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Araştırma Makalesi / Research Article

An Experimental Examination on the Determination of γ-ray Shielding Parameters of Some Dielectric Materials

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Abstract

In this study, γ-ray shielding parameters (transmission factors (*TF*), linear attenuation coefficients (μ), mass attenuation coefficients (μ/ρ), mean free path (λ), radiation protection efficiency (RPE), half-value layer (HVL), and tenth value layer (TVL)) were measured of some dielectric materials (amber, plexiglass, organic glass, quartz, bakelite, NaCl, porcelain, and marble). The absorption measurements were done by EDXRFS (Energy Dispersive X-ray Fluorescence Spectrometer). The study aims to create new areas of use thanks to the measurements and calculations to be made on these technologically important dielectric materials. According to the results obtained, amber is the best gamma ray shielding material, while quartz is not suitable for gamma ray shielding.

Keywords: Dielectric, EDXRFS, RPE, HVL, TVL.

Bazı Dielektrik Malzemelerin Gama Işını Zırhlama Parametrelerinin Belirlenmesi Üzerine Deneysel Bir Çalışma

Öz

Bu çalışmada, bazı dielektrik malzemelerin (kehribar, pleksiglas, organik cam, kuvars, bakalit, NaCl, porselen ve mermer) transmisyon faktörleri (*TF*), lineer soğurma katsayıları (μ), kütle soğurma katsayıları (μ/ρ), ortalama serbest yol (λ), radyasyondan korunma verimliliği (RPE), yarı kalınlık değeri (HVL) ve onda bir kalınlık değeri (TVL) ölçülmüştür. Soğurma ölçümü EDXRFS (Enerji Ayrımlı X-ışını Flöresans Spektrometresi) ile yapılmıştır. Çalışmanın amacı, teknolojik öneme sahip bu dielektrik malzemeler üzerinde yapılacak ölçümler ve hesaplamalar sayesinde yeni kullanım alanları oluşturulmasıdır. Elde edilen sonuçlara göre kehribar en iyi gama ışını zırhlama malzemesiyken, kuvars gama ışını zırhlaması için uygun değildir.

Anahtar Kelimeler: Dielektrik, EDXRFS, RPE, HVL, TVL.

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1. Introduction

Many applications in science, medicine, and engineering use transmission factors and attenuation coefficients. Therefore, it is important to measure and calculate them. New materials also need to be found to protect different radiation energy ranges. There are many studies in the literature for this purpose. Subedi and Lamichhane (2023) investigated radiation shielding efficiencies of bulk metallic glasses (BMGs) with various physical and chemical features. Özkan et al. (2023) have analyzed aluminum alloy AA6082 + (0–40%) B4C materials by PSD software. They have computed some shielding parameters. Abualroos et al. (2023) evaluated the effectiveness of lead-free polymer-based radiation shielding bricks in attenuating gamma radiation by using an open-mold casting technique. Tüysüz and Dizman (2022) have determined the radiation absorption capacity of some ceramics for low-energy gamma. Kurtuluş et al. (2021) investigated the effect of Nb_2O_5 on waste soda-lime glass in gamma-ray shielding applications. Ali et al. (2020) have investigated electronic polarizability, dielectric, and gamma-ray shielding features of $PbO–P_2O_5–Na_2O–Al_2O_3$ glasses doped with MoO_3. Öztürk et al. (2020) have investigated the mechanical properties electromagnetic, and shielding effectiveness of concrete samples containing boron. Donya and Sulami (2019) investigated the shielding effectiveness of a modified titania-bismuth-boro tellurite glass system. Higgins et al. (2019) have prepared composites containing WO_3 or HfO_2 nanoparticles and investigated them as alternative shielding materials using radioactive sources. Pomaro et al. (2019) investigated the shielding properties of two types of heavyweight concretes experimentally and numerically. They have also numerically analyzed shielding characteristics. Reda (2016) has calculated the attenuation coefficients of a shielding material containing Al, Fe, Cu, and Pb by using MCNP5 computer code.

