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A Method for Simultaneous Determination of Effective Removal Cross-section for Fast Neutrons and Mass Absorption Coefficient for Gamma Rays

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Abstract

A method for determining the effective removal cross section ($\sum_R$) of fast neutrons and mass absorption coefficient (μ_R) for gamma rays at energies 661.6 keV and 1332.5 keV is proposed. It is based on relating the ratio (R) of $\sum_R$ to μ_R at 661.6 keV and 1332.5 keV to effective atomic number (Z_{eff}) for elements, compounds, composite materials and alloys. It is shown that the R-values versus Z_{eff} for the most studied materials lie on two master curves. The method was tested by determining $\sum_R$ and μ_R for several materials. There is a good agreement between results obtained from the present developed method and the traditional method. Some deviations from the values obtained from the traditional method are discussed as well.

Keywords: Effective removal cross-section; Mass absorption coefficient; Fast neutrons; Gamma rays; Composite materials; Alloys

Introduction

The study of photon and neutron interactions with matter is an important issue for several applications, e.g. in industry, medical radiation dosimetry, security inspections, radiation shielding and nuclear engineering materials. In this aspect, an interdisciplinary science between nuclear physics and materials science emerges, which can much help in engineering novel materials for the required application. Mass attenuation coefficient, μ_R (cm^2/g), effective atomic number (Z_{eff}), effective electron density, and photon mean free path are the most important quantities for determining the penetration of X-ray and gamma rays in matter. Theoretical values of the mass attenuation coefficients for elements, compounds and mixtures (composites) from 1 keV to 100 GeV can be obtained using WinXCom software [1]. Besides, the scattering and absorption of X-ray and gamma radiation in matter are related to the densities and atomic numbers of its elemental constituents. However, when such scattering and absorption take place in composite materials, it is then related to the density and the effective atomic number (Z_{eff}). Z_{eff} is introduced to describe the properties of composite materials in terms of equivalent elements. Values of the effective atomic number for many composite materials and alloys have been reported [2-6].

The effective removal cross-section, $\sum_R$ (cm^2/g) is the probability that a fast or fission energy neutron undergoes a first collision, which removes it from the group of penetrating, uncollided neutrons. It is considered to be approximately constant for neutron energies between 2 and 12 MeV [7]. To use the concept of $\sum_R$, the shielding material under investigation should contain some scattering atoms. However, when there are no scattering atoms, another quantity i.e. the total mass neutron cross-section $\sum_T$ (cm^2/g) is used. The observed value of the $\sum_R$ is roughly 2/3 of $\sum_T$ for neutrons having energies in the range of 6-8 MeV [8].

Non-Destructive Testing (NDT) of materials is a well-known technique applied in several fields such as inspection of luggage and containers. NDT methods are mainly based on gamma or X-ray scanners, which produce high resolution images. In addition, photons inspection provides materials recognition when traditional transmission measurements at fixed energy are implemented with special technologies as in the case of the so-called ‘‘dual energy radiography’’, ‘‘backscattering imaging’’ or ‘‘computed tomography’’ [7-9]. Materials recognition in such applications is based on the atomic number Z dependence of the relevant photon absorption coefficients: it is a well-established method at low photon energy where the photoelectric effect dominates, while it becomes critical for increasing photon energy, as it is required in order to increase the penetration of radiation to inspect thick objects [8-10]. A drawback in utilizing photon-based inspection approaches is that when the photon penetration is not sufficient, the object’s image appears black. Thus, developing new approaches to overcome the latter problem is a concern in security inspections.

Therefore, in most cases when photon irradiation is unable to disentangle the problem of inspections, the use of neutrons as probing radiation has been often proposed. To this end, sophisticated techniques have been developed in order to enhance materials recognition, especially for low-atomic-number materials, in an effort to optimize the detection of explosives and drugs in customs operation. Examples of such developments

are represented by the "combined fast-neutron and gamma-radiography" and the "fast neutron resonance radiography" [11-15], or by detection of neutron induced gamma rays [15]. Combined fast-neutron and gamma radiography systems [9] perform materials recognition by transmission measurements of fast neutrons and gamma rays [16,17]. Neutrons and gamma rays are obtained from either separate sources such as 14 MeV neutrons (produced by a D+T generator) and gamma rays from an intense ^{60}Co radioactive source [16], or from the same source such as ^{252}Cf [17,18].

