Gamma-Ray Shielding Properties of PVA Reinforced with Sodium Tungstate

Ali A. Abbas, Basil Ali Abdullah, Murtedha Ali abd Al-Hussain

Physics Department, Science College, Basra University, Iraq

E-mail: Murtedha_Ali@yahoo.com

Abstract:

The buildup factor (BF), half value layer (HVL), effective atomic numberZ_{eff}, and mass attenuation coefficientμ_m were calculated for poly vinyl alcohol (PVA) polymer (as matrix element) reinforced by Sodium Tungstate Na_2WO_4 with different ratio (10-50wt%) as a function of shield thickness, in the wide gamma ray energy range (10^{-3} – 10^{2}) MeV using XCOM-code, and measured at energies (0.356, 0.6616, 1.253) MeV by using (^{133}Ba, ^{137}Cs, ^{60}Co) radioactive sources and gamma spectrometry SAM940^{TM} detector. We note from the results that mass attenuation coefficient increases with increase thickness and on other hand it's increase with increased the weight fraction of Sodium Tungstate in sample. Obtained experimental coefficients were compared with the calculated values from XCOM-code where found agree between them. It is observed that the BF values for all the selected samples decrease very rapidly with increasing photon energy, and shows decreases of BF with increases the effective atomic number Z_{eff} of the shielding material, likes the behavior of mass attenuation coefficient with Z_{eff}. Also, the buildup factor is variation with weight fraction (wt%) of Sodium Tungstate-PVA samples with constant gamma ray energy. The results are in the graphical form and it valid the gamma absorption law.

Key words: Attenuation coefficient, Buildup factor, SAM940 identifier, gamma energy source.

1- Introduction

Photons of gamma and X-ray widely used in radiotherapy and medical imaging. The problem of reducing flux deposition in the body and their biological effects is very important in shielding analysis. Then the protection of the body from unnecessary radiation exposure when working in a radiation area is a priority for every health physicist [1,2]. So the protective shields of radiation which has become an important part in our daily life is one of the important things, especially after the great scientific progress which began to concentrate on the subject of the use of radioactive materials and other sources of radiation in medical and agricultural fields as well as other scientific fields such as building of nuclear reactors [3].

Polymers-supported mineral have been used to replace the lead metal in the shielding of medical devices, especially that are used in nuclear medicine after that possessed a small shielding property when compared to the lead as well as the polymers characterized by being non-toxic and easy configuration and low-cost materials. The high-density composite materials have similar behavior of heavy metals when increasing the proportion of material supported in composite material [4].

With the advancement of technology, there is a constant need to develop materials (such that materials) which can be used under a hostile environment of high radiation exposure and can act as good radiation shield [5]. Then this material should have some important properties such as high attenuations coefficient and high density and other properties [3, 5]. Water has good shielding capability for neutrons. But its liquid state at room temperature is the issue. Polymers and plastic materials are rich in H-atom content, solid state at room temperature and low density in comparison to the conventional shielding materials [6].

The aim of this work has been undertaken to evaluate applicability of PVA as gamma-ray radiation shielding.

2-Theoretical Background

2-1 Attenuation coefficient and effective atomic number:

The study of the properties of a substance shielding against gamma rays is mainly depend on the calculation of radiation attenuation coefficient values and buildup factor of radiation [3].

A parallel beam of monoenergetic gamma-ray or X-ray photons is attenuated in matter according to the Lambert–Beer law:

$$I = I_0 e^{-\mu x} \qquad (1)$$

where I_0 and I are the incident and transmitted intensities, x is the thickness (cm) of the absorbing medium and μ (cm^{-1}) is the linear attenuation coefficient. The linear attenuation coefficient for a compound or mixture is given by:

$$\mu_{mix} = \mu_1 + \mu_2 + \cdots\cdots \qquad (2)$$

For photons in an attenuating medium, the mass attenuation coefficient, ($\mu_m = \mu/\rho$), where ρ is the density of the sample, is more fundamental importance than linear attenuation coefficient because all mass attenuation coefficients are independent of the density and physical state (gas, liquid or solid) of the absorber. The mass attenuation coefficient for a compound or mixture is given by [4]:

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \qquad (3)$$

where w_i and $(\frac{\mu}{\rho})_i$ are the weight fraction and mass attenuation coefficient of the constituent element i, respectively.

This coefficient is useful because only the atomic composition of the attenuator is taken into account and not the individual density of the material. The mass attenuation coefficient is a measure of the average number of interactions between incident photon and matter that occur in a given mass-per-unit area per thickness of the material. It is distinguished sharply from the absorption coefficient which is always a smaller quantity, and absorption coefficient measures the energy absorbed by the medium. The values of mass attenuation coefficient can be used to determine the total atomic cross-section (σ_a) by the following relation [7].

$$\sigma_a = \frac{\mu_m}{N_A \sum \frac{w_i}{A_i}} \quad (4)$$

where

N_A: is Avogadro's number

A_i: is atomic weight of constitute element of mixture. Also, the total electronic cross-section (σ_{el}) for the element is expressed by the following formula [8]:

$$\sigma_{el} = \frac{1}{N_A} \sum_{i=1}^{n} \frac{f_i A_i}{Z_i} (\mu_m)_i \quad (5)$$

where f_i is the number of atoms of element i relative to the total number of atoms of all elements in mixture, Z_i is the atomic number of the ith element in mixture. Total atomic cross-section and total electronic cross-section are related to effective atomic number (Z_{eff}) of the compound through the formula [7].

