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Research Article

Calculation of Fast Neutron Shielding Parameters for Some Essential Carbohydrates

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Abstract

This study is concerned with the attenuation of fast (or fission energy) neutrons by some essential carbohydrates which carry importance for most of the living cells. For this purpose, eleven carbohydrates having different densities have been investigated by means fast neutron effective removal cross sections (Σ_R) and attenuation lengths. The calculations have been performed using the mass removal cross section data compiled from NCRP No. 20 (1957) and elemental compositions of carbohydrates. The obtained results show that the Hydrogen element plays the major role for fast neutron attenuation in selected carbohydrates. According to our best knowledge, this could be the first study on the fast neutron removal cross sections of selected carbohydrates. Also, the data presented here is expected to contribute the related literature significantly.

Keywords: Neutron attenuation, fast neutron removal, attenuation length, carbohydrate.

Bazı Temel Karbonhidratlar İçin Hızlı Nötron Zırhlama Parametrelerinin Hesaplanması

Öz

Bu çalışma, hızlı (veya fisyon enerjili) nötronların canlı hücrelerin pek çoğu için önem taşıyan bazı temel karbonhidratlar tarafından zayıflatılması üzerinedir. Bu amaçla, farklı yoğunluklu on bir çeşit karbonhidrat etkin etkin hızlı nötron sökme tesir kesitleri (Σ_R) ve hızlı nötronları zayıflatma mesafeleri bakımından incelenmiştir. Hesaplamalar NCRP No. 20 (1957)'den derlenen kütlesel sökme tesir kesiti ve karbonhidratlara ait elementsel bileşim verileri kullanılarak yapılmıştır. Elde edilen sonuçlar, seçilen karbonhidratlar içinde hızlı nötronların zayıflatılmasında en büyük rolü Hidrojen elementinin oynadığını göstermektedir. Bildiğimiz kadarıyla bu çalışma, hızlı nötronların seçilmiş olan karbonhidratlara ait etkin hızlı nötron sökme tesir kesitleri üzerine yapılan ilk çalışmadır. Ayrıca, çalışma sonucunda sunulan verilerin ilgili literatüre kayda değer bir katkı sunacağı umulmaktadır.

Anahtar Kelimeler: Nötron zayıflatma, hızlı nötron sökme, zayıflatma mesafesi, karbonhidrat.

1. Introduction

Depending on the extensive usage of nuclear technology, the utilization of radioactive substances in many fields of human life - such as medical technology, power generation, and scientific research - has increased during the recent decades. So, the amount of ionizing radiations emitted from these substances has increased which has made it a significant task to protect the living organisms against their harmful effects. These ionizing radiations mainly consist of alpha, beta, gamma and neutron particles. Among them, neutron carries a particular importance because it is uncharged, it interacts with the atomic nuclei only and causes indirect ionizations, and it has a higher penetration capability through materials. The shielding capability of a material against neutrons is characterized by the attenuation concept. Neutron attenuation is related to several parameters such as the macroscopic effective removal cross section

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of fast (or fusion) neutrons and the macroscopic thermal neutron cross section. Both parameters are highly dependent on the energy of interacting neutrons and the physical properties of the target nuclei (Jaeger, 1965; Kaplan, 1989)

When fast neutron (with energies in the MeV region) attenuation is in question, effectiveness of a material against fast neutrons is measured by means of another parameter called the fast neutron effective removal cross section (Σ_R, in cm^{-1}) (NCRP No. 20, 1957; Price et al., 1957). In this study, the effective removal cross sections for some essential carbohydrates consisting of Carbon, Hydrogen and Oxygen have been calculated and presented. As known, carbohydrates, which are organic compounds, are of significant importance by many aspects, such as: they are consumed in living cells to perform various physiological functions, are widely used in biological, chemical, medical, food, nuclear power and textile industries, etc. Also, starch and sugar forms of carbohydrates are the two of major part of the caloric supply for humans and animals, as well. In fact, some of the carbohydrates, which are also subjects of this study, have previously been investigated by Nair et al. (1993) and by Gagandeep et al. (2000) in the context of gamma-ray attenuation parameters such as mass attenuation coefficients, effective atomic numbers and electron densities. In this respect, it is judged by the author that investigating these essential carbohydrates in terms of fast neutron attenuation parameters could give a significant contribution to the related literature. Also, as far as is known by the author, this is most probably the first study on the fast neutron effective removal properties of given carbohydrates.