It was shown that the ratio of the effective removal cross-section for fast neutrons to the mass absorption coefficient of gamma rays, R can be utilized for the purpose of non-destructive testing for materials recognition [11,12,15,17,18]. However, this ratio was not applied before for determining the effective removal cross-section and the mass absorption coefficient for any material.

The present work aims at developing a simple method based on using the ratio (R) of $\sum_R$ to μ_R at 661.6 keV and 1332.5 keV, for elements for determining $\sum_R$ and μ_R with the knowledge of Z_{eff} for any material.

Theory

The mass absorption coefficient for gamma rays, μ_R and the effective removal cross-section for fast neutrons, $\sum_R$ can be calculated for mixtures, alloys and compounds, with the knowledge of the weight percentages w_i, and the values of μ_R and $\sum_R$ of the constituting elements. This is achieved by the following simple addition rules [7,19]:

$$\mu_R = \sum_i w_i (\mu_R)_i \quad (1)$$

and

$$\sum_R = \sum_i w_i \left(\sum_R\right)_i \quad (2)$$

for gamma rays and fast neutrons, respectively.

It was proposed that the following empirical formulas [19]:

$$\sum_R = 0.21 A^{-0.56} cm^2 g^{-1}, \quad (3)$$

$$\sum_R = 0.00662 A^{-1/3} + 0.33 A^{-2/3} - 0.211 A^{-1} cm^2 g^{-1} \quad (A > 12), \quad (4)$$

$$\sum_R = 0.190 Z^{-0.743} cm^2 g^{-1} \quad (Z \leq 8), \quad (5)$$

and

$$\sum_R = 0.125 Z^{-0.565} cm^2 g^{-1}, \quad (Z > 8) \quad (6)$$

Can be used to determine $\sum_R$ as a function of the atomic weight A and the atomic number, Z .

The effective atomic number for composites, compounds and alloys for gamma rays can be determined as follows [20]:

The total photon interaction cross section, σ_m, per molecule can be written

$$\sigma_m = \sum_i \sigma_i n_i \quad (7)$$

where n_i is the number of atoms of the i^{th} constituent element, and σ_i is total photon interaction cross section per atom of element i. The total number of atoms in the compound n is given by:

$$n = \sum_i n_i \quad (8)$$

Suppose that the cross section per molecule can be written in terms of an effective (average) cross section, σ_a, per atom and an effective (average) cross section, σ_e, per electron as

$$\sigma_m = n\sigma_a = n Z_{eff} \sigma_e \quad (9)$$

Eq. (9) can be regarded as the definition of the effective atomic number. Essentially, it assumes that the actual atoms of a given molecule can be replaced by an equal number of identical (average) atoms, each of which having Z_{eff} electrons. From Eqs. 7 and 9 one obtains

$$\sigma_a = \left(\sum_i n_i \sigma_i\right) / n \quad (10)$$

$$\sigma_e = \left(\sum_i n_i \sigma_i / Z_i\right) / n \quad (11)$$

It follows from the last equality of Eq. (9) that the effective atomic number can be written as the ratio between the atomic and electronic cross sections:

$$Z_{eff} = \sigma_a / \sigma_e = \left(\sum_i n_i \sigma_i\right) / \left(\sum_i n_i \sigma_i / Z_i\right) \quad (12)$$

Eq. (12) is then the basic relation for calculating the effective atomic number of a chemical compound.