$$Z_{eff} = \frac{\sigma_a}{\sigma_{el}} \quad (6)$$

Recently, the theory takes one further step by inserting analytical expressions for the atomic and electronic cross sections in Eq. (7) below [8].

$$Z_{eff} = \frac{\sum_{i=1}^{n} f_i A_i (\mu_m)_i}{\sum_{i=1}^{n} f_i (\frac{A_i}{Z_i}) (\mu_m)_i} \quad (7)$$

2-2 Half value layer (HVL)

The thickness of the material that reduces the photon beam intensity to half of its original value (I_0), i.e. (½) I_0, is called the half value layer (HVL) and can be calculated using the following formal [2].

$$\text{HVL} = \frac{0.693}{\mu} \quad (8)$$

2-3 Buildup factor (BF)

Gamma radiation impinging shielding material gives rise to two radiation components within or beyond the shield. At any given penetration depth, one radiation component consists of those particles which have not had an interaction. The number of these non-interacted particles decreases exponentially with penetration distance. The other component consists of those particles which have had one or more interactions and still reached that point, as well as those which were created within the material through secondary processes [10].

The photon buildup factor is defined as the ratio of the total photon beam response "uncollided plus scattered" (e.g., flux, dose or exposure) to the response of the uncollided photon beam fraction [11]. In general, the buildup factor depends on the energy of the photon, the thickness traveled by the photon in the shield, the geometry of the source (parallel beam or point isotropic),and on the geometry of the attenuating medium (finite, infinite, slab, etc.).The formal definition of *B* upon which its calculation is based in [12]**:**

$$B(E_\gamma, x) = \frac{\text{quantity of interest due to total flux}}{\text{quantity of interest due to unscattered flux}} \quad (9)$$

We can write equation (9) as the following [13]:

$$B(E_\gamma, x) = \frac{(\frac{I}{I_0})_b}{(\frac{I}{I_0})_g} \quad (10)$$

$(\frac{I}{I_0})_b$, $(\frac{I}{I_0})_g$ fraction intensity for bad and good geometry, respectively.

3- Experimental procedure

3-1 Preparation of Samples:

Polyvinyl alcohol (PVA) is a water-soluble synthetic polymer has formula $[CH_2CH(OH)]_n$, it's molecular weight equal to (40000) supplied from Thomas Baker , Mumbai, India. Sodium Tungstate also a water soluble material (Na_2WO_4) its molecular weight (275.85) supplied from Sigma Aldrich. Six samples of PVA polymer prepared in different weight ratio of Na_2WO_4 (0, 10,20,30,40 and 50) % by dissolving the mixture in beaker contain 100ml distilled water then stirred at temperature 75° C for 3 hours until the solution became homogenous and thick then casting the solution in circular mold and left to dry in room temperature for 12 days to remove any residual solvent.

3-2 Measurement of Density:

The density values are shown in table (1) where calculated from these equations [14]:

$$\rho = V_f \times \rho_f + (1 - V_f)\rho_m \quad (11)$$

$$\Psi = \frac{W_f}{W_c} \times 100\% \quad (12)$$

$$W_c = W_f + W_m \quad (13)$$

Where:
W_c: weight fraction for composite material,
W_m: weight fraction for matrix material,
W_f: weight fraction for filler. Either fraction volume can be calculated from:

$$V_f = \frac{1}{1+\frac{1-\psi}{\psi}.\frac{\rho_f}{\rho_m}} \quad (14)$$

ρ_f : density for filler,
ρ_m: density for matrix material,
V_f : The fraction volume.
From table (1), it can be seen that the density values increase with increase the concentration of Sodium Tungstate in PVA polymer according to equation (11).

Concentrations	Density (g/cm^3)
Na_2O_4W	4.18
PVA	1.10
10% Na_2O_4W	1.1779
20% Na_2O_4W	1.268
30% Na_2O_4W	1.3721
40% Na_2O_4W	1.495
50% Na_2O_4W	1.643

Table (1) Density of composite material

3-3 System of Measurement and Radioactive Source:

Measurement was performed using a SAM940^{TM} gamma ray spectrometer. This system has NaI(Tl) crystal 2×2 inch with 256 channel, the detector measures the spectrum emitted from radioactive isotopes and low level Becquerel measurement. The device works at operation voltage of 600 volts. It is of coarse gain=1, fine gain=1.1386, Upper Level Discriminator (ULD) =100 volts and Lower Level Discriminator (LLD) =0.8 volts. SAM940^{TM} operating with Quadratic Compression Conversion (QCC) which allows for identification of mixed isotopes in one second [17]. The detector was calibrated by standard radioactive elements ^{137}Cs which has the energy of 0.6616 MeV photopeaks and activity ($5\mu Ci$) and a half-life of (30.07yr), ^{133}Ba with energies of (0.08099, 0.27639, 0.30285, 0.356, 0.3838) MeV photopeaks and activity ($1.057\mu Ci$) and a

half- life of (10.51yr), i.e. it emits gamma rays at high probability emission of 0.356 MeV, and ^{60}Co with activity ($5\mu Ci$) and a half-life of (5.27yr), which has the energies of (1.17324, 1.3325) MeV, i.e. it emits gamma rays at of average energy 1.253 MeV.