The importance given to the neutron attenuation and shielding encourages many investigators for studying this subject. As a result of this, the literature contains various works on very different materials from concretes to superconductors. However, some examples can be given as: on concretes containing different kinds of minerals and materials (Yarar and Bayülken, 1994; Bashter, 1997; Abdo, 2002; El-Khayatt, 2010; Korkut et al., 2010; Gencel et al., 2011; Yımaz et al., 2011; Korkut et al., 2012; Akkurt and El-Khayatt, 2013; El-Khayatt and Akkurt, 2013; Wang et al., 2014; Tuna and Bayrak, 2017; Aygün and Karabulut, 2018), on some composites (El-Khayatt and Abdo, 2009; El-Khayatt, 2011; El-Sarrafa and Abdo, 2013; Osman et al., 2015), on some glass systems (Singh et al., 2014; Mallawany and Sayyed, 2018; Salama et al., 2019) and on some other materials such as polymers, superconductors, resins and lunar soils (Kurudirek et al., 2011; Elmahrough et al., 2014; Tellili et al., 2014; Singh et al., 2015; Issa et al., 2018).

In the following sections, firstly, the removal cross section concept is introduced and the method of calculation for fast neutron effective removal cross sections of carbohydrates is explained. Then, the results are given and discussed.

2. Materials and methods

As mentioned in the previous section, the interaction mechanisms of neutrons with a material depend on the energy of incoming neutron and the physical properties of the target nuclei. The total microscopic cross section (σ_t, generally in barn) of neutrons of any energy expresses the probability of the interaction with the medium traversed. It includes two terms, which are the total microscopic scattering cross section (σ_s) and the microscopic absorption cross section (σ_a), as follows.

$$\sigma_t = \sigma_s + \sigma_a \quad (1)$$

In this expression, σ_s includes inelastic and elastic scattering while σ_a includes nuclear fusion, nuclear spallation and capture of neutrons. The total microscopic cross section given by Equation 1 is related to the macroscopic cross section (Σ_t, in cm^{-1}) by the number of nuclei per unit volume of the material (N, in cm^{-3}). If the material of interest is a compound or a mixture, then the mixture rule applies such that Σ_t can be written as the sum of the individual components in that compound or mixture as given below:

$$\Sigma_t = \sum_i N_i(\sigma_t)_i \quad (2)$$

Here, N_i is the number of nuclei per unit volume and $(\sigma_t)_i$ is the microscopic cross section of the element i. When the attenuation is through a pure material Σ_t simply becomes $N\sigma_t$ (Woods, 1982; Chilton et al., 1984).

Particularly, in the case that fast (or fission energy) neutron attenuation is in question as in this study, another useful parameter called the fast neutron effective removal cross section plays an important role. It is useful since it serves well for situations when there is not sufficient hydrogen in the material. So, it is worth calculating the removal cross sections of different materials for which some example studies are listed in the previous section. The removal cross section is defined as the occurrence probability of a first collision which removes that neutron from its uncollided fast group (Blizard and Abbott, 1962). The dominant interaction mechanism for fast neutrons is elastic scattering. But they can also experience other interaction types (say, inelastic scattering) with the medium they traverse. As a result, if the material is not substantially hydrogenous, the effective removal cross section is always less than the total fast neutron cross section and is roughly equal to two thirds of it in 6 – 8 MeV region. On the contrary condition, it is almost equal to the total cross section due to the fact that elastic collisions with hydrogen nuclei of the fast neutrons result a great loss of energy. Between 2 – 12 MeV, the effective removal cross section will remain approximately constant (Woods, 1982; Chilton et al., 1984; Kaplan, 1989). Also, the attenuation length (in cm) for fast neutrons is the inverse of the effective removal cross section and can be defined as the average path length between two successive interactions of a fast neutron in the material (NCRP No. 20, 1957).

In this study, the fast neutron effective removal cross sections (Σ_R) and attenuation lengths for 11 different essential carbohydrates have been calculated. Some specifications of carbohydrates which are necessary for the calculations are listed in Table 1. Their molecular weights have been calculated using the elemental data reported by Wieser et al., (2013). The data of molecular formulas and densities have been obtained from Haynes et al., (2017) except for the density data of ribose (Merck).

Table 1. The carbohydrates investigated in the study. Molar weights are in g/mol.

C.hydrate	Mol. formula	Mol. weight	ρ (g/cm^3)
Arabinose	$C_5H_{10}O_5$	150.118	1.585
Ribose	$C_5H_{10}O_5$	150.118	0.800
Glucose	$C_6H_{12}O_6$	180.142	1.562
Mannose	$C_6H_{12}O_6$	180.142	1.539
Fructose	$C_6H_{12}O_6$	180.142	1.665
Maltose	$C_{12}H_{22}O_{11}$	342.269	1.546
Sucrose	$C_{12}H_{22}O_{11}$	342.269	1.581

Lactose	$C_{12}H_{22}O_{11}$	342.269	1.590
Lactose monohydrate	$C_{12}H_{24}O_{12}$	360.283	1.547
Melezitose	$C_{18}H_{32}O_{16}$	504.396	1.547
Raffinose	$C_{18}H_{32}O_{16}$	504.396	1.465