A more general expression for Z_{eff} can be obtained by introducing the molar fraction, f_i (sometimes expressed in units of atomic percent, at.%). For a chemical compound, one has

$$f_i = n_i / \sum_i n_i = n_i / n \quad (13)$$

where $\Sigma_i f_i = 1$. Rewriting Eq.12 in terms of f_i one has

$$Z_{eff} = \left(\sum_i f_i \sigma_i\right) / \left(\sum_i f_i \sigma_i / Z_i\right) \quad (14)$$

Eq. (14) is then the basic relation for calculating the effective atomic number for all types of materials, compounds as well as composites.

The atomic cross section, σ_i, of the i^{th} constituent element is related to the corresponding mass attenuation coefficient, $(\mu/\rho)_i$, through the relation

$$\sigma_i = (\mu/\rho)_i A_i / N_A \quad (15)$$

where A_i is the atomic mass, and N_A is the Avogadro's constant. Inserting expression (15)

for σ_i in the eq. 14 gives

$$Z_{eff} = \left(\sum_i f_i A_i (\mu/\rho)_i\right) / \left(\sum_i f_i (\mu/\rho)_i A_i / Z_i\right) \quad (16)$$

Eq. (16) can be used for calculating the effective atomic number for both compounds and composites in terms of the mass absorption coefficients.

Results and Discussions

The physical data of most elements, atomic masses, mass

removal cross-sections Σ_R, and mass absorption coefficients for gamma rays at 661.6 keV and 1332 keV for elements needed for the calculations [1,7,8,19], were prepared and stored in an Excel spread sheets. The equations written above were implemented in the sheets. They were used to calculate mass absorption coefficients, effective removal cross-sections and effective atomic numbers for the chosen materials.

The estimated ratios of effective removal cross section to mass absorption coefficients at the gamma ray energies 661.6 keV and 1332 keV for most elements (R), as well as effective removal cross section versus atomic number for elements (Z=1-92) are shown in Figure 1. As one can see, the R-values at 1332.5 keV are higher than those at 661.6 keV.

The R-values and Z_{eff} were calculated for some compounds, composites and alloys. These are : H_2O, B_4C, CO, CO_2, MgO, MgCO, SO_3, $MgCO_3$, NaCl, SO2, NaO,Na_2O, SiO_2, P_2O_5, Al_2O_3, CaO, CaO_3, TiO_2, MnO_2, K_2O, FeO, Fe_2O_3, NiO, CuO, ZnO, RbO, SrO, H-Li , H_2Li, H_3-Li, H_4Li, HB, H_2B, HBe, HC, HO, CH_2 HNa, Zn-Cu-Ni, Mn-Zn-As, Zr-Mo-Cd, Ag-Sn-Nd, As-Ga, Mn-Sc, Mn-Zn-Rb, Mn-Zn-Sr, Dy-H, Dy-Lu, Lu-W-Au, Hf-Pb, H-Pb, Sn-Pb, Sn-Pb, Zr-Pb, Zn-Pb, Sn-H, and Zr-H. Also, for some of these materials, the R-values and Z_{eff} were calculated for different concentrations of their constituents. Figure 2 shows these results along with those for the corresponding elements. As one can see, the Σ_R and R-values (calculated relative to μ_R at 661.6 keV and 1332.5 keV) coincide with the data for the elements. The calculated values of Z_{eff} at 661.6 keV and 1332.5 keV for any of the above mentioned materials were found roughly the same, which implies an energy independence of Z_{eff} in the mentioned range of energies. Of worth noting, the values of Σ_R and μ_R (at 661.6 keV and 1332.5 keV) for any material can be determined simultaneously. The determination of Σ_R and μ_R is based on the knowledge of the corresponding Z_{eff} at either 661.6 keV or 1332.5 keV. Namely, once Z_{eff} is determined for any material, the table containing the

