Carbohydrate based materials for gamma radiation shielding

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Abstract. Due to the limitation in using lead as a shielding material for its toxic properties and limitation in abundance, price or non-flexibility of other commonly used materials, finding new shielding materials and compounds is strongly required. In this conceptual study carbohydrate based compounds were considered as new shielding materials. The simulation of radiation attenuation is performed using MCNP and Geant4 with a good agreement in the results. It is found that, the thickness of 2 mm of the proposed compound may reduce up to 5% and 50% of 1 MeV and 35 keV gamma-rays respectively in comparison with 15% and 100% for the same thickness of lead.

1. Introduction
There are many reasons for searching for new materials for radiation shielding. For example lead is one of the most commonly used materials in gamma-ray shielding which known as a toxic substance with high risk for workers and it is recommended to search for the lead-free shields [1]. The most widely used materials for gamma-ray shielding are made of heavy elements or concrete. The conventional gamma-ray shielding materials due to their weight, price or mechanical properties may not be suitable for some applications such as astronomic applications [2, 3], portable sources or plasma focus systems (PF) but, polymeric compound [1-7] may be promising candidate for such applications.

In this work, we conceptually studied the attenuation of gamma-ray (or X-ray) by a polymeric compound doped with gadolinium. Two typical energies of 35 keV and 1 MeV for photons were considered corresponding to the average energy of photons emitted from a small plasma focus and two tokamaks (Alvand and Damavand) at Plasma and Nuclear Fusion Research School in Iran respectively. Furthermore, the attenuation of thermal neutrons using the proposed compounds was investigated too.

The calculations were conducted using MCNPX2.4.0 [8] and GEANT4.9.4.p02 [9] Monte Carlo simulation tools which play important role in radiation shielding calculations especially for the problems with the complicated geometries or compound materials. Also, a comparison between the mass attenuation coefficients of the proposed compounds and some common shielding materials are presented in the results and discussion section.

2. Materials and methods
The Monte Carlo techniques give the results based on the statistical calculations and cross-sections. This will cause some discrepancies between the simulation results and the experimental data [10, 11]. In the standpoint of nuclear safety, to decrease the uncertainty in calculations we have used MCNPX [4, 12-15] and GEANT4 [15-18] tools and compared the results for more reliable prediction of experimental
data. A comparison between the mass attenuation coefficients of the proposed compounds and widely used shielding materials are presented later in this work.

At the stage of conceptual design, two typical photon energies of 35 keV and 1 MeV corresponding to the average energy of photons emitted from a small plasma focus and two tokamaks (Alvand and Damavand) at Plasma and Nuclear Fusion Research School in Iran respectively. Later, the attenuation of thermal neutron was studied to determine the ability of these materials for attenuating the both gamma and thermal neutron radiation.

Regarding to gadolinium large cross section for thermal neutron [15] the calculations were performed for different atomic percentages of gadolinium and lead for comparison. Table 1 presents the atomic fraction of hydrogen, carbon, oxygen, silicon and gadolinium or lead with the total densities from ~2 g/cm$^3$ to ~8 g/cm$^3$ defining the input materials in simulation. Conventionally, we called the compounds with 2% and 6% dopant as CHGd2 and CHGd6 with ~2 g/cm$^3$ to ~8 g/cm$^3$ densities respectively.

Table 1. The elemental atomic fraction.

| Element | Atomic fraction in the compound |
|---------|---------------------------------|
| H       | 0.32 – 0.37                    |
| C       | 0.15 – 0.17                    |
| O       | 0.25 – 0.27                    |
| Si      | 0.13 – 0.16                    |
| Gd/Pb   | 0.02 – 0.06                    |

In both MCNPX and GEANT4 we used one directional point source and the slab shield with surface dimension of 10cm x 10cm. MCNPX was tallied by $f_1$ as surface current and both $f_6$ and $*f_4$, average energy deposited over a cell. Since for photon/electron problems with thin shield electron may not deposit their energies locally, we used both $f_6$ and $*f_4$ tally to reduce the results uncertainties [8].

In GEANT4 calculation we used EMLOW6.19 and G4ENDL3.14 for photon neutron libraries. Neutron interactions were considered by means of G4NeutronHP data set in the physics lists.

3. Results and discussion

Figure 1 and figure 2 show the attenuation of 1 MeV photon versus target thickness for CHPb6 and CHGd6 respectively. The circular symbol depicts GEANT4 results and square show MCNPX results. As it was explained, CHPb6 corresponds to 6 % Pb and CHGd6 corresponds to 6 % Gd. The compound density is 8 g/cm$^3$. Less than 2 % discrepancies between two results for larger thicknesses are due to the small differences between the two libraries used by each tools. The increase in the thickness means the more interaction of photons with material and more different results consequently. This could be the good reason for using more than one method when there are no experimental references.

