Determination of the electron density of dry hydrophilic copolymer tissue-equivalent materials

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Cross-linked hydrophilic copolymer materials have the potential to be used as tissue-equivalent materials as they have the major elements found in soft-tissues. Two types of hydrophilic copolymer materials designated as ED1S and ED4C were used in a 90° Compton scattering arrangement using a Am-241 source and a NaI(Tl) detector system. The electron density of ED1S was $(3.1 \pm 0.4) \times 10^{23}$ e cm^{-3} and that of dry ED4C was $(4.4 \pm 0.4) \times 10^{23}$ e cm^{-3}.

I. INTRODUCTION

Two new hydrophilic cross-linked copolymer materials [1,2] might have the potential to be new phantom materials in dosimetry. The interest in these materials started as part of the development of contact lens materials [3,4].

One of the main advantages of cross-linked hydrophilic copolymer is its ability to absorb water which is one of the main components of human tissue. Basically, the copolymers used in our studies consists of a mixture of methylmethacrylate (MMA) which is a hydrophobic monomer and vinylpyrrolidone (VP) which is a hydrophilic monomer [4] have all the required major elements, such as hydrogen, carbon, nitrogen and oxygen, found in tissues. The elemental composition of the individual monomers are as shown in Table I.

The hydroplilicity of the cross-linked copolymer can be tailored by changing the composition ratio of the monomers. The two samples which were used in this study were designated as ED1S and ED4C. Their monomers composition ratio are as shown in Table II.

Al-Bahri and Spyrou [5] had determined the electron density of normal and pathological breast tissues and hydrophilic copolymer materials using Am-241 59.54 keV photons and a high purity germanium (HPGe) detector. The present study is to determine the electron density of dry hydrophilic copolymer materials using the same Am-241 source but using a NaI(Tl) detector due to its higher sensitivity.

II. THEORY

The Compton scattering formula is given by

$$E'_\gamma = \frac{E_\gamma}{1+\left(\frac{E_\gamma}{mc^2}\right)(1-\cos\theta)} \tag{1}$$

where E_r is the energy of the incoming photons, E'_r is the energy of the scattered photons and θ is the scattering angle.

The photon differential inelastic cross-section of an atom is given by

$$\frac{d_a\sigma^{incoh}}{d\Omega} = \frac{d_e\sigma^{KN}}{d\Omega}\cdot Z \tag{2}$$

at photon energies larger than the binding energies of the electrons concerned. Here, $\frac{d_e\sigma^{KN}}{d\Omega}$ is the Klein-Nishina differential cross-section for a free electron. Thus, at high energies, the incoherent cross-section is proportional to *Z*.

The number of singly scattered photons detected at an angle θ is given by

$$N_{scat}(\theta) = N_0 nV \frac{d_a\sigma^{incoh}(\theta)}{d\Omega} \tag{3}$$

where N_0 is the initial number of photons in the beam which are incident on unit area of the sample, *n* is the number of atoms per unit volume of the scatterer and *V* is the scattering volume of the sample.

TABLE I. The elemental composition of the hydrophilic materials. (Fraction by weight %) [2].

Material	H	C	N	O
Vinyl pyrrolidone (VP) (hydrophilic monomer)	8.16	64.84	12.6	14.39
Methyl methacrylate (MMA) (hydrophobic monomer)	9.59	71.4	-	19.02

TABLE II. Typical sample composition (ratio) used in this report [2].

Sample	MMA	VP
ED1S	1	3
ED4C	1	4

At sufficiently high photon energies, the electrons are effectively free. Thus

$$N_{scat}(\theta) = N_0 (nZ V) \frac{d_e \sigma^{KN}(\theta)}{d\Omega} \quad (4)$$

where $nZ = \rho_e$ is the electron density per unit volume.