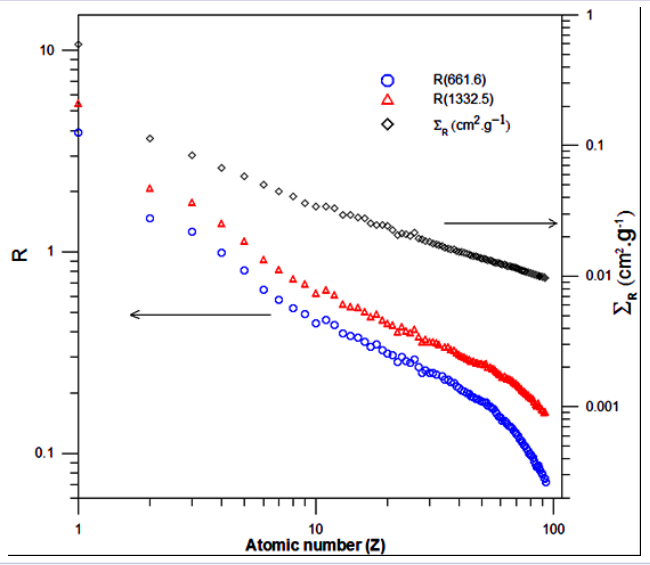

Figure 1: The ratio R at 661.6 keV, 1332.5 keV and Σ_R versus Z for elements.

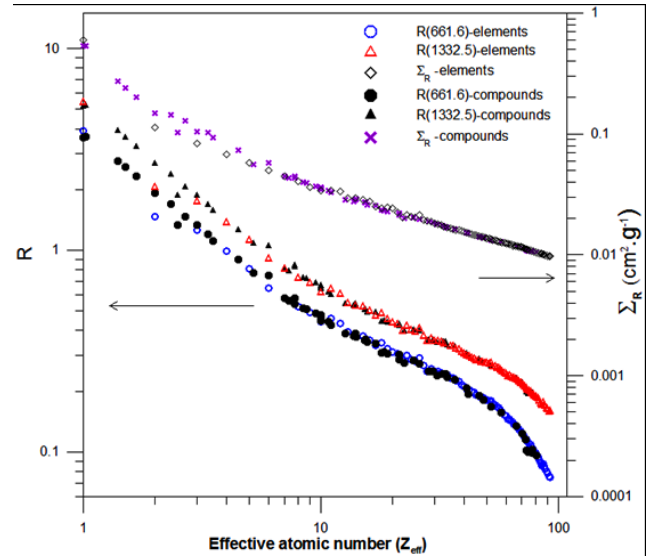

Figure 2: The ratio R and Σ_R values for some compounds, composites and alloys versus Z_{eff}. Results of Figure. 1 are also included.

values of R including μ_R at 661.6 keV and 1332.5 keV and Σ_R is searched for the closest value to Z_{eff}. At this value of Z_{eff}, the values of μ_R at 661.6 keV and 1332.5 keV and Σ_R are the required ones for such material.

To check the proposed method, the results (for compounds, alloys and mixtures stated above), were used to determine Σ_R and μ_R with the knowledge of Z_{eff} for the following materials [21]: 1%, 5%, 5.45%, and 30% borated polyethylene, 7.5% Lithium Polyethylene, 78.5% and 90% bismuth-loaded polyethylene, borated silicone, flexi-boron shielding, borated Hydrogen-Loaded castable dry mix, borated hydrogenated mix, borated-lead polyethylene, K-resin, resin 250WD, SUS304, krafton-HB, and premadex. The numbers from 1 to 17 in Table 1 refer to them respectively. The chemical composition of these composites was taken from reference [21]. The obtained results of Σ_R and μ_R in comparison with the corresponding values calculated by the traditional method (Eqs.1-16) are listed in Table 1. In most cases, good agreement can be noticed between the determined values by the proposed method and the traditional method. Besides, the determined Σ_R, μ_R and Z_{eff} for these materials along with those shown in Figure 2 were used to determine Σ_R, μ_R for natural Fiber–Plastic (FP), Fiber–Plastic–Lead (FPPb), Cement–Fiber (CF) and Cement–Fiber–Magnetite (CFM) composites, along with the shielding materials of dolomite-sand, barite-barite, magnetite-limonite, ilmenite–ilmenite [22-24]. The chemical compositions shown in Table 2 were taken from references [22-24]. The results obtained by the present method along with those obtained by the traditional method are listed in Table 1. One can note good agreements between the values obtained by using the two methods. It can also be noticed in Table 1 for 78.5% bismuth-loaded polyethylene (number "6"), compound number "12", FPPb, Barite-barite, and Magnetite-limonite that, there are two values of Z_{eff} calculated by the traditional method. These values are obtained from values of μ_R at 661.6 keV and 1332.5 keV. In such case, the table containing the R-values including μ_R at 661.6

