Research Article GU J Sci 36(2): 898-907 (2023) DOI: 10.35378/gujs.984496

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

A Study on Radiation Shielding Abilities of Some Compounds of 3d Transition Elements by Using Phy-X/PSD Code

Zeynep AYGUN[1,*], Murat AYGUN[2]

[1]Bitlis Eren University, Vocational School of Technical Sciences, Bitlis, Turkey
[2]Bitlis Eren University, Faculty of Science and Arts, Department of Physics, Bitlis, Turkey

Highlights

- Photon attenuation parameters of the compounds have been determined by Phy-X/PSD.
- The radiation shielding potentials of the compounds have been evaluated.
- Fast neutron shielding performances of the compounds have been studied.

Article Info

Received: 18 Aug 2021
Accepted: 01 Apr 2022

Keywords

Radiation attenuation parameters
Radiation shielding
3d transition elements

Abstract

In the present study, it was aimed to calculate the radiation-matter interaction parameters of some compounds of 3d transition elements. The radiation attenuation parameters, which are important to have knowledge about the radiation shielding potentials, were calculated by using Phy-X/PSD code in the energy range of 0.01-15 MeV. The calculated mass attenuation coefficient and effective atomic number results were compared with the experimental data which were measured at 19.63 and 22.10 keV previously and, a good agreement was achieved. In order to evaluate the shielding properties of the compounds, we also compared the mass attenuation coefficients of the compounds with ordinary concrete, steel-scrap, ilmenite-limonite and basalt-magnetite, which are widely used as radiation protective materials. According to the obtained results, it is concluded that the studied compounds have radiation shielding potentials.

1. INTRODUCTION

Recently, protection of all living creatures from the harms of radiation becomes more important due to the increase in application fields of radiation such as agriculture, technology, industry, medicine, medical imaging and radiotherapy etc. There has been an enormous interest in researches including radiation attenuation parameters that can assure significant knowledge about radiation shielding potentials of materials [1-5]. These parameters consist of mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), mean free path (MFP), half-value layer (HVL), tenth-value layer (TVL), total atomic and electronic cross-sections (ACS and ECS), effective atomic number (Z_{eff}), effective electron density (N_{eff}), effective conductivity (C_{eff}) and fast neutron removal cross section (FNRCS). Several methods are developed in order to calculate the photon interaction coefficients of materials such as, XCOM [6], WinXCom [7,8], XMuDat [9], Phy-X/PSD [10], Py-MLBUF [11], EpiXS [12] and simulation code Geant4 [13]. Recently, researchers widely use the codes for determination of the shielding potentials of various materials such as alloys, glasses, rocks, soils, etc. [2-5,14-18].

The 3d transition elements and their compounds have a considerable effect in the development of technologic applications because of the well-known features such as hardness, high density, good thermal conductivity, high melting-boiling temperatures and having more than one oxidation state. Due to the diversity of physical properties of the 3d transition elements, many applications of these elements and their compounds indicate the need to get information about various physical parameters [19]. Many studies have

* Corresponding author, e-mail: zeynep.yarbasi@gmail.com, zaygun@beu.edu.tr

been done about coefficients, Z_{eff} of the 3d transition metal elements, their compounds and alloys at several photon energies before [19-23]. But these works are limited only by some parameters in several energies. We believe that it would be important to determine the radiation attenuation parameters such as MAC, LAC, HVL, TVL, MFP, ACS, ECS, Z_{eff}, N_{eff}, C_{eff} and FNRCS, hence, radiation shielding potentials of 3d transition metal compounds for different energy values. By this comprehensive investigation, we can conclude that which compound has better radiation shielding potential.

In this work, it is aimed to calculate radiation attenuation parameters of some compounds of the 3d transition elements (CoO, CoF_2, CoF_3, Cr_2O_3, CrF_2, CrF_3, FeO, Fe_2O_3, MnO_2, TiO_2, V_2O_3, VF_3, V_2O_5, VF_4 and ZnO) in the photon energy range of 0.01-15 MeV theoretically by using Phy-X/PSD software which can calculate quickly and accurately all specified shielding parameters for different materials in the continuous energy range and selected energies [10]. At 19.63 and 22.10 keV energies, calculated MAC and Z_{eff} values of the compounds were also compared with the experimental MAC and Z_{eff} results given by Yılmaz et al., [23].

2. MATERIAL METHOD

The MAC is a quantity that defines the interaction possibility between gamma photons and the mass per unit area for a particular medium and can be calculated by the Beer–Lambert formulated as:

$$I = I_0 e^{-\mu t} \tag{1}$$

$$\mu_m = \frac{\mu}{\rho} = ln(I_0/I)/\rho t = ln(I_0/I)/t_m \tag{2}$$

where I_0 and I are incident and attenuated photon intensities, ρ (g/cm^3) is the density of material, μ_m(cm^2/g) and μ(cm^{-1}) are mass and linear attenuation coefficients, t_m (g/cm^2) and t (cm) are sample mass thickness (the mass per unit area) and the thickness, respectively.