When the literature is examined, it is seen that determining shielding parameters for different samples is very popular. This study aims to measure gamma shielding properties for some dielectric materials. Moreover, the study aims to investigate whether dielectric constants change with gamma shielding parameters and, if so, how they change. When the literature was examined, no such study was found. This work is very important as it contains the first experimental data on this subject.

2. Materials and Methods

2.1. Theoretical Basis

The interaction of the photon with matter and its absorption are related to the law of Lambert-Beer:

$$I = I_0 e^{-\mu t} \quad (1)$$

$$\mu = -\left[\frac{ln(I/I_0)}{t}\right] \quad (2)$$

Where I_0 is the initial photon intensity, and I is the reduced photon intensity after traveling through the thickness t (cm) of the sample and linear attenuation coefficient μ (cm^{-1}). The linear attenuation coefficient depends on the thickness of the sample and expresses the energy absorption fraction per unit thickness.

TF (Transmission factor) for the sample is determined as follows [Turhan et al. (2020)]:

$$TF= \frac{I}{I_0} x100 \quad (3)$$

The transmission factor is a parameter used in many applications such as medical, and industrial applications, and shows how permeable the substance is.

μ/ρ (Mass attenuation coefficient) (cm^2/g) for a multi-element material constituting the sample can be obtained from the coefficients for the constituent elements that are assumed to be additive according to the weighted average,

$$\mu/\rho = \sum_i w_i (\mu/\rho)_i \quad (4)$$

where w_i is the proportion by weight of the ith constituent element and ρ (g/cm^3) is the density of the sample. The mass attenuation coefficient does not depend on the material thickness and is a measure of how much the material interacts with radiation. λ (cm) is the average distance between two successive interactions. It has been measured using the following equation [Singh et al. (2008); El-Khayatt et al. (2014); Shams Iss (2016)].

$$\lambda = \frac{1}{\mu} \quad (5)$$

RPE (Radiation protection efficiency) of shielding material is defined as [Harjinder et al. (2016)]:

$$RPE = (1 - \frac{I}{I_0}) \times 100 \quad (6)$$

The radiation protection efficiency provides information about the absorption percentage of the sample.

HVL (Half-value layer) (cm) (the thickness of radiation shielding material needed to reduce the incident intensity of the gamma-ray to its half) can be calculated from the μ as:

$$HVL = \frac{ln2}{\mu} \quad (7)$$

TVL (Tenth value layer) (cm) is defined as the thickness of the shield required for attenuating a radiation beam to 10% of its radiation level and is calculated by,

$$TVL = \frac{ln10}{\mu} \quad (8)$$

2.2. Experimental Basis

In the study, first of all, a source-sample-detector system was created. The experiment positioned the source, sample, and detector on the same plane. In the system, cylindrical collimators with different hole diameters are used to obtain sufficient photon flux to create a narrow beam geometry. To eliminate the effects of air scattering, measurements without samples were taken under the same experimental conditions, and these counts were subtracted from the measurements with the samples. A sample spectrum for the marble sample, showing the counts with and without samples, is given in Figure 1. The experimental geometry used in this study is given in Figure 2. In the study, transmission factors, linear attenuation coefficients, mass attenuation coefficients, mean free path, radiation protection efficiency, half-value layer, and tenth value layer for amber, plexiglass, organic glass, quartz, bakelite, NaCl, porcelain, and marble samples showing dielectric properties were determined using EDXRFS, and a point source of Am-241 of intensity 100 mCi which emits 59.54 keV gamma rays. This study used a semiconductor detector (Si(Li)) with an active diameter of 3.91 mm, an active area of 12 mm^2, and an FWHM of 160 eV at 5.9 keV. During the experiment, the counter crystal and the FET were kept at liquid nitrogen temperature, and connected to a 30-liter liquid nitrogen container. The detector has a 0.025 mm thick beryllium window to prevent surface contamination from the outside environment. Care was taken not to change the environmental conditions as much as possible during the measurement process. The analyzer used in the study is the Canberra DSA-1000 multi-channel pulse height (MCPHA) analyzer. The analyzer was set at 4096 channels, and the counting times were 600 s. In the study first, the calibration process was carried out using test sources. The energies corresponding to the channels in the analyzer are calculated and determined with the help of test sources (Am-241, Ba-133 vb.), and a linear graph is obtained. This indicates that the calibration is correct. For accurate measurement, calibration must be done precisely and accurately.

