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Authors: Dilara İCKECAN, Nureddin TURKAN, Doğan ERBAHAR, Hasan GÜLBİÇİM

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Comparing the Shielding Features of Graphene and Impregnated Activated Carbon with Selected Traditional Shielding Materials For Gamma-Rays

Dilara ICKECAN *[1], Nureddin TURKAN[2], Dogan ERBAHAR[3], Hasan GULBICIM[4]

Abstract

Graphene and carbon-based materials are widely used in daily life applications. The richness of optical and electronic properties has made them rapidly rising materials on the horizon of material science and condensed matter physics. Having the sheets of atoms stacked in disorganized manner makes activated carbon different from other forms of graphitic structures. The research about the shielding properties of reduced graphene oxide (RGO) and activated carbon for gamma-rays are very rare and active domain of study. Since the use of radioactive sources in different fields (nuclear industry, shielding materials, radiation biophysics and space research application, etc.) has been increasing expeditiously, the photon interactions with matter have gained importance in the world of material science technology. In this work, we review the basics of the impregnated activated carbon (AC) and RGO, as well as the relationship between the structures and the gamma shielding properties in terms of both quality and efficiency. XCom software and EGSnrc simulation code were used to obtain the theoretical values of various shielding parameters which are significantly important to be able to understand the shielding properties of AC and RGO for gamma-rays. We report the mass attenuation coefficients (μ_m), the half value layer (HVL), the tenth value layer (TVL), and the mean free path (MFP) values and compare them with other commonly used shielding materials like lead, borosilicate, concrete, and vermiculite. The calculated data showed that AC is very appropriate and consistent to be one of the candidates for shielding materials of gamma-rays even though the graphene is seen as inconsistent for such purpose.

Keywords: Activated carbon, graphene, absorption, shielding materials, gamma-rays

1. INTRODUCTION

The use of radiation sources has been increasing in various technological and industrial domains. Considering the potential health risks of ionizing radiation, shielding becomes an important issue in all these applications. For this reason, research on

* Corresponding author: dilaraickecan@marun.edu.tr (D. ICKECAN)
[1] Marmara University, Department of Physics, 34724, Istanbul, Turkey
[2] Istanbul Medeniyet University, Department of Physics Engineering,Istanbul, Turkey
[3] Dogus University, Department of Mechanical Engineering, Istanbul, Turkey
[4] Ondokuz Mayıs University, Department of Nuclear Medicine,Samsun, Turkey
E-mail: nureddin.turkan@medeniyet.edu.tr; derbahar@dogus.edu.tr; hasanglbcm@gmail.com
ORCID: https://orcid.org/0000-0002-6957-9095, https://orcid.org/0000-0002-0452-9484, https://orcid.org/0000-0002-8633-4284, https://orcid.org/0000-0003-4518-2509

radiation shielding material for protection radiation have become important [1]. In the field of radiation shielding, studies are continuing to develop light, durable, economical, and non-toxic [2, 3] materials. In this context Carbon-based materials constitute an important candidate [4-9].

Carbon is a strange special material having s[low dimensional structures such as activated carbon (AC), graphite, graphene, and carbon nanotubes. The graphene has excellent mechanical, thermal, electrical and optical properties coming from its two-dimensional structure [10] for various applications [11, 12] (supercapacitors, batteries, solar cells, biosensors etc.).The activated carbon structures are similar to graphite, but it is an amorphous carbon structure primarily containing six-membered rings with sp2 hybridized carbons and is one the first materials applied as absorbent [13] for filtering purposes. AC has been widely used for water treatment, chemical industry, food industry, etc .[14] Recently it has been demonstrated that AC impregnated with various metal atoms (copper, silver, chromium, etc.) which usually exists in the form of an oxide crystallite can be effective for gamma ray shielding [9]. This form of carbon is called impregnated activated carbon (AC).

The purpose of this work is to search the shielding features of graphene along with AC for gamma-ray absorption. The important shielding parameters like the the half-value layer (HVL), mean free path (MFP), mass attenuation coefficients (μ_m), and the tenth value layer (TVL) were calculated for reduced graphene oxide (RGO) and AC. These values were compared with the data from vermiculite, borosilicate glass, lead, and concrete samples. The obtained results show that AC can be thought to be one of the candidates for shielding materials of gamma-rays, but graphene can not be.