If the sample has various elements, we can write the total mass attenuation coefficient for any compound as follows [24];

$$\mu/\rho = \sum_i w_i(\mu/\rho)_i \tag{3}$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and the mass attenuation coefficient of the ith constituent element, respectively.

The total atomic cross-section (σ_a) for any sample can be calculated using the equation formulated as;

$$ACS = \sigma_a = \frac{N}{N_A}(\mu/\rho) \tag{4}$$

where N_A and N respectively are the Avogadro's number and the atomic mass of materials.

The total electronic cross-section (σ_e) is formulated by the following equation [7];

$$ECS = \sigma_e = \frac{\sigma_a}{Z_{eff}}. \tag{5}$$

By using the Equations (4) and (5), we can find the effective atomic number, Z_{eff}, of the material as follows;

$$Z_{eff} = \frac{\sigma_a}{\sigma_e}. \tag{6}$$

We can calculate the effective electron number, N_{eff}, as follows [21],

$$N_{eff=\frac{\mu m}{\sigma_e}} \quad . \tag{7}$$

HVL and TVL are the thicknesses parameters that are used to reduce the radiation intensities by one half and one tenth, respectively. MFP is the average distance at which a photon travels through the material between two interactions. The μ is used to obtain the parameters given by

$$HVL = \frac{In(2)}{\mu} \tag{8}$$

$$MFP = \frac{1}{\mu} \tag{9}$$

$$TVL = \frac{In10}{\mu}. \tag{10}$$

Effective conductivity (C_{eff}) of materials can be given by the following equation [25]:

$$C_{eff} = (\frac{N_{eff}\rho e^2 \tau}{m_e})10^3 \tag{11}$$

where m_e (kg) and e (C) are mass and charge of electron, respectively.

FNRCS ($\sum R$) values of the materials can be calculated by the following equation [26,27]:

$$\sum R = \sum_i \rho_i (\sum R/\rho)_i \tag{12}$$

where $(\sum R/\rho)_i$ and ρ_i are the mass removal cross-section of the ith constituent element and partial density of the material, respectively.

3. THE RESEARCH FINDINGS AND DISCUSSION

The radiation shielding parameters of the compounds of the 3d transition elements which were reported previously by Yılmaz et al. [23] are theoretically calculated by using Phy-X/PSD code [10]. The theoretically calculated and experimentally reported MAC and Z_{eff} values of the compounds are given at photon energies 19.63 and 22.10 keV and listed in Table 1. It is clearly seen in the Table 1 that the calculated parameters are in good agreement with those obtained experimentally [23]. Due to the good agreement between calculated and experimental MAC and Z_{eff} results at 19.63 and 22.10 keV, we also wanted to obtain all radiation-matter interaction parameters theoretically in the energies of 0.015-15 MeV. Variations of the calculated values versus photon energies are given in Figures 1-5.

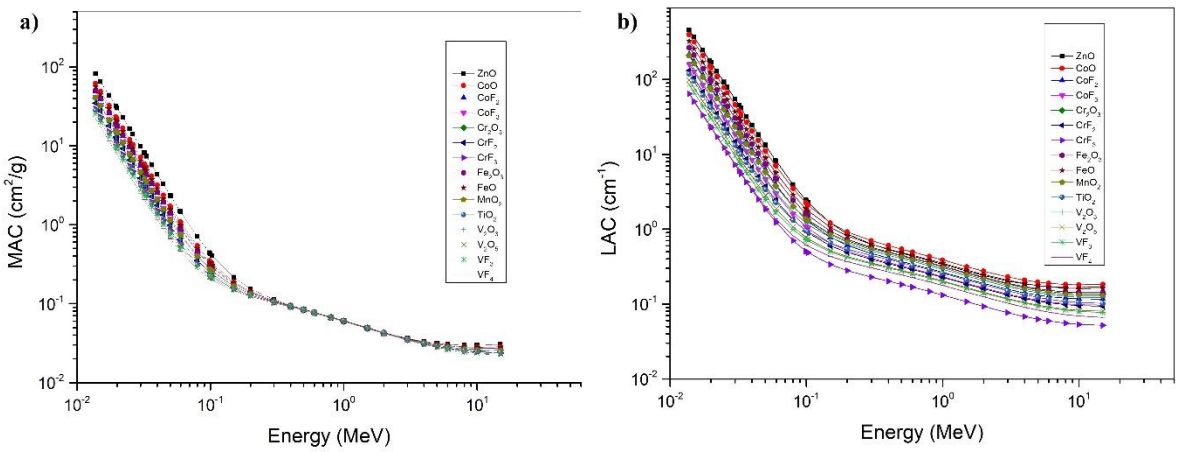

Figure 1. *The changes of MAC (a) and LAC (b) as a function of incident photon energy*