3-4 Geometric arrangement of the system:

The detector was shielded with lead cylinder to reduce the radiation background as low as possible and two collimators were used to obtain the good geometric arrangement. By lifting the collimators, we get the bad geometric arrangement, as shown in figure (1), which represents the measurement system. The distance between detector and source was 10 cm. while taking the readings a sufficient number of counts were collected under photo peak. For each prepared sample, $I_0$and I intensities which are without and after investigated sample were measured.

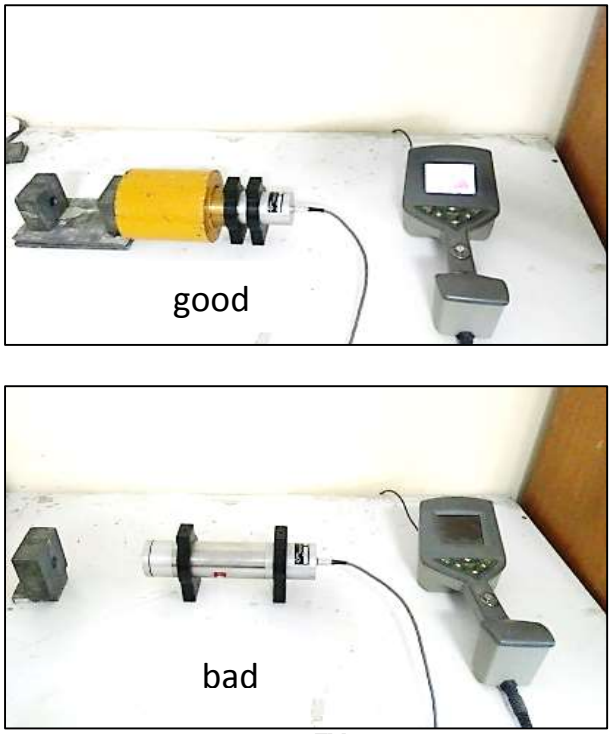

Fig.(1): SAM940^{TM} gamma ray spectroscopy system for good and bad geometry.

3-5 Attenuation Coefficient Measurement:

By taking gamma ray beam I_0 and gamma ray beam after depositing I in a certain shielding material then taking natural logarithm for this quantity $\frac{I_0}{I}$ where plotted on y-axis and thickness material on x-axis, then calculation slope where represent linear attenuation coefficientμ according to equation (1).

4- Results and discussion:

4-1 Linear and Mass Attenuation coefficients (μ_l, μ_m)

Fig.(2) – Fig.(4) show linear attenuation coefficient μ calculation from slope for each ratio (wt%), then divided on density to get mass attenuation coefficient μ_m according to equation (3). Thereafter theoretical mass attenuation coefficient calculation from XCOM program where use energy from 1.0 keV to 1000 GeV, and comparison between theoretical and experimental values shows as in Fig. (5) - Fig.(7) for three energies. Values in table (2) shows experimental absorption coefficients for samples Sodium Tungstate-PVA polymer at energy (0.356, 0.6616, 1.253) MeV from (^{133}Ba, ^{137}Cs, ^{60}Co) at different ratio then compared with theoretical values obtained from the XCOM where found agree between them.

We note from Fig. (8), which explain mass attenuation coefficient calculating from XCOM-code on y-axis and energy in (MeV) on x-axis that mass attenuation coefficient decreases with increase incident photon energy with a peak due to photoelectric effect around the K, L and M-absorption edges, this may be due to the dominance of different partial interaction processes (Photoelectric effect, Compton Scattering, Pair production).

E_γ(MeV)	Wt % (Na_2WO_3)	μ_{exp} (cm^2/g)	μ_{th} (cm^2/g)
^{133}Ba 0.356	0	0.0985	0.1095
	10	0.189	0.12566
	20	0.21	0.14182
	30	0.23	0.15798
	40	0.29	0.17414
	50	0.3295	0.1903
^{137}CS 0.662	0	0.0686	0.0846
	10	0.074	0.08779
	20	0.081	0.09098
	30	0.0846	0.09417
	40	0.0873	0.09736
	50	0.0941	0.10055
^{60}CO 1.25	0	0.056	0.0621
	10	0.0576	0.062599
	20	0.0596	0.063145
	30	0.061	0.0637
	40	0.0625	0.06425
	50	0.063	0.065

Table (2): Mass Attenuation coefficient for sample at different energies.

4-2- Half value layer (HVL) :

Values of HVL have been calculated according to Eq.(8) and also from XCOM program. Fig. (9), Show the values of HVL for samples as a function of photon energy. HVL decreases with the increase in weight fraction of Sodium Tungstate and the better shielding properties are achieved at higher Sodium Tungstate concentrations. This can be attributed to increasing values of Tungstate which has higher atomic number as compared to other elements.

4-3 Effective Atomic number(Z_{eff}):

The effective atomic number Z_{eff} for each sample was determined by using the effective atomic cross section (σ_a) and total electronic cross-section (σ_{el}) according to equation (7). Fig.(10) shows the variation of Z_{eff} for each sample with the incident photon energy in energy range (10^{-3} – 10^5) MeV from XCOM program.

The Z_{eff} values show a broad peak and a maximum value at 0.01 MeV and minimum at 1 MeV for all Sodium Tungstate - PVA samples. The variation of Z_{eff} with photon energy may be attributed to the relative domination of the partial processes : Photoelectric effect, Compton scattering and pair production [16]. At low energies the photoelectric effect is dominant and hence Z_{eff} for the photon absorption is mainly described by Z_{eff} for this partial process. Hence at low energies, where photoelectric effect dominates, Z_{eff} value is more and at higher energies, where the scattering and pair production process dominate, the Z_{eff} value is less.