Table 1: μ_R, $\sum_R$ and Z_{eff} calculated by the traditional and the present methods.

Compound/ mixture/alloy number or name	μ_R, $\sum_R$ in (cm^2/g) , and Z_{eff} calculated by traditional method				μ_R and $\sum_R$ in (cm^2/g) , calculated in this work			
	661.6 (keV)	1332.5 (keV)	$\sum_R$	Z_{eff}	661.6 (keV)	1332.5 (keV)	$\sum_R$	Z_{eff}
1	0.0809	0.0576	0.0718	4.60	0.0818	0.0583	0.0735	4.50
2	0.0857	0.0611	0.1119	3.00	0.0784	0.0559	0.104	3.00
3	0.0811	0.0578	0.0728	4.53	0.0818	0.0583	0.0735	4.50
4	0.0817	0.0582	0.1001	3.22	0.0886	0.0612	0.1029	3.43
5	0.0818	0.0583	0.0927	3.50	0.0831	0.0592	0.0926	3.50
6	0.1080	0.0581	0.0358	8.40 8.66	0.0772 0.0769	0.0549 0.0548	0.0398 0.0394	8.40 8.66
7	0.1110	0.0575	0.0222	15.85	0.0741	0.0526	0.0259	15.6
8	0.0803	0.0572	0.0641	5.20	0.0727	0.0519	0.0562	5.20
9	0.0778	0.0554	0.0591	5.45	0.0727	0.0519	0.0562	5.20
10	0.0850	0.0606	0.1010	3.43	0.0831 0.0858	0.0592 0.0612	0.0926 0.103	3.40 3.34
11	0.0799	0.0564105	0.05507794	6.1	0.0774	0.0552	0.0578	6.00
12	0.1060	0.0587	0.0302	10.6/10.8	0.0774	0.0551	0.0341	10.7
13	0.0934	0.0666	0.129	2.96	0.0881	0.0628	0.1289	2.67
14	0.0825	0.0587	0.0844	3.89	0.0831	0.0592	0.0926	3.50
15	0.0740	0.0522	0.0214	25	0.0718	0.0507	0.0204	24.5
16	0.0850	0.0605	0.107	3.11	0.0784	0.0559	0.104	3.00
17	0.0859	0.0612	0.109	3.12	0.0784	0.0559	0.104	3
FP	0.0836	0.0595	0.0939	3.51	0.0831	0.0592	0.0962	5.5
FPPb	0.0912	0.0571	0.0598	5.03/4.92	0.0727	0.0519	0.0562	5.2
Dolomite -sand	0.0776	0.0552	0.0403	8.6	0.0769	0.0548	0.0394	5.66
Barite-barite	0.0779	0.0526	0.0287	12.5/12.4	0.0741	0.0526	0.0285	12.7
Magnetite-limonite	0.0766	0.0543	0.0365	10/10.1	0.0767	0.0544	0.0354	10.00
Ilmenite -ilmenite	0.0755	0.0536	0.0327	11.2	0.0776	0.0552	0.0331	10.02
CF	0.0799	0.0568	0.0509	6.74	0.0782	0.0558	0.0499	6.50
CFM	0.0772	0.0548	0.0448	7.63	0.0795	0.0522	0.0429	7.74

Table 2: Weight fractions of some materials used in neutron and **γ**-ray shielding.