Table 1. *Comparison of the calculated and experimental values of MAC and Z_{eff} for 3d transition elements compounds*

Comp	Phy-X/PSD MAC values		Experimental MAC values (Yılmaz *et al.* 2016)		Phy-X/PSD Z_{eff} values		Experimental Z_{eff} values (Yılmaz *et al.* 2016)	
	19.63 (keV)	**22.1 (keV)**	**19.63 (keV)**	**22.1 (keV)**	**19.63 (keV)**	**22.1 (keV)**	**19.63 (keV)**	**22.1 (keV)**
CoO	23.41	16.82	21.347±0.949	15.467±1.314	26.48	26.45	24.457±1.078	24.327±1.508
CoF_2	18.41	13.23	17.297±0.778	12.597±1.070	25.70	25.66	24.157±1.065	24.097±1.494
CoF_3	15.59	11.21	13.827±0.622	10.717±0.910	25.12	25.07	23.277±1.026	23.077±1.430
Cr_2O_3	14.98	10.73	14.947±0.672	10.737±0.912	23.12	23.07	23.027±1.015	22.997±1.425
CrF_2	12.91	9.25	11.937±0.536	8.2927±0.705	22.54	22.49	20.797±0.916	20.127±1.247
CrF_3	10.86	7.79	10.367±0.466	6.5827±0.559	21.91	21.85	20.237±0.892	18.377±1.138
FeO	21.23	15.23	22.077±0.993	16.207±1.377	25.46	25.43	26.907±1.186	26.607±1.649
Fe_2O_3	19.20	13.77	20.337±0.915	14.657±1.245	25.20	25.15	26.637±1.174	26.057±1.615
MnO_2	15.33	10.99	13.677±0.615	9.4547±0.803	23.90	23.84	21.347±0.941	20.507±1.271
TiO_2	10.38	7.41	10.327±0.464	7.3127±0.621	20.73	20.66	20.657±0.911	20.197±1.252
V_2O_3	12.96	9.26	13.997±0.629	9.8647±0.838	22.07	22.02	23.897±1.097	23.467±1.454
VF_3	9.42	6.74	11.137±0.456	7.8927±0.585	20.84	20.77	22.447±1.039	21.187±1.317
V_2O_5	10.84	7.75	10.367±0.556	7.3217±0.622	21.52	21.44	21.567±0.989	20.247±1.251
VF_4	8.19	5.86	7.3817±0.332	5.0027±0.425	20.26	20.18	18.277±0.806	17.227±1.067
ZnO	31.62	22.84	29.557±1.329	22.427±1.906	29.54	29.52	27.637±1.218	29.017±1.799

Table 2. *Calculated MAC values of the investigated compounds and widely used shielding materials*

