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Mass attenuation coefficients and effective atomic numbers of biological compounds for gamma ray interactions

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ABSTRACT

The mass attenuation coefficients (μ/ρ) for some enzymes, proteins, amino acids and fatty acids were measured at 122, 356, 511, 662, 1170, 1275 and 1330 keV photon energies, by performing transmission experiments using ^{57}Co, ^{133}Ba, ^{137}Cs, ^{60}Co and ^{22}Na sources collimated to produce 0.52 cm diameter beams. A NaI (Tl) scintillation detector with energy resolution 8.2% at 663 keV was used for detection. The experimental values of (μ/ρ) were then used to determine the atomic cross section (σ_a), electronic cross section (σ_e), effective atomic number (Z_{eff}) and electron density (N_{eff}). It was observed that (μ/ρ), σ_a and σ_e decrease initially and then tends to be almost constant at higher energies. Values of Z_{eff} and N_{eff} were observed roughly constant with energy. The deviations in experimental results of radiological parameters were believed to be affected by physical and chemical environments. Experimental results of radiological parameters were observed in good agreement with WinXCom values.

1. Introduction

Carbohydrates, enzymes, proteins, amino acids and fatty acids are composed of C, H, N and O elements. These complex bio-molecules perform a variety of physiological functions inside living systems. Data on the interaction of gamma radiations with the biological samples and organic compounds are essential for some fields such as medical physics, medicine, biological and radiological protection. Photoelectric effect, Compton scattering and pair production are the main photon interaction processes by which gamma radiations interact with matter (Hubbell, 1999; Gowda et al., 1995; Nayak and Badiger, 2007; Manohara and Hanagodimath, 2007). Photoelectric absorption occurs at low energies ($E < 0.05$ MeV), whereas Compton scattering is the main interaction process dominates at intermediate energies (0.05 MeV < E < 1.02 MeV), and pair production at high energies (E > 1.02 MeV). Rayleigh scattering is being widely used in mammography, occurs at very low energy X-rays (15–30 keV).

Use of radioactive isotope is rapidly increasing in the field of diagnostics, industrial radiation processing and agriculture. Thus, the knowledge of radiation interaction with the human body and organic compounds is of prime importance. The radiological parameters μ/ρ, N_{eff}, Z_{eff} are the basic quantities required for determining the energy deposition and penetration in a given material. The attenuation coefficients of X-rays and gamma photons in alloys, soil, plastic and biological materials are of significant interest for nuclear medicine, diagnostics, radiation protection and radiation physics (Hubbell, 2006; Teli et al., 2000; Manohara and Hanagodimath, 2007). For each of the different photon interaction processes, the atomic number in composite materials cannot be represented by a single number uniquely in the entire energy region, as in the case of pure elements. This number for composite materials is called as Z_{eff}, and it varies with energy depending on the interaction processes involved. The Z_{eff} is a convenient parameter for representing X-ray and gamma photon interactions in a composite material and particularly in designs of radiation shielding or in medical dosimetry for calculations of absorbed dose.

In literature, several authors determined scattering cross sections and data related to μ/ρ for compounds, mixtures and elements (Berger et al., 2010; Hubbell and Seltzer, 2004; Chantler et al., 1995, 2005; Chantler, 2000). Morabad and Kerur (2010) measured the attenuation of X-rays in few medicinal plants. Recently, Z_{eff} values of biological compounds, tissues, diametric interest and nonlinear optical materials have been investigated at different energies (Akar et al., 2006; Demir et al., 2012; Manohara and Hanagodimath, 2008; Manjunathaguru and Umesh, 2009; Manjunatha and Rudraswamy, 2013; Ladhaf and Pawar, 2015; Pawar and Bichile, 2013; Gaikwad et al., 2016; Awasarmol et al., 2017; Bhosale et al., 2016). Ekinci and Astam (2007) have given a novel method for (μ/ρ) and density measurement of biological samples using energy dispersive X-ray fluorescence spectrometry. Similarly, M

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Table 1
List of organic compounds with their chemical formula.

Sr. No.	Samples	Chemical formula	Molar Mass (g mol-1)	Mean atomic number, Ẑ
1	Tryptophan	$C_{11}H_{12}N_2O_2$	204.225	4
2	Lysine	$C_6H_{14}N_2O_2$	146.188	3.33
3	L-Sirene	$C_3H_7NO_3$	105.093	4
4	Glycoprotein	$C_{28}H_{47}N_5O_{18}$	741.696	4.02
5	Thrombin	$C_{12}H_{10}ClN_3S$	371.843	5.29
6	Subtilisin	$C_{26}H_{32}N_3O_6Cl$	518.002	4.03
7	6-Aminocapric acid	$C_6H_{13}NO_2$	120.086	3.27
8	Lactose	$C_{12}H_{22}O_{11}$	342.297	4.04
9	Margaric Acid	$C_{17}H_{34}O_2$	270.45	2.87
10	Nonadecylic Acid	$C_{19}H_{38}O_2$	298.51	2.85
11	Arachidic Acid	$C_{20}H_{40}O_2$	312.56	2.84
12	Heneicosylic Acid	$C_{21}H_{42}O_2$	326.56	2.83
13	Behenic Acid	$C_{22}H_{44}O_2$	340.58	2.82

sub shell X-ray emission cross sections were reported first time by employing linear polarized photon beam from Indus-2 synchrotron source facilities (Kaur et al., 2014).