Element	FP	FPPb	Dolomite - sand	Barite-barite	Magnetite-limonite	Ilmenite – ilmenite	CF	CFM
H	0.0860	0.043500	0.0082538	0.006	0.011460	0.0064622	0.0284	0.01780
B	-	0.149100						0.09290
C	0.5774	0.323700	0.0839755	0.0029	0.000076		0.1091	0.09457
O	0.3333	0.128800	0.5098378	0.33128	0.392600	0.384150	0.4323	0.32820
Zn	0.0010	0.000800						
Pb		0.353700						
Ca	-	-	0.2611081	0.061000	0.090200	0.053300	0.3162	0.126800
Mg	-	-	0.069146	0.004200	0.003860	0.001721	0.00602	0.005000
Na			0.002732	0.003100	0.006800	0.006944		
K			0.0002803		0.000446	0.002232		
Fe			0.004129	0.00300	0.421100	0.280000	0.0294	0.274200
P			0.0000164	0.000005	0	0.000785		
Si			0.05412	0.022441	0.0694738	0.015600	0.0644	0.025800
S			0.0004093	0.106300	0.0002412	0.000854	0.0043	0.001700
Al			0.00064078	0.011200	0.0043540	0.003720	0.0151	0.006100
Ba				0.443965				
Cl				0.004757				
Ti						0.243800		0.028700
Mn						0.001550		
Ni						0.000366		
Cr								0.001640

keV and 1332.5 keV and Σ_R is searched for the closest value and/or values to Z_{eff}. For example, for the compound number "12", the calculated values of Z_{eff} are 10.6 and 10.8 and the closest value is 10.7.

Deviations between μ_R (at 661.6 keV and 1332.5 keV) and Σ_R determined by the present approach and the traditional method are noticed for some mixtures (Table 3). These can be noticed for 78.5% bismuth-loaded polyethylene (0.785 Bi, 0.184 C, 0.0309 H), 90% bismuth-loaded Polyethylene (0.9 Bi, 0.0866 C, 0.0144 H), borated lead polyethylene (0.8 Pb, 0.0122 Ca, 0.0047 Si, 0.042 O, 0.1071 C, 0.061 B, 0.0179 H) and Fiber–Plastic–Lead (FPPb) in Table2. These deviations are only for μ_R at 661.6 keV. There are no deviations at 1332.5 keV. For Σ_R, deviations do not exceed 17%.

It was noticed that when a composite mixture consisting of elements having high atomic numbers (with high weight fraction), and the rest of the constituting elements having low atomic numbers, the resultant value of μ_R at 661.6 keV or Σ_R for the mixture deviates from the traditional method. This is noticed for 78.5% and 90% bismuth loaded polyethylene, borated lead polyethylene and Fiber-Plastic-Lead (FPPb) composites. Also, it is noticed that the values of Z_{eff} determined for these mixtures at 661.6 keV and 1332.5 keV are slightly different. The deviations noticed in this work can be minimized, e.g. by preparing separate tables containing data for mixtures consisting of elements having high and low atomic numbers. Namely, for every mixture, compound and/or alloy of interest, a separate table should be prepared. These concerns along with electron density calculations, for composites containing light and heavy elements, will be considered in a forthcoming work.

Table 3: Deviations of μ_R at 661.6 and 1332.5 keV, and $\sum_R$ determined in this work from traditional method.

Compound/ mixture/ alloy number or name	μ_R(this work)/ μ_R(traditional) at 661.6 keV	μ_R(this work)/ μ_R(traditional) at 1332.5 keV	$\sum_R$(this work)/ $\sum_R$ (traditional)
1	1.01	1.01	1.02
2	0.92	0.92	0.93
3	1.01	1.01	1.01
4	1.08	1.05	1.02
5	1.02	1.02	1.00
6	0.72	0.95	1.11
7	0.67	0.92	1.17
8	0.91	0.91	0.88
9	0.93	0.94	0.95
10	0.98	0.98	0.92
11	0.97	0.98	1.05
12	0.73	0.94	1.13
13	0.94	0.94	1.00
14	1.01	1.01	1.10
15	0.97	0.97	0.95
16	0.92	0.92	0.97
17	0.91	0.91	0.95
FP	0.99	1.00	1.02
FPPb	0.78	0.91	0.94
Dolomite - sand	0.99	0.99	0.98
Barite-barite	0.95	1	0.990
Magnetite-limonite	1.00	1.00	0.97
Ilmenite -ilmenite	1.03	1.03	1.01
CF	0.98	0.98	0.98
CFM	1.03	0.95	0.96