Energy (MeV)	**ZnO**	**CoO**	**FeO**	**Fe_2O_3**	**CoF_2**	**CoF_3**	**MnO_2**	**Cr_2O_3**	**V_2O_3**	**CrF_2**	**CrF_3**	**V_2O_5**	**TiO_2**	**VF_3**	**VF_4**	**OC [28]**	**SS [28]**	**IL [28]**	**BM [28]**
$1.50x10^{-02}$	65.57	49.16	44.78	40.47	38.68	32.74	32.44	31.86	27.65	27.46	23.11	23.11	22.23	20.11	17.47	7.079	37.92	29.64	20.47
$2.00x10^{-02}$	30.05	22.22	20.15	18.22	17.49	14.80	14.55	14.21	12.29	12.25	10.31	10.28	9.848	8.941	7.772	3.105	17.02	13.28	9.156
$3.00x10^{-02}$	9.769	7.129	6.440	5.832	5.625	4.776	4.652	4.521	3.903	3.907	3.304	3.283	3.131	2.863	2.502	1.048	5.445	4.250	2.971
$4.00x10^{-02}$	4.377	3.186	2.879	2.616	2.531	2.162	2.098	2.035	1.763	1.769	1.510	1.499	1.430	1.316	1.161	0.541	2.446	1.907	1.295
$5.00x10^{-02}$	2.366	1.732	1.569	1.433	1.391	1.199	1.162	1.129	0.984	0.990	0.856	0.849	0.813	0.753	0.673	0.358	1.345	1.074	0.789
$6.00x10^{-02}$	1.452	1.074	0.979	0.900	0.874	0.762	0.740	0.720	0.635	0.638	0.560	0.557	0.536	0.500	0.454	0.241	0.849	0.690	0.526
$8.00x10^{-02}$	0.705	0.540	0.500	0.467	0.454	0.407	0.397	0.389	0.351	0.353	0.320	0.319	0.310	0.293	0.274	0.204	0.445	0.378	0.309
$1.00x10^{-01}$	0.430	0.344	0.324	0.307	0.299	0.274	0.270	0.266	0.245	0.246	0.229	0.229	0.225	0.215	0.205	0.172	0.296	0.261	0.227
$1.50x10^{-01}$	0.215	0.188	0.183	0.178	0.174	0.167	0.166	0.165	0.158	0.158	0.153	0.154	0.153	0.148	0.145	0.142	0.176	0.165	0.157
$2.00x10^{-01}$	0.154	0.142	0.141	0.139	0.136	0.133	0.133	0.133	0.129	0.129	0.127	0.128	0.128	0.124	0.123	0.127	0.139	0.134	0.132
$3.00x10^{-01}$	0.113	0.109	0.109	0.109	0.106	0.106	0.106	0.107	0.105	0.104	0.104	0.105	0.105	0.102	0.102	0.108	0.109	0.108	0.109
$4.00x10^{-01}$	0.095	0.094	0.094	0.095	0.092	0.092	0.093	0.093	0.092	0.092	0.091	0.092	0.093	0.090	0.090	0.096	0.095	0.095	0.096
$5.00x10^{-01}$	0.085	0.084	0.085	0.085	0.083	0.083	0.084	0.084	0.083	0.083	0.083	0.084	0.084	0.082	0.082	0.088	0.085	0.085	0.087
$6.00x10^{-01}$	0.078	0.077	0.078	0.078	0.076	0.076	0.077	0.077	0.076	0.076	0.076	0.077	0.077	0.075	0.076	0.079	0.079	0.079	0.080
$8.00x10^{-01}$	0.067	0.067	0.068	0.068	0.066	0.067	0.067	0.068	0.067	0.067	0.067	0.067	0.068	0.066	0.066	0.071	0.068	0.069	0.072
$1.00x10^{0}$	0.060	0.060	0.061	0.061	0.060	0.060	0.060	0.061	0.060	0.060	0.060	0.060	0.061	0.059	0.059	0.064	0.063	0.061	0.063
$1.50x10^{0}$	0.049	0.049	0.050	0.050	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.050	0.048	0.048	0.052	0.051	0.050	0.050
$2.00x10^{0}$	0.043	0.043	0.043	0.043	0.042	0.042	0.043	0.043	0.042	0.042	0.042	0.043	0.043	0.042	0.042	0.045	0.045	0.043	0.044
$3.00x10^{0}$	0.036	0.036	0.036	0.036	0.035	0.035	0.036	0.036	0.035	0.035	0.035	0.035	0.035	0.034	0.034	0.036	0.037	0.036	0.036
$4.00x10^{0}$	0.033	0.032	0.033	0.032	0.032	0.031	0.032	0.032	0.031	0.031	0.031	0.031	0.031	0.030	0.030	0.031	0.033	0.032	0.031
$5.00x10^{0}$	0.031	0.031	0.031	0.030	0.029	0.029	0.029	0.030	0.029	0.029	0.029	0.029	0.029	0.028	0.028	0.028	0.031	0.029	0.029
$6.00x10^{0}$	0.030	0.029	0.029	0.029	0.028	0.028	0.028	0.028	0.028	0.027	0.027	0.027	0.027	0.026	0.026	0.026	0.030	0.028	0.027
$8.00x10^{0}$	0.030	0.028	0.028	0.028	0.027	0.026	0.026	0.027	0.026	0.026	0.025	0.025	0.026	0.025	0.024	0.024	0.028	0.026	0.025
$1.00x10^{1}$	0.030	0.028	0.028	0.027	0.026	0.025	0.026	0.026	0.025	0.025	0.024	0.025	0.025	0.024	0.023	0.022	0.027	0.025	0.024
$1.50x10^{1}$	0.030	0.028	0.028	0.027	0.026	0.025	0.026	0.026	0.025	0.025	0.024	0.024	0.024	0.023	0.022	0.021	0.027	0.025	0.023

The variations of the MAC values versus the incident photon energies for all compounds are shown in Figure 1(a). It was obtained that the highest three MAC values are found for ZnO, CoO and FeO compounds both at high and low energies, respectively. It is clearly seen that MAC values decrease with the increasing photon energy which affects the penetration of the photon. In order to evaluate the shielding properties of the compounds, the calculated MAC values were compared with the widely used shielding materials (ordinary concrete, steel-scrap, ilmenite-limonite and basalt-magnetite) reported by Bashter [28], and the results are given in Table 2. It can be mentioned that all the studied compounds show higher shielding features than ordinary concrete (OC). ZnO, CoO, FeO, Fe_2O_3, and CoF_2 have higher shielding potentials than steel-scrap. The obtained MAC values of ZnO, CoO, FeO, Fe_2O_3, CoF_2, CoF_3, MnO_2, and Cr_2O_3 are greater than those of ilmenite-limonite, while except from VF_3 and VF_4 all the other compounds show higher shielding abilities than basalt magnetite.