For a particular size of scattering volume and at a certain scattered photon energy

$$N_{scat}(\theta) = k\rho_e \quad (5)$$

where k is a constant. Water is usually used as a reference material (ρ_e for water = 3.341×10^{23} e cm^{-3}). Hence, for a given sample *s*, its electron density can be determined by using

$$\frac{[N_{scat}(\theta)]_s}{[N_{scat}(\theta)]_w} = \frac{[\rho_e]_s}{[\rho_e]_w}. \quad (6)$$

III. MATERIALS AND METHODS

IIIa. NaI(Tl) Detector System

Balogun [6] suggested that NaI(Tl) is a better choice detector because of the need to make efficient use of the surface area of the detector. He used a converging collimator in order to make use of the total surface area of the detector.

A Canberra series 35 multichannel analyser (MCA) was used. The NaI(Tl) Be window detector was connected to a Canberra pre-amplifier Model 2005, which was then connected to an external Canberra spectroscopy amplifier Model 2010.

The Am-241 spectrum has two peaks as shown in Fig. 1. The first peak is made up of several low energy peaks of Americium-241 due to the poor resolution of the NaI(Tl) detector. In addition, the contribution of iodine K escape peaks cannot be ignored as iodine formed a component of the detector. The iodine K escape peaks is about 28 keV below the associated full energy photopeak. For the 59.54 keV Americium-241 peak, the expected iodine K escape peak should occur at about 31.54 keV.

IIIb. Shift In Energy (Or Channel Number) With Different Scattering Angles

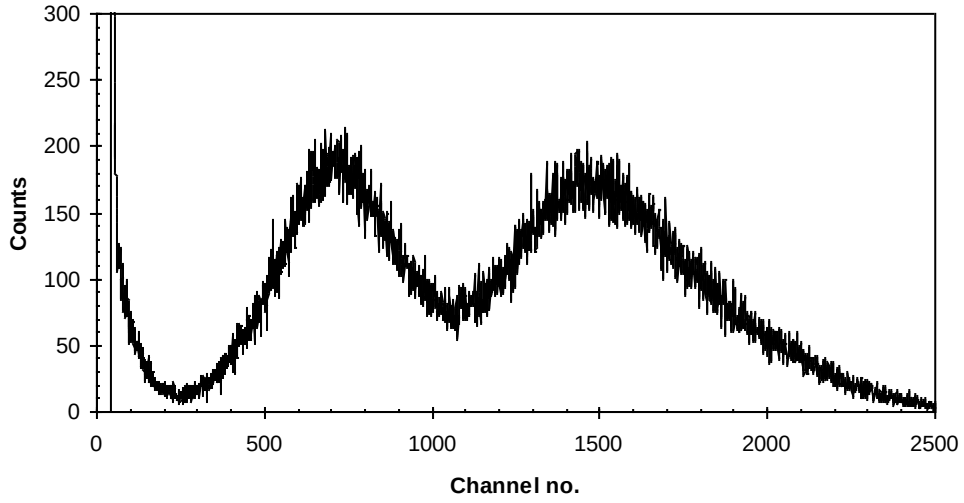
In Compton scattering, the incident photons are scattered with a reduced energy depending on the scattering angle. This properties were studied on the NaI(Tl) Be window detector.

A collimated Am-241 source (2 mm diameter) was used to irradiate water sample in a plastic vial 15 mm diameter. The scattered photons were detected using a NaI(Tl) Be window detector collimated to a 4 mm diameter hole. The angle of scattering was changed from 0° to 110°.