4-4 **Buildup factor (BF)**:

Variation buildup factor with weight fraction (wt%) of Sodium Tungstate-PVA samples is shown in figur (11), where BF values decreases with the increase in weight fraction of Sodium Tungstate-PVA polymer. This can be attributed to increasing values of Sodium Tungstate which has higher effective atomic number Z_{eff} as compared to other elements. The study showed that the BF values decreases with increases the effective atomic number Z_{eff} of the shield material likes the behavior of mass attenuation coefficient withZ_{eff}, as shown in figure (12). It is observed that the BF values for all the selected Sodium Tungstate-PVA samples decrease rapidly with Z_{eff}. At photon energy 0.356 (^{133}Ba) MeV, we can be explained on the basis of the dominance of the photoelectric effect for low photon energy whose cross section depends on atomic number as Z_{eff}^4. At energy 0.6616 MeV (^{137}Cs), BF values decrease slowly with Z_{eff} because the Compton effects process becomes dominant, and whose cross section varies linearly with Z_{eff} and is inversely proportional to the incident photon energy. The BF values also decrease slowly with Z_{eff} at energy 1.253MeV, where the pair production process starts dominating whose cross section depends on effective atomic number as Z_{eff}^2 and is proportional to the incident photon energy.

Conclusion

- Increasing of the mass attenuation coefficient with increasing of the concentration of reinforcement materials in a sample that used for the prepared shields.
- decreasing of buildup factor with increasing of the concentration of reinforcement materials in a sample that used for prepared of shields.
- Each of the mass attenuation coefficient and buildup factor increase with increasing of used samples thickness.
- Mass attenuation coefficient increases and buildup factor decreases with increased effective atomic number and density of reinforcement material.
- Agreement between experimental and theoretical result.

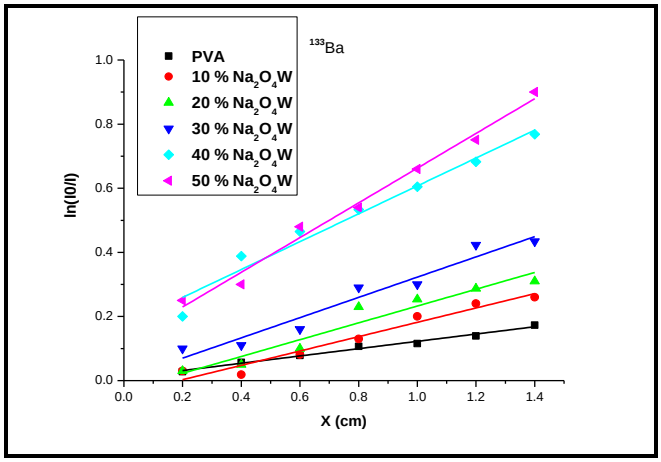

Fig (2): Linear attenuation coefficients for different ratio of Sodium Tungstate+ PVA polymer samples at 0.356 MeV.

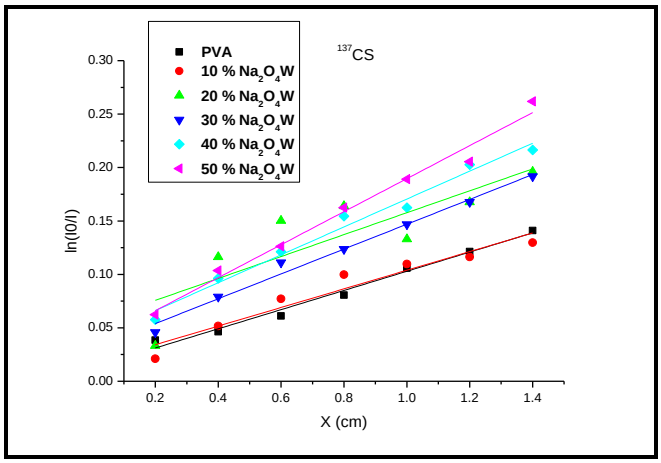

Fig (3): Linear attenuation coefficients for different ratio of Sodium Tungstate + PVA polymer samples at 0.662 MeV.

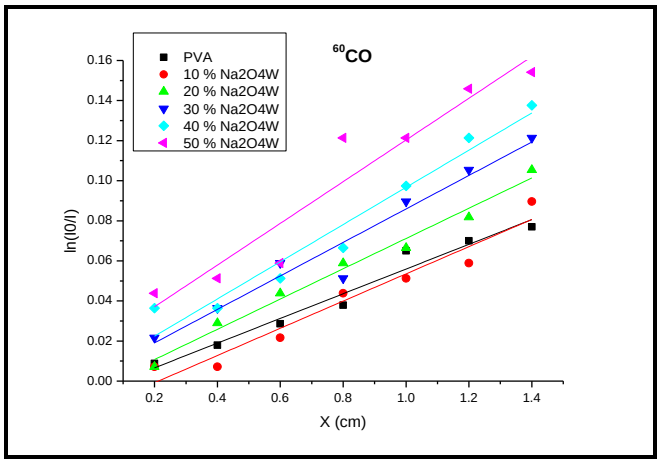

Fig (4): Linear attenuation coefficients for different ratio of Sodium Tungstate+ PVA polymer samples at 1.253 MeV.