LAC is one of the parameters for defining the photon-matter interaction, but it is not sufficient. Additionally, it is evaluated to calculate MAC, HVL and MFP shielding parameters. The value of LAC depends on both MAC and density of compound. We can see the dependence of LAC values on photon energies in Figure 1(b). We observed the highest LAC value for ZnO at low energies while this was observed for CoO compound at high energies. Due to the density effect, differences of LAC values are greater than those of MAC values.

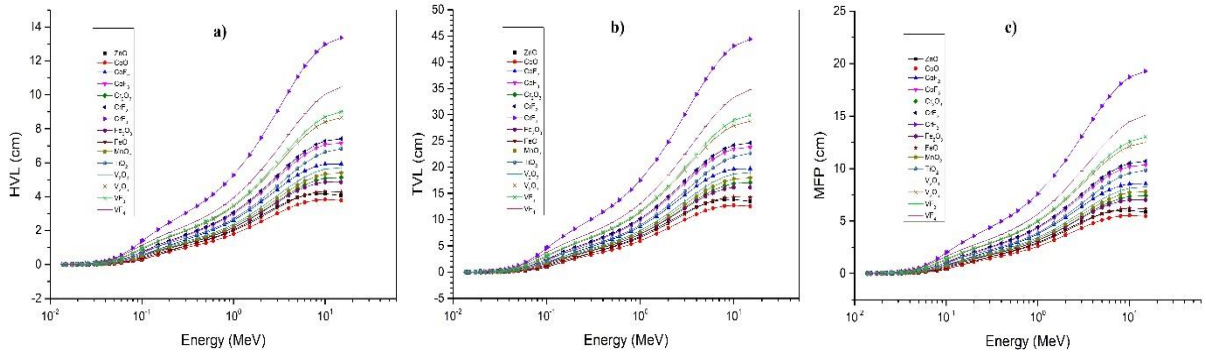

Figure 2. *Dependence of HVL (a) TVL (b) and MFP (c) versus incident photon energy*

The HVL and TVL are the parameters to understand the ability of radiations to penetrate materials. HVL, TVL and MFP parameters changing with the incident photon energies are given in Figure 2(a-c). It is desirable to have low HVL, TVL and MFP values in the high energy regions. It is seen that the lowest HVL, TVL and MFP values were obtained for CoO, ZnO and FeO compounds in high energy regions. Due to the obtained HVL, TVL and MFP values, it can be concluded that the best radiation shielding property is shown by CoO compound.

The interaction possibility of per atom and per electron in a unit volume of any material is given by ACS and ESC, respectively. In Figure 3(a-b), changing of ACS and ECS values as a function of incident photon energies are given. If the ACS and ECS values are high, the compounds with these values can be evaluated as better shielding compounds. According to these parameters, we can mention that the highest shielding properties belong to ZnO, CoO and FeO compounds, respectively and the lowest shielding capacity is determined for VF_4. This result is compatible with the mentioned parameters above.

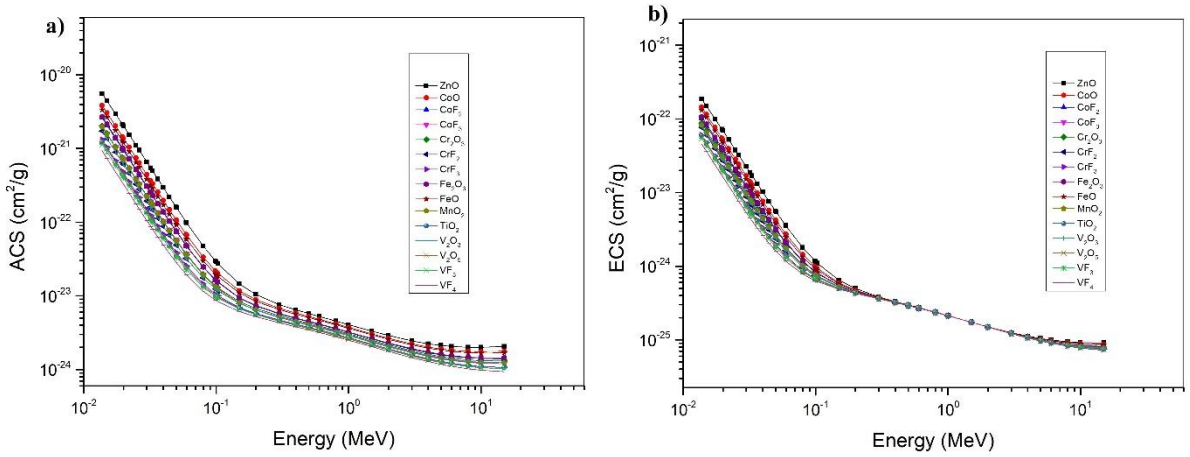

Figure 3. *The variations of ACS (a) and ECS (b) as a function of incident photon energy*

The energy dependence of Z_{eff} and N_{eff} are given in Figure 4(a-b). Z_{eff} values are high for ZnO, CoO and FeO compounds while those are low for VF_4 compound in the all energies. Due to the higher Z_{eff} values, it can be said that ZnO has the highest shielding potential among others. N_{eff} is one of the most important parameter that represents the effective conductivity of the compound depending on the excitatory photon energy [5]. As seen in the figure, the dependence of the N_{eff} values on the incident photon energies is similar with the variations of Z_{eff} values.