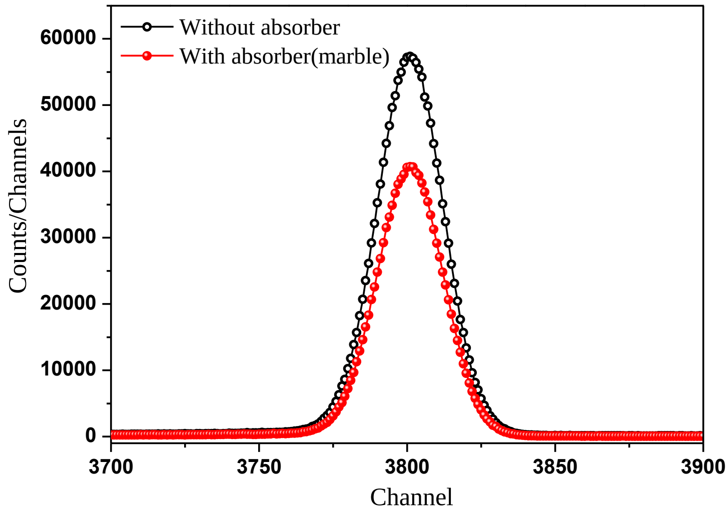

Figure 1. A sample spectrum for Marble.

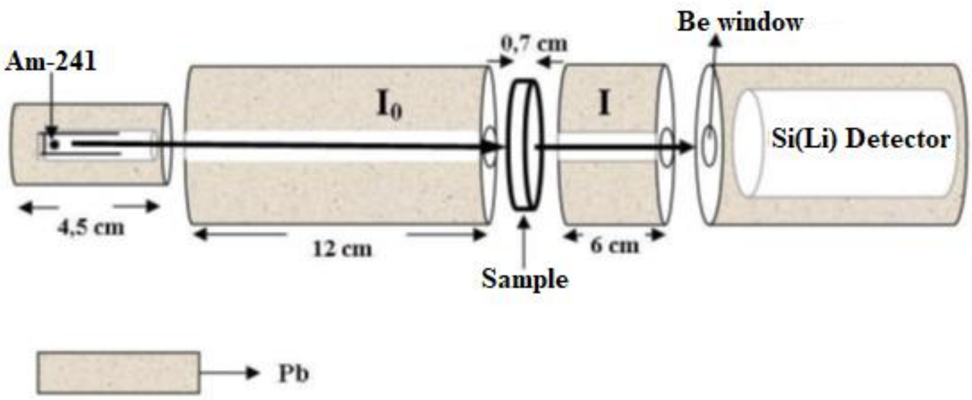

Figure 2. Narrow beam geometry to be used in the experiment.

Obtained measurements were converted into spectra by selecting 4096 channels in the Genie-2000 program, and then the recorded data was converted to a text file. Peaks with Matlab 7.0 software intensities were determined from the fields of the spectra by transferring them to the OriginPro 8 program.

3. Findings and Discussion

The γ-ray shielding parameters of amber, plexiglass, organic glass, quartz, bakelite, NaCl, porcelain, and marble are given in Table 1. Additionally, previous studies and this study are compared for 59.54 keV gamma energy in Table 1. The γ-ray shielding parameters versus the dielectric constant are shown in Figure 3-9. An insulating material (dielectric) is a body or substance that has no free electrons capable of carrying an electric current, is polarized by an electric field, and has zero or very weak electrical conductivity. This study discussed how the γ-ray shielding parameters change with the dielectric constant (κ). A study could not be found for these samples in the literature review, this study is very important in terms of initial experimental data. Measuring γ-ray-shielding parameters is very important in terms of determining the degree of γ-ray shielding of the material. The transmission factor shows how permeable the material is, the linear attenuation coefficient shows how much γ-ray it absorbs according to its physical state and thickness, and the mass attenuation coefficient shows how much the material interacts with the γ-ray regardless of its physical state and how much it absorbs. The mean free path is how far the γ-ray can travel in the sample, radiation protection efficiency is how efficient the γ-ray protection is, the half value layer is the thickness of the sample where the intensity of the γ-ray is halved, and the tenth value layer is the material thickness that reduces the intensity of the γ-ray to 1/10. Examining these parameters to determine a good shielding material is very important half value layer, tenth value layer, and mean free path are important indicators of how deeply a photon with a given energy will penetrate a sample. Radiation protection efficiency is an important parameter in predicting the effectiveness of radiation protection material. A good shielding material should have a low mean free path, half value layer and tenth value layer, and a large mass attenuation coefficient and radiation protection efficiency. This situation shows the strong interaction of radiation with matter. That is, it means a good shielding material that absorbs radiation well.