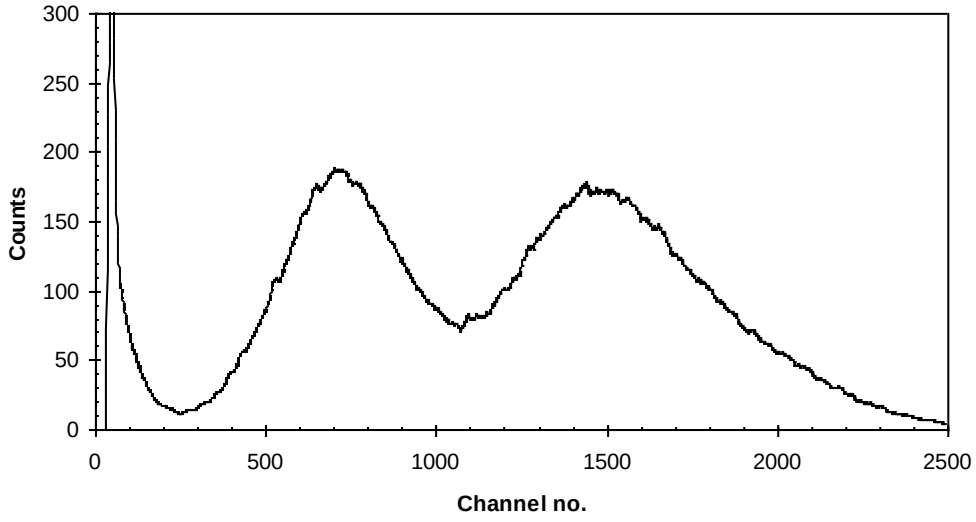
The arrangements of the apparatus are as shown in the Fig. 2. The measured energy value was compared with the scattered energy calculated from the energy equation and plotted in Fig. 3. At a scattering angle of 90°, the calculated scattered photon energy is 53.3 keV whilst the measured one is 54.9 keV.

IIIc. Multiple Scattering And Attenuation

Main limitations to the density resolution derive from the attenuation of the incident and scattered beam and from contamination introduced by multiple scattering of photons in the target material [7]. In fixed point densitometry, the attenuation could be taken to be constant. Attenuation correction is not necessary as the Eq. (5) compares with water under identical conditions.



(a)



(b)

FIG. 1. Smoothing of Am-241 spectrum detected by the NaI(Tl) Be window detector for 1000 s. (a) Original spectrum, (b) the smoothed spectrum.

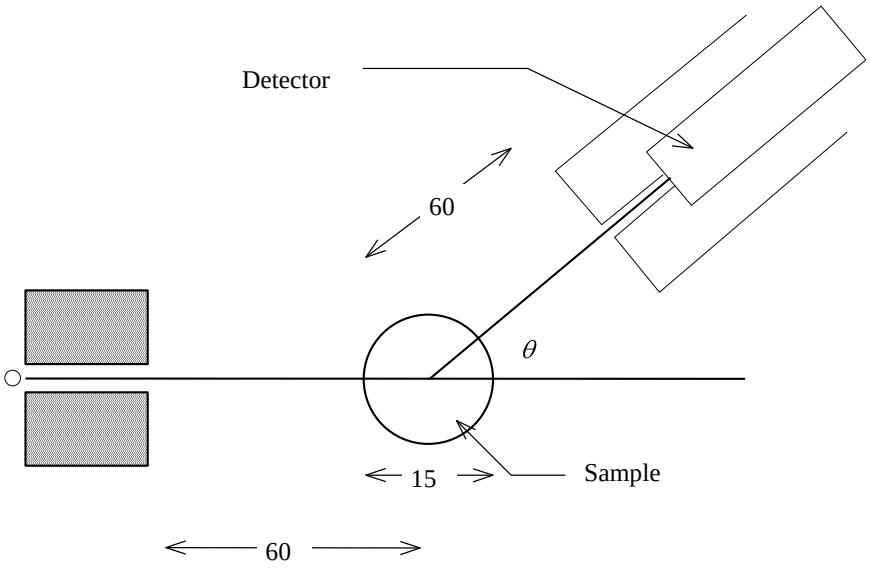


FIG. 2. Arrangement of the apparatus used for the Compton scattering experiments. All dimensions are in mm.