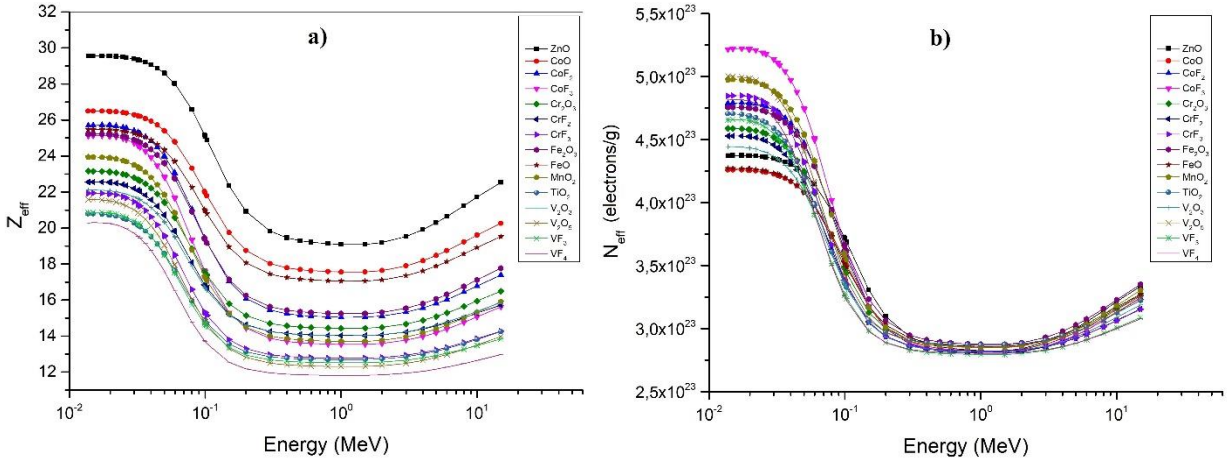

Figure 4. *The changes of Z_{eff} (a) and N_{eff} (b) as a function of incident photon energy*

The interactions between photons and material with photo-electric effect, Compton scattering, and pair production interaction processes cause changes in the number of free electrons in the material. This change depends on the N_{eff} values because of the conduction electron numbers. Hence, C_{eff} is proportional to N_{eff} of the compounds. Change of C_{eff} values versus photon energies is given in Figure 5. CoO, compound has the highest C_{eff} values in all energies compared to others.

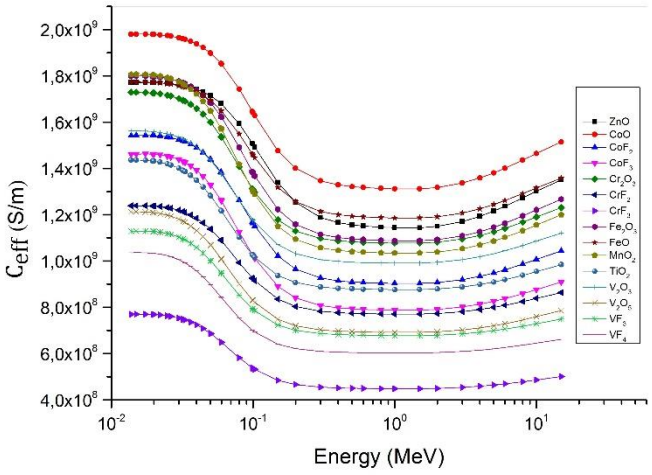

Figure 5. *The variations of C_{eff} versus photon energy*

Additionally, it is important to learn the neutron shielding capacity of the compounds for neutron applications. The fast neutron attenuation capabilities of the compounds were also determined by Phy-X/PSD. FNRCS and densities of the studied compounds are given in Figure 6. It was concluded that there is a direct relation between the densities and FNRCS values of the compounds. The lowest FNRCS (0,063) is observed for CrF_3 and the highest one (0.154) is observed for CoO. It can be noted that CoO compound has the best neutron shielding ability among the compounds, while CrF_3 has the least.