Table 1. γ-ray shielding parameters of Amber, Plexiglass, Organic glass, Quartz, Bakelite, NaCl, Porcelain, and Marble.

Samples	Dielectric Constant (κ)(Average)	ρ (g/cm³)	TF	μ (cm⁻¹)	μ/ρ (cm²/g)	λ (cm)	RPE	HVL (cm)	TVL (cm)
Amber	2.7	0.96-1.3	10.022	7.798	6.901	0.128	89.978	0.089	0.295
Plexiglass	3.4	1.11-1.19	94.320	0.195[a] 0.227[d]	0.170[a] 0.193[b]	5.128	5.680	3.555	11.808
Organic Glass	3.5	1.17-1.20	95.930	0.157	0.132	6.386	4.070	4.426	14.704
Quartz	4.3	2.650	99.933	0.004	0.001	263.158	0.067	182.407	605.943
Bakelite	4.9	1.450	8.840	2.635	1.817[a] 0.192[b] >0.190[c]	0.379	91.160	0.263	0.874
NaCl	5.9	2.170	79.514	0.834	0.384[a] 0.343[e]	1.200	20.486	0.832	2.763
Porcelain	6.0	2.2-2.5	56.670	1.420	0.604	0.704	43.330	0.488	1.622
Marble	7.0	1.95-2.80	70.766	0.875[a] 0.786-1.084[f]	0.368[a] 0.324-0.419[f] 0.398[g]	1.142[a] 0.922-1.273[f]	29.234	0.792[a] 0.639-0.882[f]	2.630

[a]This work., [b][Shivaramu et al. (2001)]., [c][Abdel-Rahman et al. (2000)]., [d][Manoj et al. (2015)]., [e][Akça and Erzeneoğlu (2014)]., [f][Büyükyıldız et al. (2020)]., [g][Akça et al. (2022)].