Importantly, the new developed method would be beneficial not only in the area of nuclear physics but in materials science and engineering as well, as it would help a lot in carrying out the necessary calculations for the design of new materials used in radiation shielding and detection. Actually, the recent advances in materials science and nanotechnology allowed for the creation of new materials with superior and enhanced characteristics that qualify them to be used in radiation detection and shielding [25,26]. However, in order to understand the behavior of such advanced nanomaterials under the influence of radiation, it is necessary to know preliminary information about their characteristic parameters influencing, e.g. their radiation detection efficiency. Among these important parameters are the nanocomposites mass attenuation coefficients and effective removal cross-sections. Whence, the current developed method for estimating such parameters is important in understanding their radiation detection, or shielding characteristics measured at different radiation doses.

Conclusions

In this work, a method was developed for determining the effective removal cross-section for fast neutrons and the mass absorption coefficients for gamma rays at 661.6 keV and 1332.5 keV for any compound, alloy and/or composite material. The effective atomic number should be known at one of these energies. In most cases, good agreement is obtained between the values determined by the proposed approach and those obtained by the traditional method.

References

1. Gerward L, Guilbert N, Jensen KB, Levring H. WinXCom-a program for calculating X-ray attenuation coefficients. Rad Phys and Chem. 2004; 71, 653–4. doi:10.1016/j.radphyschem.2004.04.040
2. Murty VRK. Effective atomic numbers for W/Cu alloy for total photon attenuation. Rad Phys and Chem. 2004; 71, 667–9. doi: 10.1016/j.radphyschem.2004.04.046
3. Gowda S, Krishnaveni S, Gowna R. Studies on effective atomic numbers and electron densities in amino acids and sugars in the energy range 30-1333 keV. Nucl Instr and Meth B. 2005; B, 239, 361–9. doi: 10.1016/j.nimb.2005.05.048
4. Icelli O, Erzeneoglu S, Karahan IH, Cankaya G. Effective atomic numbers for CoCuNi alloys using transmission experiments. JQSRT.

2000; 91, 485–91. doi: 10.1016/j.jqsrt.2004.07.006

5. El-Kateb AH, Rizk RAM, Abdul-Kader AM. Determination of atomic cross-sections and effective atomic numbers for some alloys. Annals of Nuclear Energy. 2000; 27, 1333-43. doi: 10.1016/S0306-4549(99)00121-8

6. Manohara SR, Hanagodimath SM. Studies on effective atomic numbers and electron densities of essential amino acids in the energy range in energy range 1 keV–100 GeV. Nucl Instr and Meth B. 2007; 258, 321–8. doi: 10.1016/j.nimb.2007.02.101

7. Kaplan MF. Concrete Radiation Shielding. nuclear physics, concrete properties, design and construction. New York, USA: Longman Scientific & Technical; 1989.

8. Glasstone S, Sesonske A. Nuclear Reactor Engineering. 3rd ed. New York, USA: Springer ; 1986.

9. Vogel H, Haller D. Luggage and shipped goods. Eur J Radiol. 2007; 63(2), 242-53.

10. Ogorodnikov S, Petrunin V. Processing of interlaced images in 4–10 MeV dual energy customs system for material recognition. Phys Rev ST Accel Beams. 2002; 5, 104701.