Since selected carbohydrates are multi-element materials, calculation of effective removal cross sections require the use of the mass removal cross sections (Σ_R/ρ, in cm^2/g) of constituent elements, and the mixture rule. The mass removal cross sections of constituent elements have been compiled from NCRP report (NCRP No. 20, 1957), which are 0.051 cm^2/g for Carbon, 0.602 cm^2/g for Hydrogen and 0.041 cm^2/g for Oxygen. The mixture rule states that the effective removal cross section of a multi-element material is the sum of the products of partial density with the mass removal cross section over all elements in the material as follows:

$$\Sigma_R = \sum_i \rho_i (\Sigma_R/\rho)_i \qquad (3)$$

In Equation 3, $\rho_i = \rho\, w_i$ is the partial density, w_i is the weight fraction of element i and ρ is the total density of the material. Weight fraction is the ratio of the molar weight of related element to the molar weight of the material (Schmidt, 1969; Woods, 1982; Chilton et al., 1984). So, the effective removal cross sections and attenuation lengths for 11 carbohydrates have been calculated according to the numerical data and the mixture rule given above. Results are presented and discussed in the next section

3. Results and discussion

The results for calculated parameters are presented in Table 2. It is found that the effective removal cross section values of carbohydrates vary between 0.066 cm^{-1} (for ribose) and 0.138 cm^{-1} (for fructose). As a result, ribose has the greatest attenuation length with 15.122 cm against fast neutrons, while fructose has the lowest with 7.226 cm. This means, the penetration depth of a fast neutron through ribose is greater than that of other carbohydrates. Except ribose, the effective removal cross section values of other carbohydrates are closer. The difference between the maximum and the minimum values in this group is about 13%. This is most probably because the total densities in this group are fairly close to each other.

In Figure 1, the per cent contributions of the constituent elements, which are Carbon, Hydrogen and Oxygen, to effective removal cross sections of the compounds are plotted. As clearly seen from this figure, Hydrogen has by far the highest contribution in all carbohydrates. The order of Carbon and Oxygen in terms of the contribution greatness to removal cross section differs from one compound to another. This can be referred to the partial effective removal cross sections of constituent elements. In all compounds, the partial effective removal cross section of Hydrogen is approximately twofold of those of other elements. As an example, in fructose these values are 0.067, 0.034 and 0.036 cm^{-1} for Hydrogen, Carbon and Oxygen, respectively. This particular result points out the role of combined effect of the partial density and the partial mass removal cross section ($(\Sigma_R/\rho)_i$) of a constituent element in the compound. This can also explain why Hydrogen contribute more to the effective removal cross section although its weight fractions and partial densities are smaller than those of Carbon and Oxygen. However, it is also seen from Figure 1 that any element has almost identical contribution in all carbohydrates. For example, in the case of Hydrogen it is around 50% in all compounds.

Table 2. Calculated parameters for carbohydrates. w_i: weight fraction, ρ_i: partial density.

Name	w_i			ρ_i (g/cm^3)			Σ_R (cm^{-1})	Attenuation length (cm)
	C	H	O	C	H	O		
Arabinose	0.400	0.067	0.533	0.634	0.106	0.845	0.131	7.632
Ribose	0.400	0.067	0.533	0.320	0.054	0.426	0.066	15.122
Glucose	0.400	0.067	0.533	0.625	0.105	0.832	0.129	7.745
Mannose	0.400	0.067	0.533	0.616	0.103	0.820	0.127	7.861
Fructose	0.400	0.067	0.533	0.666	0.112	0.887	0.138	7.266
Maltose	0.421	0.065	0.514	0.651	0.100	0.795	0.126	7.932
Sucrose	0.421	0.065	0.514	0.665	0.102	0.813	0.129	7.758
Lactose	0.421	0.065	0.514	0.669	0.103	0.818	0.130	7.712
Lactose monohydrate	0.400	0.067	0.533	0.619	0.104	0.824	0.128	7.820
Melezitose	0.429	0.064	0.508	0.667	0.100	0.790	0.126	7.917
Raffinose	0.429	0.064	0.508	0.628	0.094	0.743	0.119	8.411