As one can see, 2 mm thick CHPb6 attenuates 5 % of 1 MeV photons, while the same attenuation is achievable at 2.6 mm thickness when using CHGd6. The discrepancy between the results for the two materials in this case is less than 4 %.

Figure 3 illustrates the attenuation of 35 keV photons versus the thickness for CHGd2. One can see, up to 75 % attenuation for the thickness of 2 mm. The discrepancy of less than 2 % shows the agreement between MCNPX and GEANT4 and the reliability of the results consequently. The same reason as what was discussed for Figures 1 and 2 can explain the small discrepancies between MCNPX and GEANT4 in this figure.
Figure 1. Attenuation of 1 MeV gamma-ray in CHPb6.

Figure 2. Attenuation of 1 MeV gamma-ray in CHGd6.
Figure 3. Attenuation of 35keV gamma-ray in CHGd2.

Table 2 shows the mass attenuation coefficients ($\mu/\rho$) of CHGd6 and CHPb6 as comparison with standard data [19, 20] for lead, tungsten and concrete. The energies of 0.035 MeV, 0.05 MeV, 0.5 MeV and 1 MeV were selected typically. Accordingly, the two proposed compounds have relatively smaller attenuation coefficients than lead and tungsten but comparable with concrete. The presented values for attenuation coefficient were obtained from the gradient of the line fitted to the curve of logarithmic intensity versus the thickness. It can be expressed as below:

$$\mu = -\frac{\ln(I/I_0)}{x}$$

where, $I$ and $I_0$ are the intensity of the incident and outgoing photons respectively, $x$ is the thickness and $\mu$ is the linear attenuation coefficient.

Table 2. CHPb6, CHGd6, lead, tungsten and concrete mass attenuation coefficients ($\mu/\rho$).

| Photon Energy (MeV) | CHPb6 ($\rho=8$ g/cm$^3$) | CHGd6 ($\rho=8$ g/cm$^3$) | lead ($\rho=11.3$ g/cm$^3$) | tungsten ($\rho=19.3$ g/cm$^3$) | concrete ($\rho=2.4$ g/cm$^3$) |
|---------------------|---------------------------|---------------------------|-----------------------------|-------------------------------|-----------------------------|
| 0.035               | 0.94                      | 0.9                       | 20.1                        | 10.67                         | 0.9                         |
| 0.05                | 2.05                      | 2.1                       | 8.041                       | 5.949                         | 0.341                       |
| 0.5                 | 0.0805                    | 0.069                     | 0.1614                      | 0.1378                        | 0.089                       |
| 1                   | 0.03                      | 0.02                      | 0.07                        | 0.06618                       | 0.065                       |

Figure 4 illustrates the ratio of the deposited energy to the incident photon energy in terms of the incident photon energy for CHGd6 compound. The absorption edge was calculated and shown as a peak at 90 keV which was explained by the both simulation results as an enhancement in photoelectric effect in the material at this energy.
Figure 4. The ratio of the deposited energy to the incident energy versus the incident photon energy for CHGd6.

Shielding the fast neutrons needs relatively thick hydric materials while the thicknesses of the discussed materials in this work are less than 1 cm and hence, we only concentrated on the thermal neutrons at this stage. Figure 5 shows the calculation results of thermal neutron attenuation for CHGd2. As mentioned before, due to gadolinium large cross-section for thermal neutron, CHGd2 with 2 % gadolinium atomic fraction has been studied as thermal neutron shield. According to the results which show a good agreement between the two tools, the thicknesses of 2 mm and 16 mm of the compound attenuate 5 % and 50 % of thermal neutrons respectively.

Figure 5. Thermal neutron attenuation in CHGd6.
4. Conclusion
In present work, we studied the attenuation of gamma-ray and thermal neutron using some typical carbohydrate compounds. The depicted results may be useful for designing the new shields for several kinds of applications such as, shielding the radioactive sources, plasma focus systems or low energy medical electron accelerators. Hopefully, the conducted calculations and studies can be developed for more energetic sources to extend the applications of these new shielding materials.

In this conceptual study, we used Monte Carlo tools but there are more considerations in the detail studies of polymeric shields. For example, the produced secondary particles like alpha particle in fast neutron shielding, thermal properties for thermodynamical calculations, physical damage and changes in properties of these materials due to continuous irradiation that it will require more precise studies.

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