11. Overley JC, Chmelik MS, Rasmussen RJ, Schofield RMS, Sieger GE, Lefevre HW. Explosives detection via fast neutron transmission spectroscopy. Nucl Instr and Meth B. 2006; 251 (2) 470-478. doi: 10.1016/j.nimb.2006.04.173

12. Rasmussen RJ, Fanselow WS, Lefevre HW, Chmelik MS, Overley JC, Brown AP, et al. Average atomic number of heterogeneous mixtures from the ratio of gamma to fast-neutron attenuation. Nuclear Instruments and Methods in Physics Research B. 1997; 124(4), 611-614. doi: 10.1016/S0168-583X(97)00120-1

13. Rynes J, Bendahan J, Gozani T, Loveman R, Stevenson J, Bell C. Gamma-ray and neutron radiography as part of a pulsed fast neutron analysis inspection system. Nucl Instr and Meth A. 1999; 422(1-3), 895-899. doi: 10.1016/S0168-9002(98)01039-0

14. Chen G, Lanza RC. Fast neutron resonance radiography for elemental imaging: Theory and applications. IEEE Trans Nucl Sci. 2002; 49: 1919.

15. Eberhardt JE, Rainey S, Stevens RJ, Sowerby BD, Tickner JR. Fast neutron radiography scanner for the detection of contraband in air cargo containers. Appl Radiat Isot. 2005; 63, 179-188.

16. Vourvopoulos G, Womble PC. Pulsed fast/thermal neutron analysis: a technique for explosives detection. Talanta. 2001; 54, 459-468.

17. Viesti G, Cossutta L, Fabris D, Lunardon M, Moretto S, Nebbia, G, et al. Material recognition by using a tagged ^{252}Cf source. Nuclear Instruments and Methods in Physics Research A. 2002; 593 (3), 592–596. doi: 10.1016/j.nima.2008.05.024

18. Stevanato L, Caldogno M, Dima R, Fabris D, Lunardon M, Moretto S, et al. A new facility for non-destructive assay using a ^{252}Cf source. Applied Radiation and Isotopes. 2013, 73, 52–59. doi: 10.1016/j.apradiso.2012.11.018

19. Wood J. Computational Methods in Reactor Shielding. New York, USA: Pergamon Press, Inc.; 1982.

20. Manohara SR, Hanagodimath SM, Thind KS, Gerward L. On the effective atomic number and electron density: A comprehensive set of formulas for all types of materials and energies above 1 keV. Nuclear Instruments and Methods in Physics Research B. 2008; 266, 3906–3912. doi: 10.1016/j.nimb.2008.06.034

21. Elmahroug Y, Tellili B, Souga C. Calculation of fast neutron removal cross-sections for different shielding materials. International Journal of Physics and Research (IJPR). 2013; 3(2), 7-16.

22. El-Sayed Abdo A, Ali MM, Ismail MR. Natural fibre high-density polyethylene and lead oxide composites for radiation shielding. Radiation Physics and Chemistry. 2003; 66, 185–195. doi: 10.1016/S0969-806X(02)00470-X.

23. El-Sayed Abdo A. Calculation of the cross-sections for fast neutrons and gamma-rays in concrete shields. Annals of Nuclear Energy. 2002; 29, 1977–1988. doi: 10.1016/S0306-4549(02)00019-1

24. El-Sayed Abdo A, Ali MAM, Ismail MR. Influence of magnetite and boron carbide on radiation attenuation of cement–fiber/composite. Annals of Nuclear Energy. 2003; 30, 391–403. doi: 10.1016/S0306-4549(02)00074-9

25. Schrempp-Koops L. Size Effects on the Efficiency of Neutron Shielding in Nanocomposites – a Full Range Analysis. International Journal of Nanoscience. 2013; 12(3), 1350015-22. doi: 10.1142/S0219581X13500154

26. Sahi S, Chen W. Luminescence enhancement in CeF3/ZnO nanocomposites for radiation detection. Radiation Measurements. 2013; 59, 139. doi: 10.1016/j.radmeas.2013.04.015