2. EXPERIMENTAL AND THEORETICAL DETAILS

2.1. Materials

The reduced graphene oxide (RGO) which is also called as graphene was used in the present work and was essentially carried out by the process having two steps. So, in the first step, the graphene oxide (GO) is obtained by oxidation of graphene and then it was reduced via the agents to form RGO as a second step. The experimental details related to the study was presented in our previous work [15, 16]. The AC (obtained by the shell of coconut having the particle size about 8~16 mesh) was supplied by Norit Company, in which such materials composing of 5 % wt of triethylenediamine TEDA [17, 18].

2.2. Methods

2.2.1 SEM/EDS analysis

The physical morphology of the surface was analyzed, and the elemental analysis of RGO and AC samples was conducted by scanning electron microscopy (*JEOL 6510-LV JSM SEM* by TUBITAK). The sample properties of AC and RGO on EDS are summarized in Table 1. EDS results show that, RGO sample contains 78.99 %C, 16.04 %O, 2.98 %S, 0.98 %H, 1.01 %N whereas AC has 3.84 % Mo, 79.88 %C, 0.55% K, 1.95 % Zn, 6% Cu, 7.65 %O and 0.13% Si.

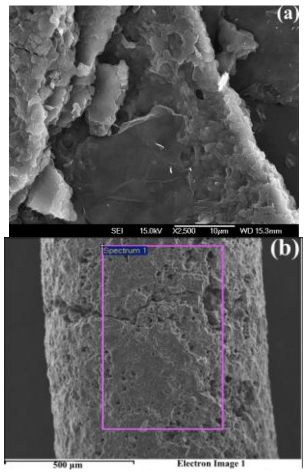

Figure 1 Comparing of (a) SEM image of RGO and (b) SEM image of AC [9].

It can be seen from Table 1 that graphene (RGO) gives the higher density 1.91 g/cm^3 when compared to AC (0.54 g/cm^3).

Table 1 The weight percentages of different elements forming the surfaces (%) of RGO, and AC samples based on EDS.

Elements	Weight percentages of surface elements	
	Graphene (RGO)	AC
C	78.99	79.88
O	16.04	7.65
S	2.98	-
H	0.98	-
N	1.01	-
Zn	-	1.95
Cu	-	6.0
Mo	-	3.84
Si	-	0.13
K	-	0.55
Density g/cm^3	1.91	0.54

SEM images of RGO and AC are given in Figure 1. (a-b). Figure 1. (a) shows SEM image of RGO with little wrinkles on the surface and some folds at the edges. It can be shown from Figure 1. (b) that AC has grains and cracks of various sizes hosting micro holes in its structure. EDS analysis is performed with the current images coming from SEM. So, such images enable assessment of the surface of a sample as well as individual components and targeted analysis of the sample.

2.1.1. Calculation Methods of Shielding Parameters

Linear attenuation coefficients (μ) is an important parameter to explain the gamma and X-rays radiation protection properties of a material. The linear attenuation coefficients (μ) is computed according to Beer-Lambert Law [19],

$$I=I_0e^{-\mu x} \quad (1)$$

where I and I_0 indicates the attenuated and incident radiation intensity and x is the thickness of the absorber. The definition of mass attenuation coefficient is the ratio of linear attenuation coefficient to the material density. It is possible to compare materials in terms of their mass attenuation coefficient. The μ_m is defined as μ/ρ. The HVL, TVL and MFP are important parameters used to compare samples for each other to understand their gamma shielding features. The HVL is defined as the absorber thickness required to halve the radiation intensity. To calculate HVL, ln 2 is divided by linear attenuation coefficient (ln 2/μ). TVL, is the absorber thickness required to absorb 90 % of the radiation intensity. TVL is calculated as ln 10/ μ. The values of HVL and TVL depend on the linear attenuation coefficient. The mean free path (MFP) of photons in matter is defined as the thickness of the sample at which 36.8 % of the initial radiation intensity can be absorbed [20]. The mean free path is equal to inverse of linear attenuation coefficient.