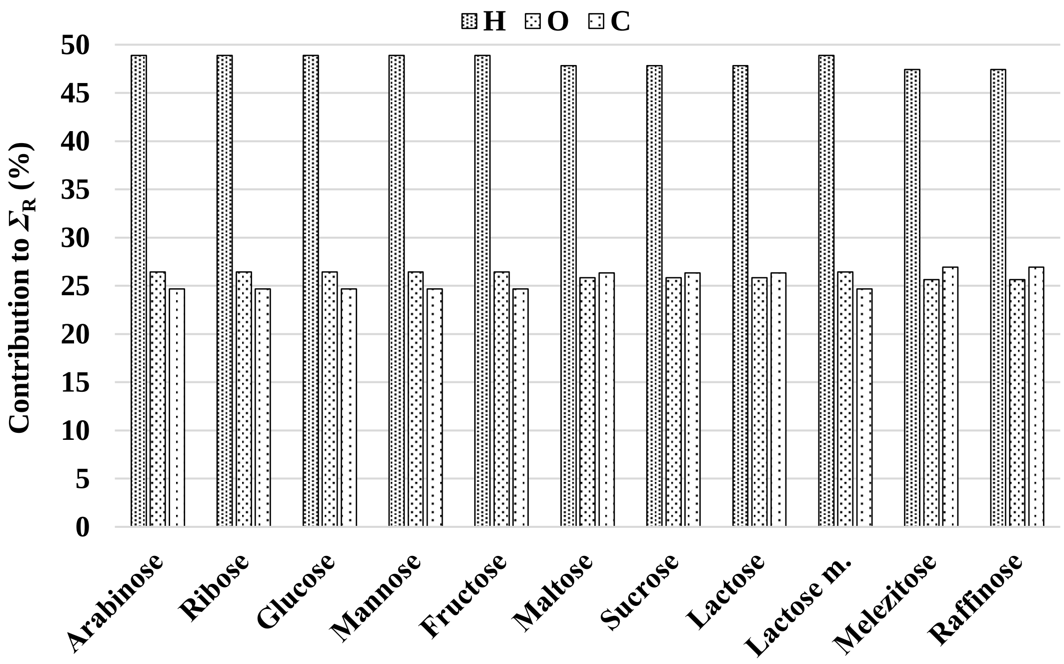

Figure 1. Contributions of the three elements present in the carbohydrates to effective removal cross sections. "Lactose m." refers to "lactose monohydrate".

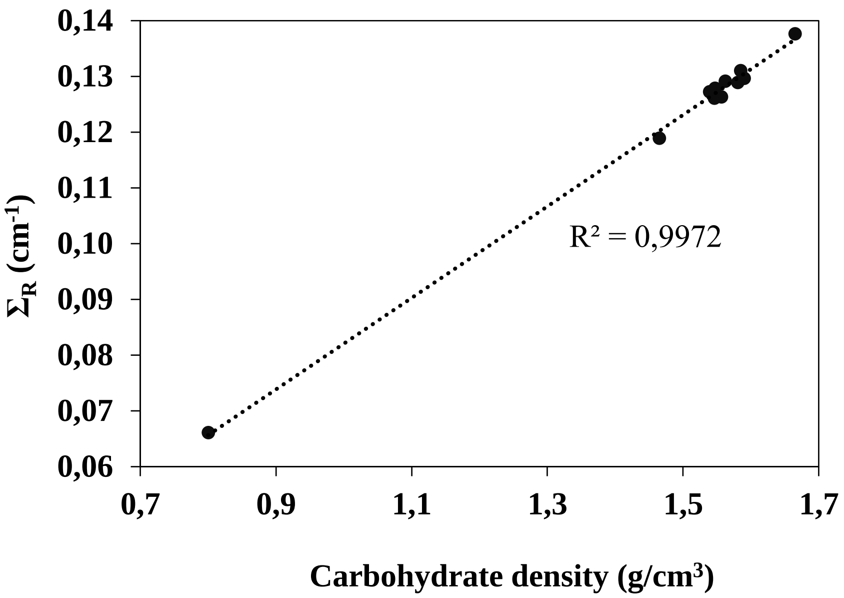

Figure 2. Effective removal cross section versus carbohydrate density.

The relation between the effective removal cross section and the total carbohydrate density is shown by Figure 2. It can be concluded from this figure that the total density of the carbohydrate has a positive effect on the effective removal cross section. It is clearly observed in the case of ribose which has the smallest density.

4. Conclusions

Fundamental fast neutron shielding parameters, namely effective fast neutron removal cross section and attenuation length, have been calculated for 11 essential carbohydrates consisting of carbon, hydrogen and oxygen. It has been found that ribose has the smallest, fructose has the greatest effective removal value. The major contribution to the effective removal comes from Hydrogen in all carbohydrates though its weight fractions are smaller than those of carbon and oxygen. This situation can be explained by that the elements with smaller atomic masses are more effective against fast neutrons. On the other hand, if a particular constituent element is considered, it can be realized that the weight fractions of it remains almost constant in all of the carbohydrates. So, the differences in effective removal values of carbohydrates are mainly due to the total densities. In carbohydrates with higher densities, the attenuation of fast neutrons will be dominated by removal process. Depending on the obtained attenuation length values, it can be argued that the dose transferred by fast neutrons to ribose will be minimum whereas it will be maximum to fructose when the equal thicknesses of carbohydrates are compared.

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