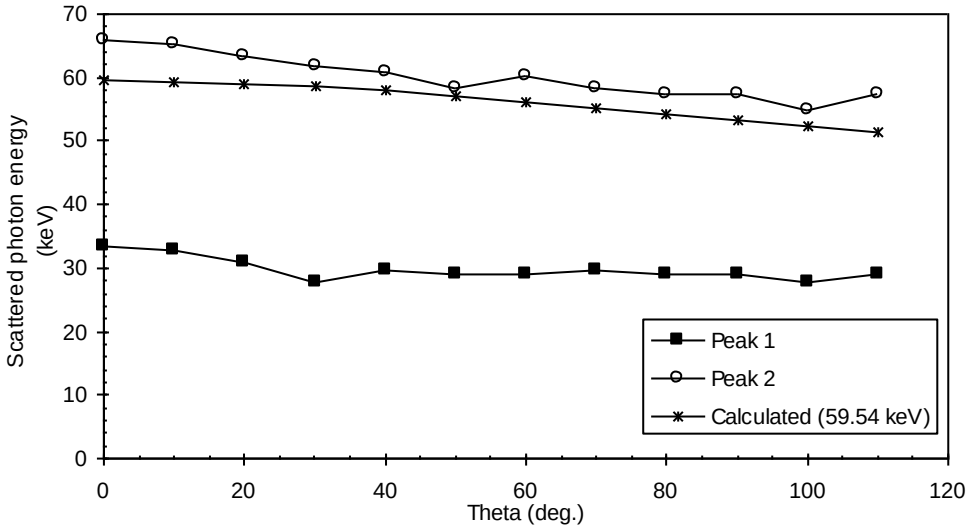


FIG. 3. Scattered photon energy at different scattering angles. The scatterer was water in a plastic vial 15 mm diameter. Peak 1 consists of unresolved low-energy peaks and Peak 2 is the 59.54 keV peak of Am-241.

IIId. Scattering Angle

Many authors used different scattering angles for their experiments. For example, Holt *et al*. [8] used a fixed angle of 171° while Morgan *et al*. [9] did scattering work using 150° backscatter.

The amount of multiple scattered photons accepted in a Compton scattering experiment increases with the volume of the exposed materials in the field of view of the detector [7,10]. Al-Bahri and Spyrou [5] and Balogun [11] concluded that the best resolution is obtained at a scattering angle of 90°. The smaller volume element at 90° reduces the contribution of multiple scattering. It is also desirable to reduce both the size of the detector's collimator and its field of view to as small as practically possible; keeping in mind that the overall count rate will decrease, necessitating a longer counting period and/or a stronger source [12].

IIIe. Smoothing Of Data

The Compton scattered photons usually have a very low intensity. This in turn caused the spectra to be noisy or highly fluctuative (Fig. 1(a)).

Smoothing of data was done by averaging the number of counts in a certain number of channels on either sides of and including the channel of interest. Several smoothing processes using different number of channels were tried on an Americium-241 spectrum and was run through the data using MSExcel.

The following process gave an adequate and sufficient smoothing of data for the given set of parameters of this experiment.

$$c'_n = \frac{c_{n-10} + ... + c_{n-1} + c_n + c_{n+1} + ... + c_{n+10}}{21} \quad (7)$$

where c_n is the number of counts in channel n and c'_n is the smoothed count for channel n. The fully smoothed spectrum is as shown in Fig. 1(b) illustrating easier identification of peaks and region of interests.

IIIf. Samples

Water sample in plastic vial was placed in the beam and the scattered photon at 90° was recorded in a Canberra series 35 multichannel analyser. The diameter of the vial was 15.0±0.5 mm diameter. The radiation source used was a 7.4 GBq Am-241 source collimated by a borehole collimator of 2 mm diameter. A 4 mm diameter borehole collimator was used to collimate the NaI(Tl) Be window detector.

Then the Compton scattered spectrum from the empty vial was taken. The scattered spectrum due to water only was obtained by data subtraction method (Fig. 4).

The same procedure was repeated for ED1S (dry) and ED4C (dry) samples. The samples were in cylindrical form 10 mm in height and 14 mm in diameter.

IV. RESULTS AND DISCUSSION

The scattering experiment for water sample was for a time duration of 57600 s. The spectra obtained are as shown in Fig. 4. For the scattered 59.54 keV Am-241 peak, the region of interest is between channels 658 and 1106. The electron density of water is taken as 3.341×10^{23} e cm^{-3}.