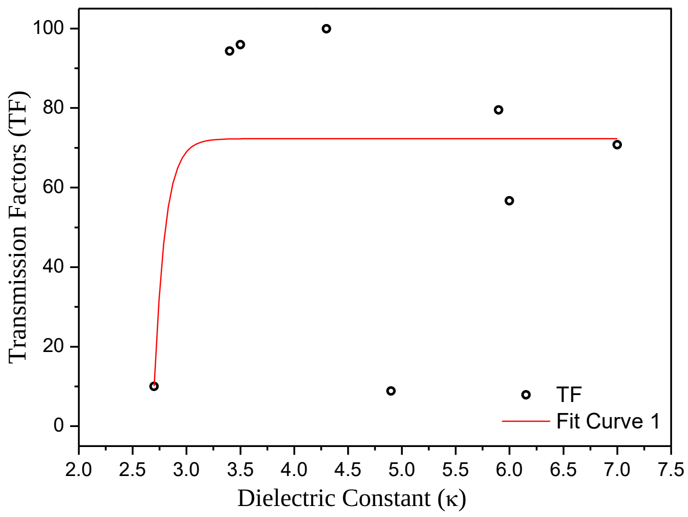

Figure 3. TF versus dielectric constant

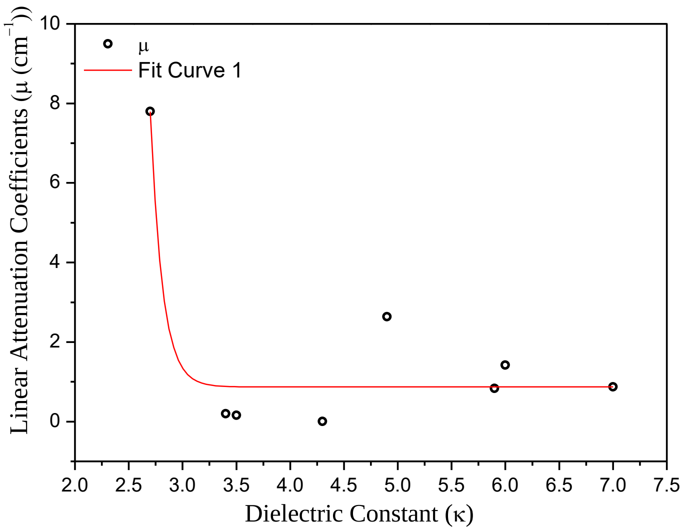

Figure 4. μ versus dielectric constant

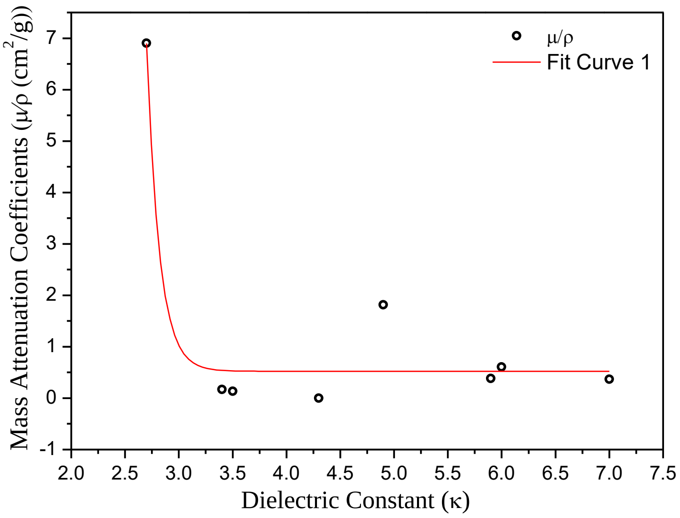

Figure 5. μ/ρ versus dielectric constant

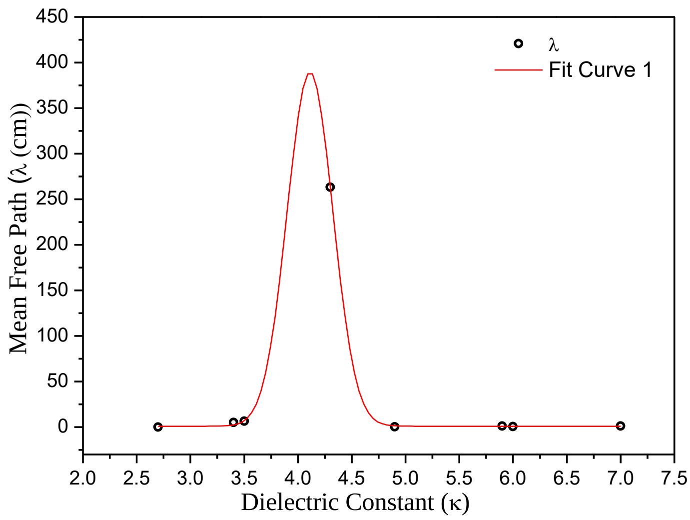

Figure 6. λ versus dielectric constant

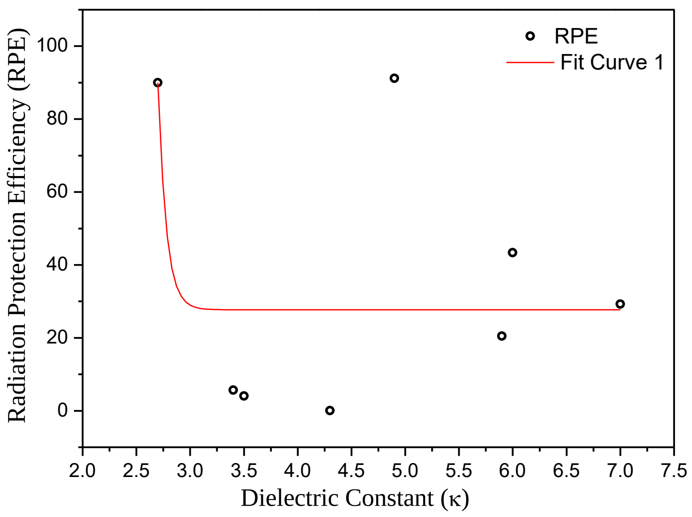

Figure 7. RPE versus dielectric constant

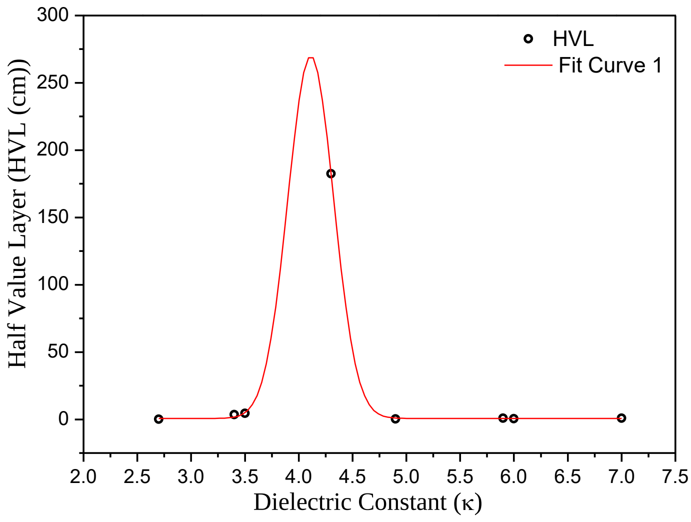

Figure 8. HVL versus dielectric constant

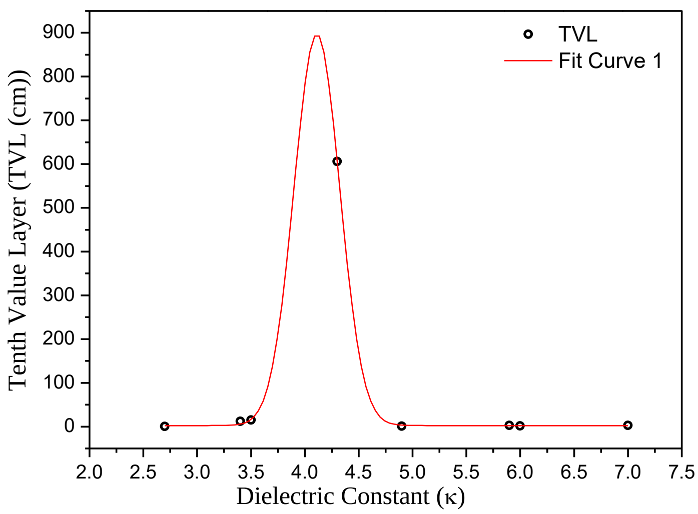

Figure 9. TVL versus dielectric constant

From Table 1, it can be seen that while marble has the biggest dielectric constant, amber has the smallest dielectric constant. When Table 1 and Figure 3 are examined, quartz has the largest transmission factor value, while bakelite has the smallest transmission factor value. In looking at Table 1 and Figure 4, it can be seen that amber has the biggest linear attenuation coefficient, while quartz has the smallest linear attenuation coefficient. In Table 1 and Figure 5, amber has the biggest mass attenuation coefficient, while quartz has the smallest mass attenuation coefficient. In looking at Table 1 and Figure 6, it is seen that quartz has the biggest mean free path, while amber has the smallest mean free path. In Table 1 and Figure 7, while bakelite has the biggest radiation protection efficiency, quartz has the smallest radiation protection efficiency. When Table 1 and Figure 8 are examined, quartz has the biggest half-value layer, while amber has the smallest half-value layer. When Table 1 and Figure 9 are examined, while quartz has the biggest tenth-value layer, amber has the smallest tenth-value layer. When the results obtained are evaluated, amber with the lowest mean free path, half value layer, and tenth value layer, and the highest mass attenuation coefficient and radiation protection efficiency value are seen as the best gamma shielding material. In Figures 4, 5, and 7, linear, mass attenuation coefficients and radiation protection efficiency showed similar changes with the dielectric constant. When Figures 6, 8, and 9 are examined, it is clear that the mean free path, half value layer, and tenth value layer show similar changes with the dielectric constant. When Table 1 is examined, it is seen that there is a good agreement with the values