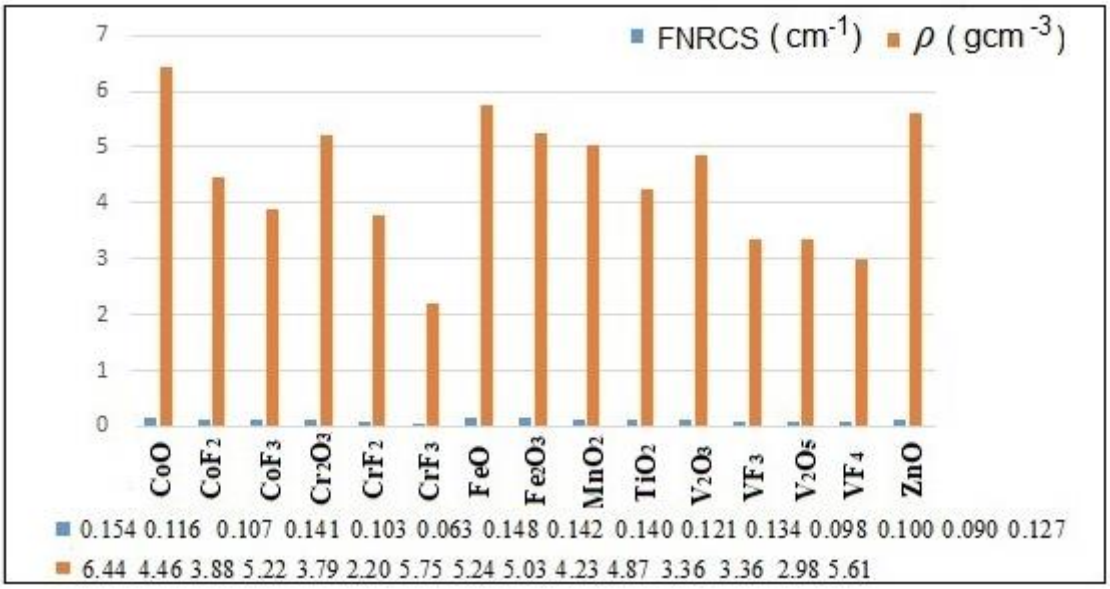

Figure 6. *The changes of FNRCS values and densities of the compounds*

4. RESULTS

In the present study, radiation-matter interaction parameters of compounds of 3d transition elements were calculated to determine the radiation shielding capabilities. For the purpose of determining the parameters Phy-X / PSD software was applied. The MAC and Z_{eff} parameters were calculated and compared with experimental results at 19.63 and 22.10 keV energies. In addition, MAC, LAC, HVL, TVL, MFP, ACS, ECS, Z_{eff}, N_{eff}, C_{eff} and FNRCS values of the present compounds were calculated in the range of 0.01-15 MeV. According to the obtained results in the present study, it was concluded that ZnO, CoO and FeO compounds have the highest probabilities of interacting with photon and so have highest shielding

potentials compared to other compounds. According to the obtained FNRCS values of the compounds, CoO, FeO and Fe_2O_3 have more neutron shielding performances among the studied compounds.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Mann, K.S., Kaur, B., Sidhu, G.S., Kumar, A., "Investigations of some building materials for g-rays shielding effectiveness", Radiation Physics and Chemistry, 87: 16-25, (2013).

[2] Issa, S.A.M., Mostafa, A.M.A., "Effect of Bi2O3 in borate-tellurite-silicate glass system for development of gamma-rays shielding materials", Journal of Alloys and Compounds, 695: 302-310, (2017).

[3] Zhang, L., Jia, M., Gong, J., Xia. W., "Comparison study of photon attenuation characteristics of Lead-Boron Polyethylene by MCNP code, XCOM and experimental data", Radiation Effects and Defects in Solids, 172: 643–649, (2017).

[4] Al-Buriahi, M.S., Tonguc, B.T., "Mass attenuation coefficients, effective atomic numbers and electron densities of some contrast agents for computed tomography", Radiation Physics and Chemistry, 166: 1-6, (2020).

[5] Alım, B., "Determination of Radiation Protection Features of the Ag2O Doped Boro-Tellurite Glasses Using Phy-X / PSD Software", Journal of The Institute of Science and Technology, 10(1): 202-213, (2020).

[6] Berger, M.J., Hubbell, J.H., XCOM: Photon Cross Sections Database, Web Version 1.2. National Institute of Standards and Technology, Gaithersburg, MD 20899, USA, (1987). available at: http://physics.nist.gov/xcom

[7] Gerward, L., Guilbert, N., Jensen, K.B., Levring, H., "X-ray absorption in matter. Reengineering XCOM", Radiation Physics and Chemistry, 60: 23–24, (2001).

[8] Gerward, L., Guilbert, N., Jensen, K.B., Levring, H., "WinXCom—a program for calculating X-ray attenuation coefficients", Radiation Physics and Chemistry, 71: 653–654, (2004).