Using the formula given in Eq. (6), the electron density of ED1S (dry) can be calculated.

$$\rho_{e\,s} = \frac{N_{scat\,s}\,\rho_{e\,w}}{N_{scat\,w}}$$

$$= \frac{2036 \times 3.341 \times 10^{23}}{2194}$$

$$= 3.10 \times 10^{23}\,\text{e/cm}^3.$$

The standard deviation was calculated using

$$\frac{\delta\rho_{e\,s}}{\rho_{e\,s}} = \frac{\delta N_s}{N_s} + \frac{\delta N_w}{N_w}$$

$$\delta\rho_{e\,s} = \left(\frac{\delta N_s}{N_s} + \frac{\delta N_w}{N_w}\right) \times \rho_{e\,s}$$

$$= 0.36 \times 10^{23}\,\text{e/cm}^3.$$

Hence, the electron density of dry ED1S sample was

$$\rho_{e\,s} = (3.1 \pm 0.4) \times 10^{23}\,\text{e/cm}^3.$$

The same method of calculation was done for the ED4C (dry) sample. The electron density of ED4C (dry) was (4.4±0.4) × 10^{23} e/cm^3.

The values obtained were then compared with the values of Al-Bahri and Spyrou [5] as shown in Table III. The present values are generally lower especially for the ED1S (dry) sample. The ratio of the electron density of ED1S to ED4C in our study is 0.7 as compared to 0.97 of Al-Bahri and Spyrou study. Estimated ratio from chemical composition of ED1S and ED4C is about 0.8. Hence, our ratio of electron density is closer to the estimated ratio.

The higher uncertainty in our data is due to the poor resolution of the NaI(Tl) detector. The detector might not be suitable to be used in this low-energy region [13].

V. CONCLUSIONS

The electron density of ED1S (dry) was (3.1±0.4) × 10^{23} e cm^{-3} and of ED4C (dry) was (4.4±0.4) × 10^{23} e cm^{-3}.

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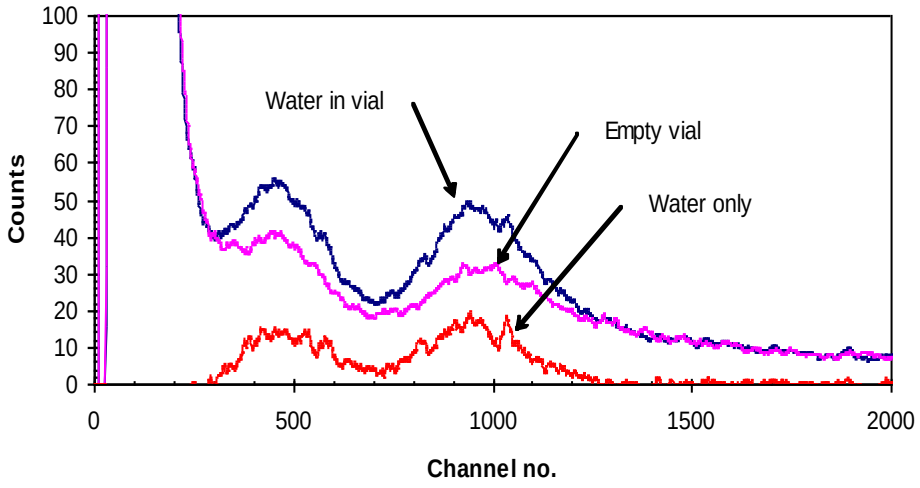

FIG. 4. The spectra of scattered Am-241 photons from water in a plastic vial at a scattering angle of 90° for a collection time of 57600 s.

TABLE III. Electron density of dry hydrophilic material samples with water as a comparator using scattered 59.54 keV photons from an Am-241 source.

	ED1S(dry)	ED4C(dry)
Electron density (e cm^{-3})	$(3.1 \pm 0.4) \times 10^{23}$	$(4.4 \pm 0.4) \times 10^{23}$
Electron density (e cm^{-3}) from Al-Bahri and Spyrou [5]	$(4.026 \pm 0.033) \times 10^{23}$	$(4.170 \pm 0.033) \times 10^{23}$

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