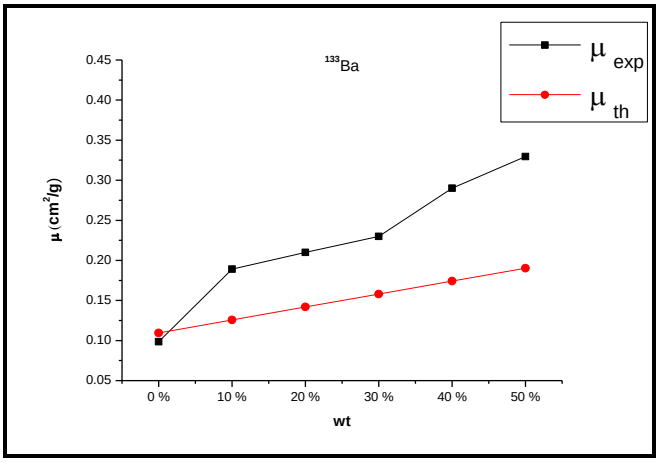

Fig (5): Comparison between Experimental and Theoretical values for 0.356 MeV.

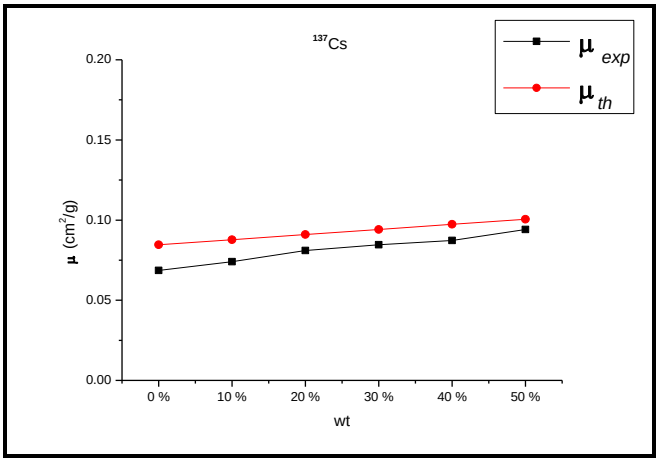

Fig (6): Comparison between Experimental and Theoretical values for 0.662 MeV

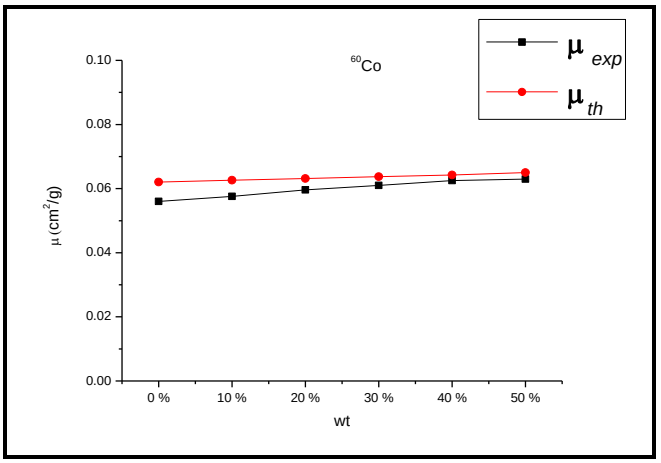

Fig (7): Comparison between Experimental and Theoretical values for 1.253 MeV

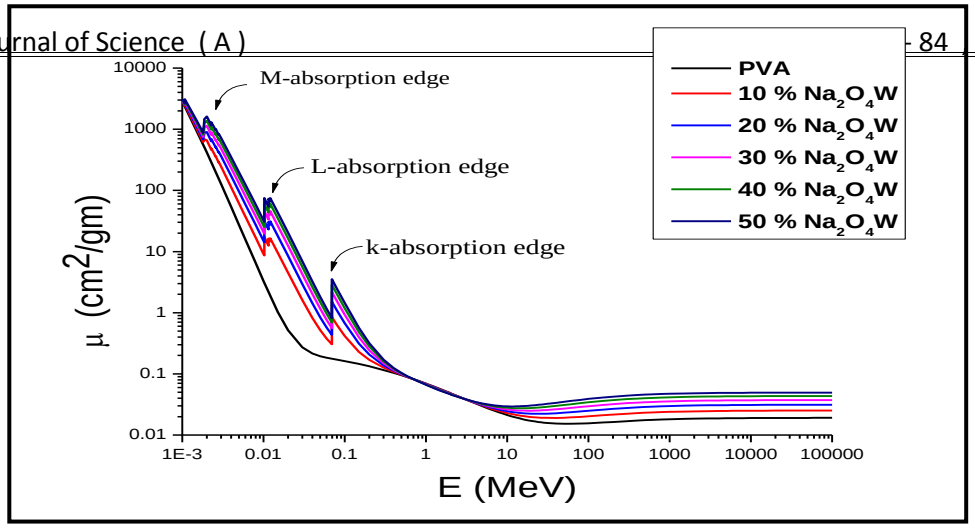

Fig (8): Variation total mass attenuation coefficient for Sodium Tungstate+ PVA polymer samples with energy photon range (10^{-3} -10^{5}) MeV from XCOM

