seen that there is good agreement between the derived and directly measured values of the water content in the leaf and wood samples.

Variations of mass attenuation coefficients with grain diameter are shown in figures 3 and 4 for sand and sugar samples respectively. From these plots, it is clear that for the energy 59.54 keV, μ/ρ decreases with increase of the grain size d for these samples. Some of the sand samples collected from the Neendakara beach showed abnormal increases at some grain sizes. This was identified as due to the presence of excess iron or titanium in these samples, having these particular grain sizes.

The value of the mass attenuation coefficient for pure water obtained in the present studies is 0.206 ± 0.012 and the corresponding theoretical (XCOM) value is 0.2066. The agreement between these two values is excellent. For KBr, the values of the mass attenuation coefficient as determined in the separate studies as mentioned in the previous section, are respectively 1.92 ± 0.10 and 2.00 ± 0.13 in

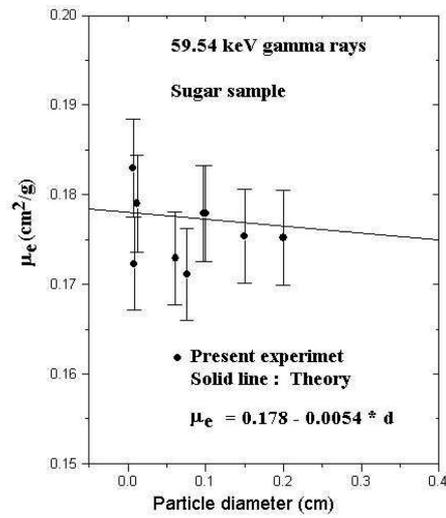


Figure 4. Variation of the attenuation coefficients with grain size at 59.54 keV for sugar sample.

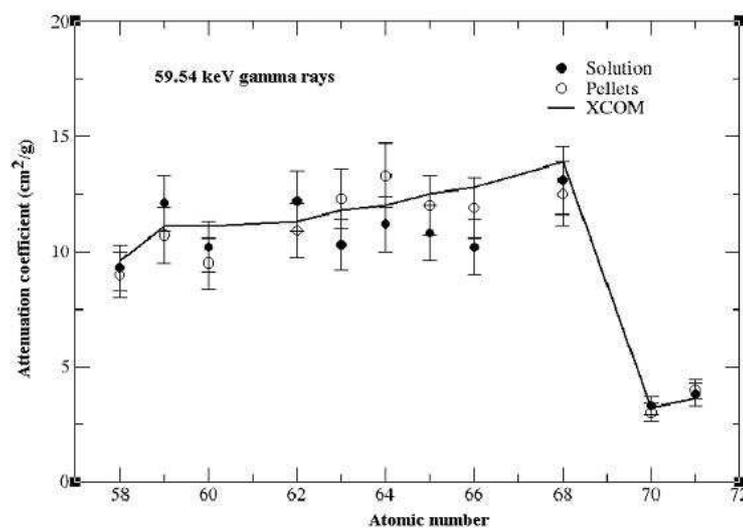


Figure 5. Variation of the attenuation coefficients at 59.54 keV for rare earth elements.

units of cm²/g. The XCOM value is 1.96. It is seen that the agreement is reasonably good. The values of the mass attenuation coefficients, obtained from the present investigations, for the various rare earth elements are given in table 3. This table gives the experimental values of the coefficients, obtained from the data on aqueous solutions as well as the pellet samples. The experimental errors are estimated to be around 10%. These experimental attenuation coefficient values are also compared

Table 3. Comparison of experimental mass attenuation coefficients with XCOM values for rare earth elements at 59.54 keV.

Atomic number	Element	Mass attenuation coefficient (cm^2/g)		
		Present experiment		XCOM
		Using aqueous solution	Using pellets	
58	Ce	9.3 ± 1.0	9.0 ± 1.0	9.6
59	Pr	12.1 ± 1.2	10.7 ± 1.2	11.1
60	Nd	10.2 ± 1.1	9.5 ± 1.1	11.1
62	Sm	12.2 ± 1.3	10.9 ± 1.2	11.3
63	Eu	10.3 ± 1.1	12.3 ± 1.3	11.8
64	Gd	11.2 ± 1.2	13.3 ± 1.4	12.0
65	Tb	10.8 ± 1.2	12.0 ± 1.3	12.5
66	Dy	10.2 ± 1.2	11.9 ± 1.3	12.8
68	Er	13.1 ± 1.5	12.5 ± 1.4	13.9
70	Yb	3.3 ± 0.4	3.0 ± 0.4	3.2
71	Lu	3.8 ± 0.5	4.0 ± 0.4	3.6

Table 4. Comparison of experimental photoelectric cross-sections with XCOM values for rare earth elements at 59.54 keV.

Atomic number	Element	Photoelectric cross-section (barns)	
		Present experiment	XCOM values
58	Ce	2140 ± 195	2144
59	Pr	2033 ± 234	2284
60	Nd	2335 ± 328	2422
62	Sm	3254 ± 386	2712
64	Gd	3559 ± 543	3015
65	Tb	3173 ± 452	3173
66	Dy	2752 ± 445	3342
69	Tm	3953 ± 440	3920

with the theoretical values derived using the XCOM package. It is seen that the agreement with the XCOM values is reasonable, taking into account the errors involved. Figure 5 shows a plot of the experimental and theoretical values of the mass attenuation coefficients for the elements investigated. The sudden fall in the mass attenuation coefficient near $Z = 70$ (Yb) is worth noticing. This corresponds to the fact that the γ -energy (59.54 keV) is in between the K-edge energies of thulium ($Z = 69$) and ytterbium ($Z = 70$).

The results of the photoelectric studies are presented in table 4 along with theoretical values based on the XCOM package. There is reasonable agreement between theory and experiment within the experimental errors involved.

4. Conclusions

We have shown that low energy γ attenuation method is suitable for the determination of the water content in leaf and wood samples. By studying the variation of γ -ray attenuation coefficients with particle size, we have shown that this method can be used to study the voids in various samples. The reasonable agreement between the experimental values of the mass attenuation coefficients for the rare earth elements with the XCOM values suggest the usefulness of the mixture rule. The overall agreement of the photoelectric cross-sections with theoretical values show that even with a low resolution scintillation detector, it is possible to derive reasonably accurate values of the interaction cross-sections.

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