[9] Nowotny, R. "XMuDat: Photon attenuation data on PC", IAEA Report IAEA-NDS 195, (1998).

[10] Şakar, E., Özpolat, Ö.F., Alım, B., Sayyed, M.I., Kurudirek, M., "Phy-X / PSD: Development of a user friendly online software for calculation of parameters relevant to radiation shielding and dosimetry", Radiation Physics and Chemistry, 166: 1-12, (2020).

[11] Mann, K.S., Mann, S.S., "Py-MLBUF: Development of an online-platform for gamma-ray shielding calculations and investigations", Annals of Nuclear Energy, 150: 107845, (2021).

[12] Hila, F.C., Astronomo, A.A., Dingle, C.A.M., Jecong, J.F.M., Javier-Hila, A.M.V., Gili, M.B.Z., Balderasa, C.V., Lopeza, G.E.P., Guillermoa, N.R.D., Amorsolo, A.V., "EpiXS: A Windows-based program for photon attenuation, dosimetry and shielding based on EPICS2017 (ENDF/B-VIII) and EPDL97 (ENDF/B-VI.8)", Radiation Physics and Chemistry, 182: 109331, (2021).

[13] Agostinelli, S., Allison, J., Amako, K., Apostolakis, J., Araujo, H., Arce, P., Asai, M., Axen, D., Banerjee, S., Barrand, G., Behner, F., Bellagamba L., Boudreau, J., Broglia, L., Brunengo, A.,

Burkhardt, H., Chauvie, S., Chuma, J., Zschiesche, D., "Geant4—a simulation toolkit", Nuclear Instrumentation and Methods A, 506: 250-303, (2003).

[14] Aygun Z., Yarbasi N., Aygun M., "Spectroscopic and radiation shielding features of Nemrut, Pasinler, Sarıkamıs and Ikizdere Obsidians in Turkey: Experimental and theoretical study", Ceramics International, 47(24): 34207-34217, (2021).

[15] Aygun, Z., Aygun, M., "A study on usability of Ahlat ignimbrites and pumice as radiation shielding materials, by using EpiXS code", International Journal of Environmental Science and Technology, (in press), (2021). https://doi.org/10.1007/s13762-021-03530-9

[16] Lacomme, E., Sayyed, M.I., Sidek, H.A.A., Matori, K.A., Zaid, M.H.M., "Effect of bismuth and lithium substitution on radiation shielding properties of zinc borate glass system using Phy-X/PSD simulation", Results in Physics, 20: 103768, (2021).

[17] Mansour, A., Sayyed, M.I., Mahmoud, K.A., Şakar, E., Kovaleva, E.G., "Modified halloysite minerals for radiation shielding purposes", Journal of Radiation Research and Applied Sciences, 13(1): 94-101, (2020).

[18] Aksoy, C., "The X-Ray fluorescence parameters and radiation shielding efficiency of silver doped superconducting alloys", Radiation Physics and Chemistry, 186: 109543, (2021).

[19] Han, I., Demir, L., "Studies on effective atomic numbers, electron densities and mass attenuation coefficients in Au alloys", Journal of X-ray Science and Technology, 18: 39–46, (2010).

[20] Han, I., Demir, L., "Determination of mass attenuation coefficients, effective atomic and electron numbers for Cr, Fe and Ni alloys at different energies", Nuclear Instrumentation and Methods B, 267: 3–8, (2009).

[21] Han, I., Demir, L., "Studies on effective atomic numbers, electron densities from mass attenuation coefficients in TixCo1-x and CoxCu1-x alloys", Nuclear Instrumentation and Methods B, 267: 3505–3510, (2009).

[22] Han, I., Aygun, M., Demir, L., Sahin, Y., "Determination of effective atomic numbers for 3d transition metal alloys with a new semi-empirical approach", Annals of Nuclear Energy, 39: 56–61, (2012).

[23] Yılmaz, D., Boydaş, E., Cömert, E., "Determination of mass attenuation coefficients and effective atomic numbers for compounds of the 3d transition elements", Radiation Physics and Chemistry, 125: 65–68, (2016).

[24] Jackson, D.F., Hawkes, D.J., "X-ray attenuation coefficients of elements and mixtures", Physics Reports 70: 169–233, (1981).

[25] Manjunatha, H.C., "A study of gamma attenuation parameters in poly methyl methacrylate and Kapton", Radiation Physics and Chemistry, 137: 254–259, (2017).

[26] Wood, J., "Computational Methods in Reactor Shielding", Elsevier, (2013).

[27] Sakar, E., "Determination of photon-shielding features and build-up factors of nickel–silver alloys", Radiation Physics and Chemistry, 172: 108778, (2020).

[28] Bashter, I.I., "Calculation of radiation attenuation coefficients for shielding concretes", Annals of Nuclear Energy, 24: 1389-1401, (1997).