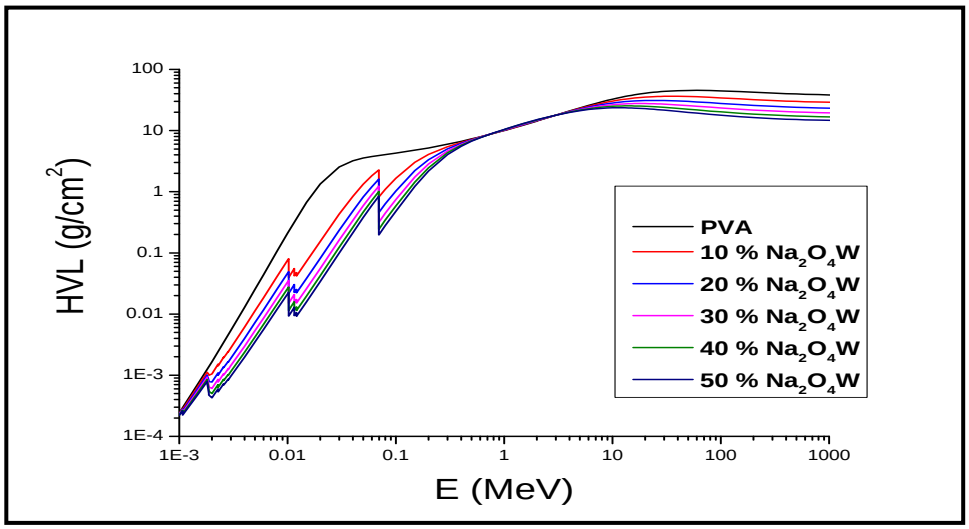

Fig (9):Half value layer for Sodium Tungstate + PVA polymer samples as a function of photon energy from XCOM program.

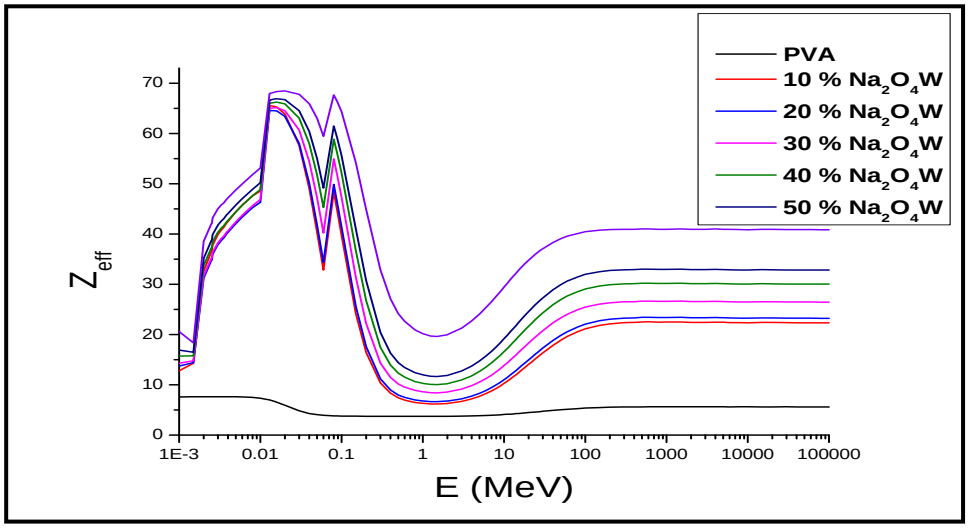

Fig (10): Variation Z_{eff} for Sodium Tungstate+ PVA polymer samples with energy photon range (10^{-3} -10^{5}) MeV from XCOM program.