2.2.3 Monte Carlo calculation

The Monte Carlo (MC) is a method which is widely used in shielding simulation. In this study, The Electron Gamma Shower (EGSnrc) simulation code and XCom software are chosen to calculate the radiation shielding parameters. For the MC calculations, the material content was first created in EGSnrc using the PEGS4 user code which is used as software of general-purpose device. So, such a simulation of coupled electron-photons are set in a random 3D geometry with a wide energy range from a few keV up to hundreds of GeV [21]. The simulation setup is then modeled as having a narrow-beam geometry. In this geometry, the sample is modeled with infinite dimensions in the x-y plane and with appropriate thickness in the z plane. The simulated photons were directed perpendicular towards the center of x-y plane and the photons having the same incident energy and direction parallel to +z-axis were counted. Afterwards, the linear attenuation coefficients were calculated for different photon energies using Eq. 1. Figure 2 gives the schematic diagram of geometry of the set up used in Monte Carlo simulations.

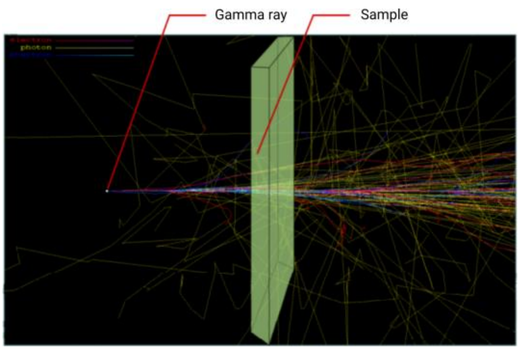

Figure 2 Schematic diagram of geometry of the set up used in Monte Carlo simulations.

The important parameters interested in the photon energies, geometry and materials definitions were provided and the simulations were performed by using 2 x 10^8 photon history to reduce the uncertainty to a value less than 1 %. The calculated μ_m of graphene for gamma-rays at photon energies of 1.0 kev-10.0 MeV were compared with the results of AC, vermiculite, borosilicate glass, lead, and concrete materials [9, 22].

3. RESULT AND DISCUSSION

The radiation shielding properties of RGO are examined to be able to understand the gamma-ray absorption characteristics along with those of AC, vermiculite, borosilicate glass, lead, and vermiculite. The XCom code and EGSnrc software are used for the theoretical calculations of the μ_m values for the RGO. The calculated results were compared to the previous theoretical [9] and experimental [21] results of some known shielding materials as AC, vermiculite, borosilicate glass, lead, and concrete. Such comparisons are clearly seen in the following figures in which the μm, the HVL, the TVL and MFP are shown as figures 3,4,5 and 6.

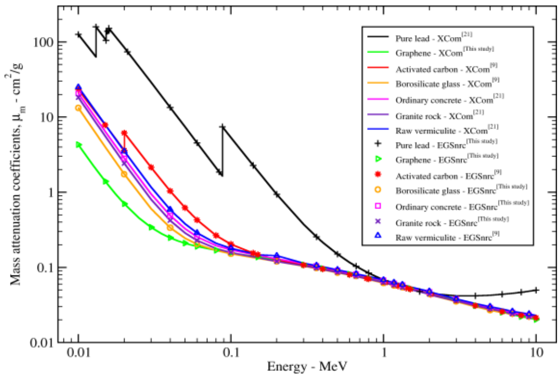

Figure 3 The comparing of the calculated μm for graphene (RGO) is supplied with some previous calculated results [9, 22] for AC, vermiculite, borosilicate glass, lead, and concrete.

As it is seen from the Figure 3, the μm are exponentially decreasing with the increase of the photon energy. The mass attenuation coefficient of RGO is at the lowest values of that of the others, which is showing that it isthe weakest candidate of shielding materials for gamma radiation when compared to the standard materials. In addition, as it is seen from the figure, the μ_m values decreases rapidly at the photon energies less than 0.1 MeV for all materials, since the interaction process between the photon and matter is more dominant in this energy region. From Figure 3, it can easily be seen that there are some jumps which are discontinuous for AC and lead in the same energy region. The reason can be defined by the absorption edges in K, L, M... shells of atoms of such elements. The μ_m values reduce slowly in the range of energy changing from 0.1 to 2.0 MeV, in which the Compton scattering is dominant. At photon energies below 0.1 MeV, photon absorption properties of materials are more prominent, and the photon absorption abilities of materials vary strongly with atomic number. However, above this energy, since the dependence on the atomic number decreases, the photon absorption ability of the materials begin to converge and decrease slowly as the energy increases. For this reason, as can be seen from the Figure 3, the results obtained at low photon energies for low-density materials are more distinctive.