Proteins, amino acids and fatty acids make up the largest portion of human body weight as these organic compounds are present in hair, organs and muscles. Lipids and proteins are the structural components of biological membrane. The major constituents of lipids are fatty acids. The main biological functions of fatty acids are storing energy and construction of cell membranes in living cells. Amino acids are the most important macromolecules present in living cells and constitute the largest living matter in the animal and plant cells. Gamma radiation and its sources are being used continually in the food industry, biological and medical field advocates detailed knowledge of (μ/ρ), N_{eff}, Z_{eff} of amino acids, proteins, fatty acids and enzymes. Thus, the main objective of the present work is to determine (μ/ρ), ε, σ_a, σ_e, Z_{eff} and N_{eff} of Tryptophan, Lysine, L – serine, Glycoprotein, Thrombin, Subtilisin, 6 – Aminocapric acid, Lactose, Margaric acid, Nonadecylic acid, Arachidic acid, Heneicosylic acid and Behenic acid in the energy range 122–1330 keV and the variations of these parameters with photon energies are also studied. Experimental results are compared with values predicted based on WinXCOM (Gerward et al., 2004). The aim of the present investigation is also to reduce error sources in narrow beam geometry transmission experiments.

2. Theory

The net counts of photon intensities with (I) and without (I_o) organic compounds of different thickness were measured. These counts after the subtraction of background was used to determine the mass attenuation coefficient (μ/ρ) by following equation (Peele et al., 2002; Manohara et al., 2008)

$$\mu_m = \frac{\mu}{\rho}(cm^2 gm^{-1}) = \frac{1}{\rho t}\ln\left(\frac{Io}{I}\right) \tag{1}$$

Where ρ (g/cm³) and t (cm) are the density and thickness of the compound.

Mass attenuation coefficient for any chemical compound or mixture of elements can be calculated by mixture rule (Manohara and Hanagodimath, 2007)

$$(\mu/\rho) = \sum_i w_i(\mu/\rho)_i \tag{2}$$

Where w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the ith constituent element, respectively. The weight fraction of a chemical compound is given by; $w_i = \frac{n_i A_i}{\sum_j n_j A_j}$ where A and n_i are the atomic weight and number of formula units, respectively.

Using the equations of atomic ($\sigma_{t,\ a}$) and electronic ($\sigma_{t,\ el}$) cross sections Manohara et al. (2008) have shown effective atomic number (Z_{eff}) by the following relation

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} = \frac{\sum_i f_i A_i(\mu/\rho)_i}{\sum_j f_j\ (A_j/Z_j)(\mu/\rho)_j} \tag{3}$$

Where $f_i = n_i/\sum_j n_j = n/n_j$ and Z_j are the fractional abundance and an atomic number of a constituent element, respectively. The effective electron density (N_{eff}) can be defined as the number of electrons per unit mass is closely related to the effective atomic number. For organic compounds, N_{eff} was calculated by following relation (Manohara et al., 2008)

$$N_{eff} = N_A\frac{nZ_{eff}}{\sum_i n_i A_i} = N_A\frac{Z_{eff}}{\langle A\rangle} \tag{4}$$

Where N_A is the Avogadro constant, n_i is the number of atoms and $\langle A\rangle$ is the average atomic mass of the compound.

Theoretical (μ/ρ) values for individual organic compounds were predicted from WinXCOM (Gerward et al., 2004). The experimental (μ/ρ) values were calculated with the aid of the mixture rule and interpolated to the given energies.

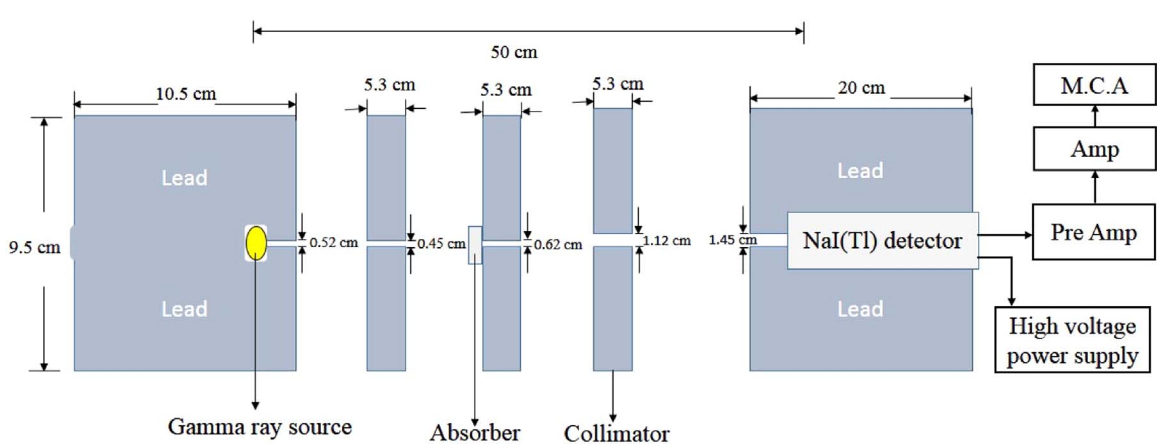

Fig. 1. The schematic arrangement of the experimental set-up.