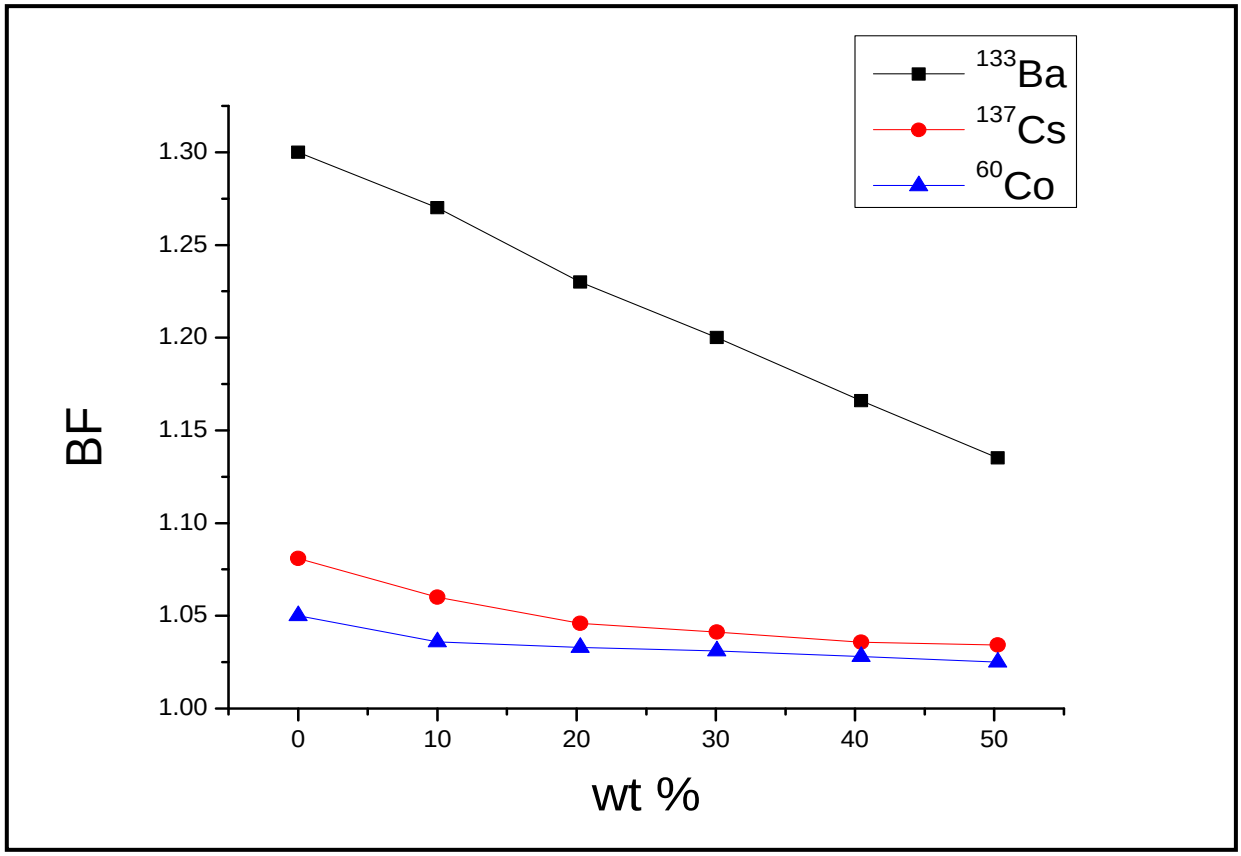

Fig (11): Variation BF for Sodium Tungstate+ PVA polymer samples with Wt % for three energies of gamma photon.

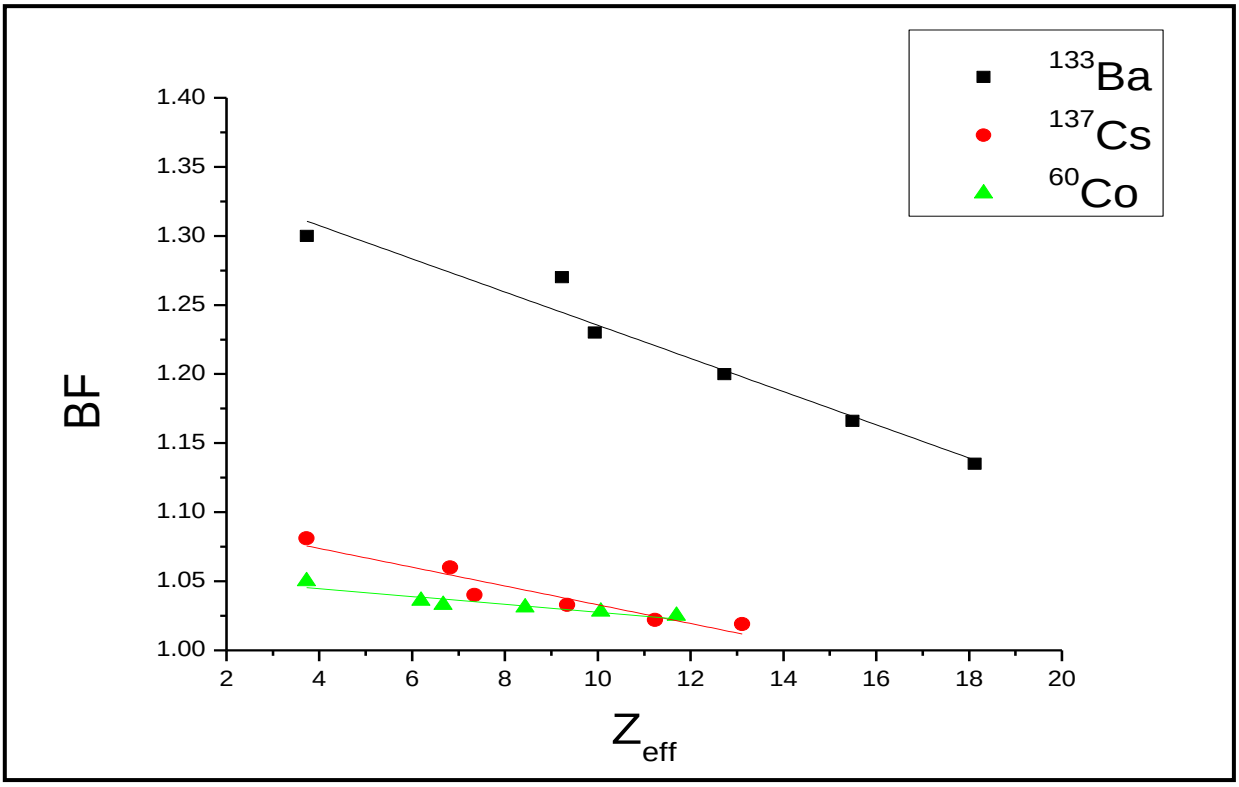

Fig (12): Variation BF for Sodium Tungstate+ PVA polymer samples with Z_{eff} for three energies of gamma photon.

References

[1] D. Saleh "Investigation of some radiation shielding parameters in soft tissue", J. of Radiation Research and Applied Sciences 8, 439-445, (2015).