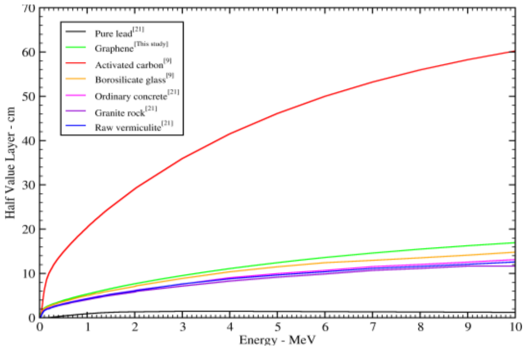

Figure 4 The comparing of the HVL values for graphene (RGO) is supplied with some previously calculated results [9, 22] for AC, vermiculite, borosilicate glass, lead, and concrete.

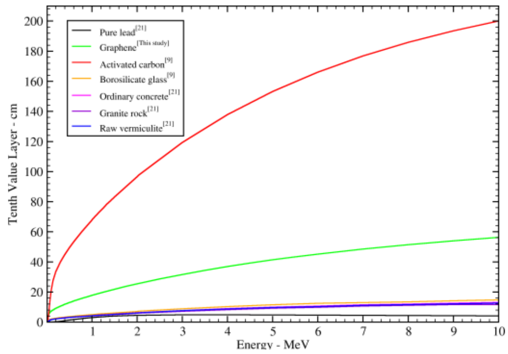

Figure 5 The comparing of the TVL values for graphene (RGO) is supplied with some previously calculated results [9, 22] for AC, vermiculite, borosilicate glass, lead, and concrete.

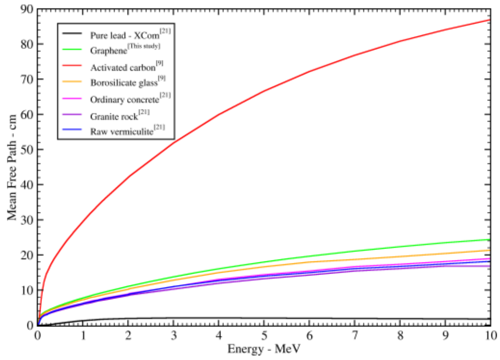

Figure 6 The comparing of the MFP values for graphene (RGO) is supplied with some previously calculated results [9, 22] for AC, vermiculite, borosilicate glass, lead, and concrete.

The calculated HVL, TVL and MFP values of graphene (1.91 g/cm^3) are given in the figures 4, 5 and 6 along with the properties of some known materials as AC (0.54 g/cm^3), vermiculite (2.5 g/cm^3), borosilicate glass (2.2 g/cm^3), lead (11.3 g/cm^3), concrete (2.4 g/cm^3) and granite (2.7 g/cm^3). Those values which are produced from the linear attenuation coefficient are also directly related to their own density. For this reason, they may take different values for the different densities of such materials.

The AC which is investigated before by the authors has better radiation absorption property than graphene in low photon energy region (<150 keV). This interpretation is based on the mass attenuation coefficients (μ_m) given in Figure 3. The μ_m parameter is one of the most studied parameter in radiation shielding, because it provides characteristic data for materials, regardless of their density. For this reason, the mass attenuation coefficients are commonly used in comparison of radiation shielding materials. However, when looking at the HVL, TVL and MFP graphs, it is understood AC should be higher than graphene because of its lower density.

4. CONCLUSIONS

In this study, the gamma-ray absorption properties are theoretically analyzed for graphene and then they were compared with AC, vermiculite, borosilicate glass, lead, and concrete. The important shielding parameters such as Mean free path (MFP), the mass attenuation coefficients (μm), the Tenth value layer (TVL), and the Half-value layer (HVL), were calculated for graphene and then compared with other materials' values that have been previously studied. The calculated results show that AC can be thought as one of the candidates of gamma shielding materials when compared to other known materials. The same conclusion about graphene is however suspicious due to its weak shielding properties. Here, it was also concluded that AC gives satisfactory results -however due to its low density requires a slightlly higher thickness especially in lower energy regime. Graphene is a weak radiation absorber due to the low atomic number value of Carbon, whereas AC is a good radiation absorber due to the absorbent atoms it contains. So as a conclusion, the calculated data of such investigated samples significantly give advantageous ideas about absorbing properties of gamma rays, besides they have good features as having low density, being cheaper and harmless effect on health, also being easy and abundant quantities to produce.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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