found experimentally and in previous studies. It is thought that the small differences between the results are due to the content, thickness, and density differences of the material used. Accordingly, if sorted, amber>bakelite is the best γ-ray shielding material, while quartz is very bad. Amber and bakelite are very absorbing materials for gamma rays. The dielectric constant of bakelite is approximately twice that of amber. It can be seen from Figure 4-5 that as the dielectric constant increases, the mass attenuation coefficients, linear attenuation coefficients, and radiation protection efficiency generally decrease. It has been observed that the dielectric constant changes depending on the atomic parameters. The increase of the dielectric constant decreased the interaction of the material and the γ-ray. Abouhaswa et al. (2020) calculated optical and gamma-ray shielding properties of lanthanum lead-borate glasses (($50B_2O_3$ – $10ZnO$ – (40-x)PbO) + x La_2O_3) wt% where (x=0, 0.25, 0.5, 1, 1.75 and 2.5)) at 0.015-15 MeV energies. In the study, it was observed that as the dielectric constant increases, the photoelectric interaction decreases for 0.356, 0.511, 0.662, 1.173, and 1.330 MeV energies. It is known that the photoelectric effect is more dominant below 100 keV energy. So the photoelectric effect is dominant in this study energy. Although the photoelectric effect is dominant in this study, it is seen that increasing the dielectric coefficient generally reduces the interaction with gamma rays. Mariselvam, (2021) investigated the gamma-ray shielding of ytterbium ions doped BLFB glasses at 15 KeV–15 MeV. The results showed that 2YbBLFB glass, which has the biggest dielectric constant, has the maximum mass and linear attenuation coefficient, while 0.05YbBLFB glass, which has the smallest dielectric constant, has the minimum mass and linear attenuation coefficient. This result is the exact opposite of our study. When this situation is evaluated, we can say that the structure, composition, and energy of the material are important for the change of the dielectric constant. The results are not the same for every dielectric material and different changes occur.