[2] A. J. Al-Saadi "Variation of gamma ray attenuation parameters for Poly vinyl alcohol reinforced by lead acetate" J. of Karbala University, vol.12 No.3 (2014).

[3] P. Limkitjaroenporn, J.Kaewkhao, P.Limsuwan, W.Chewpraditkul "Physical, optical, structural and gamma-ray shielding properties of lead sodium borate glasses" J. of Physics and Chemistry of Solids, 72, 245–251, (2011).

[4] M. J. Resen AL-Dhuhaibat "Study of the Shielding properties for some composite materials manufactured from polymer epoxy supported by cement, aluminum, iron and lead against gamma rays of the cobalt radioactive source (Co-60)." Int. J. of Appl. and Eng. & Management Vol.4, Issue 6, June (2015).

[5] N. Singha, K. J. Singha, K.Singhb, H.Singhb " Gamma-ray attenuation studies of PbO .BaO.B2O3 glass system ", ELSEVER, Vol. 41, 84–88 (2006).

[6] K. Mann "Shielding behaviors of some polymer and plastic materials for gamma-rays", Radiation Physics and Chemistry, DOI, 10.1016/j., 08.005 (2015).

[7] R. Sharma, V. Sharma, Parjit S. Singh, T. Singh, "Effective Atomic Numbers for some Calcium–Strontium-Borate Glasses", Annals of Nuclear Energy Journal, 45, 144–149 homepage: www.elsevier.com/locate/anucene (2012).

[8] O. icelli I. Elli, S. Erzeneog˘lu, M. Sag˘lam "Effective Atomic Numbers of Polypyrrole via Transmission Method in the energy range 15.74–40.93 keV ", Annals of Nuclear Energy J, 35, 432–437 homepage: www.elsevier.com/locate/anucene (2008).

[9] H. Singh, K. Singh "ZnO–PbO–B2O3 Glasses as Gamma-Ray Shielding Materials, Nuclear Instruments and Methods in Physics Research, B-207, 257–262, (2003).

[10] A. J. Al-Saadi "Calculation of Buildup Factor for Gamma-Ray Exposure in two Layered Shields made of Water and Lead." J. of KUFA- PHYSICS, Vol.4 No.1 (2012).

[11] N. Tsoulfanidis, "Measurent and detection of radiation" Second Edition, Publishing Office: Taylor& Francis, QC795.42T78, (1995).

[12] A. Shiraniand, M. H. Alamatsaz, "Calculation of Exposure Buildup Factors for Point Isotropic Gammaray Sources in Stratified Spherical Shields of Water surrounded by Lead and Optimization of Water-Lead Combination", Iranian J. of Science & Technology, A(1), 29-34 (2013).

[13] R. Esmaeel, " Calculation of Buildup factor for Cylindrical Sample from Brass, Copper and Lead " J. Bagdad for Science, Vol. 7(3) (2010).

[14] R. Abdlkudr A., "Study the Role of Novolak Composite in Repress of light Charged Particles and Make it Neutral", Eng. Magazine, Vol.17,No. 4(2011).

[15] M.J., Berger, Hubbell, J.H., XCOM: photon cross sections database, Web Version 1.2, available at http://physics.nist.gov/xcom, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA. (Originally published as NBSIR 87-3597 ‘‘XCOM: Photon Cross Sections on a Personal Computer’’), (1987/1999).

[16] B. Chilton, Shultis J. K. and Faw R.E., Principles of Radiation Shielding, Prentice-Hall, Englewood Cliffs, New Jercy,(1984).

[17] BNC, Instruction Manual, Web: www.berkeleynucleonics.com, (2014).

خواص تدريع اشعة كاما لبوليمر بولي فينيل الكحول المدعم بتنكستات الصوديوم

د. علي عبد عباس د. باسل علي عبد الله مرتضى علي عبد الحسين

العراق - جامعة البصرة - كلية العلوم - قسم الفيزياء

الملخص

تم حساب عامل التراكم BF وسمك النصف HVL والعدد الذري الفعال Z_{eff} ومعامل التوهين الكتلي μ_m للبوليمر بولي فنايل الكحول PVA (كمادة اساس) المدعم بتراكيز مختلفة من تنكستات الصوديوم Na_2WO_4 بنسب وزنية مختلفة (10-50 wt%) كدالة للسمك ولمدى واسع من طاقة اشعة كاما (10^{-3} – 10^{2}) ميكا الكترون فولت باستخدام البرنامج العالمي XCOM. وحسبت عمليا بطاقات مختلفة (0.356 , 0.6616, 1.253) ميكا الكترون فولت من مصادر مشعة قياسية (^{133}Ba, ^{137}Cs, ^{60}Co). اظهرت النتائج زيادة معامل التوهين بزيادة سمك مادة التدريع وكذلك بزيادة تركيز تنكستات الصوديوم في العينة. قورنت النتائج العملية مع القيم النظرية التي حصلنا عليها من البرنامج XCOM وكانت في حالة توافق . كما اظهرت النتائج نقصان قيم عامل التراكم BF لجميع العينات بشكل سريع مع زيادة طاقة الفوتونات، وكذلك وجد نقصان في عامل التراكم BF مع زيادة العدد الذري الفعال Z_{eff} لمواد التدريع. كذلك يتغير عامل التراكم مع تغير النسبة الوزنية لعينات تنكستات الصوديوم في PVA عند ثبوت طاقة كاما، رسمت النتائج وتحقق قانون التناقص الاسي