A highly valued gem since ancient times, amber has been used in pharmacy and medicine [Ragazzi (2016)]. It is used in alternative medicine because it is believed that it reduces bad energy and stress and is good for some diseases [Kılıç (2011)]. With this study, it is seen that amber is a very good material not only for therapeutic purposes but also for radiation protection. The results of this study showed that amber could be used not only in medicine but also in many other areas as a radiation protection material.

4. Conclusions and Recommendations

In this study, the γ-ray shielding properties of some dielectric materials are discussed at an energy of 59.54 keV. The atomic parameters for the dielectric materials whose gamma shielding properties were investigated showed changes with the dielectric constant. The mass attenuation coefficients, linear attenuation coefficients, and radiation protection efficiency generally have a decreasing change with increasing dielectric constant. In other words, as the dielectric constant increases, the interaction between gamma rays and dielectric material decreases. Amber has a low mean free path, half-value layer and tenth value layer, high mass attenuation coefficient, and radiation protection efficiency values. In this case, Amber interacts with gamma rays more than the other dielectric materials in the study. The best shielding material was determined as amber according to the results obtained. On the contrary, quartz interacts the least with gamma rays and is not suitable as a gamma shielding material. This study is very important as it contains the first experimental data on this subject. Similar studies can be done for various energies, different dielectric materials, and with different methods in the future.

Authors' Contributions

S. E: Writing, review, editing, investigation, supervision, project, administration, conceptualization, methodology, **B. A:** Writing, review, editing, investigation, data curation, original draft, conceptualization, methodology, **S. G. Y:** Review, investigation, data curation.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that all the rules required to be followed within the scope of "Higher Education Institutions Scientific Research and Publication Ethics Directive" have been complied with in all processes of the article, that The Black Sea Journal of Science and the 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 The Black Sea Journal of Science.

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