



Evaluation of Photon Shielding Parameters in NiCuFe₂O₄ and NiMgFe₂O₄ Nanoparticles.

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Abstract:

This work employed the Sol-gel auto-combustion process to produce ferrite samples of NiCuFe₂O₄ and NiMgFe₂O₄. various analytical methods were used to examine the synthetic materials' structural, optical, and functional groups, including XRD, UV-Vis, and FTIR. Furthermore, we examined the gamma-ray shielding characteristics for the produced materials using a NaI (TI) scintillation detector and various gamma-ray sources. The theoretical values and the experimental results exhibited a strong connection. This software program evaluated the synthesized ferrite nanoparticles' capability to shield against gamma radiation. By adjusting the radiation dose's strength, ferrites have been exposed to gamma radiation from an array of sources. An investigation of the mass and linear attenuation coefficients, mean free path, half value layer, and tenth value layer, for synthesized spinel ferrites at 122–1330 keV is conducted using Phy-X/PSD software. It is widely recognized that the recommended nanoparticles can aid in improving shielding against γ -radiation.

Keywords: XRD, FTIR, and Radiation shielding parameters.

1) Introduction:

The more technologies that use radiation, the more radiation-protective materials are being developed. Photons with high intensity that might ordinarily cause irreversible injury to human cells are absorbed by these radiation shields. An extended period of high-intensity radiation exposure can lead to severe cases of cancer, illness, tissue damage, and even death [1-3]. When it comes to radiation shields, material diversity offers a multitude of applications and materials to choose from [4–10]. For example, concrete is cheap and easily shaped into different forms, making it a popular material for lining the walls of laboratories and nuclear power plants [11]. Concrete, on the other hand, is prone to breaking over time and blocks your light [12]. Efforts to find a more effective radiation shield have focused on the development of ferrite nanoparticles by researchers.

The most promising material for use in radiation shielding is nanoparticles. Reducing undesired emissions and shielding materials and devices from external radiation are necessary to prevent the harmful effects of radiation on human health [13]. To evaluate the radiation shielding ability of various composite materials, numerous researches have been conducted recently to calculate the parameters of particular attenuation coefficients and γ -ray shielding. In-depth studies of the radiation shielding of cobalt (Co) and zinc (Zn)--based spinel ferrite materials were necessary to examine the previously mentioned point of view. The electrical, magnetic, radiation shielding, and spectral analyses of Mg-doped Ni–Cu–Zn Nanoferrites were conducted by Henaish et al. [14]. They discovered that the 0% sample had the highest Z_{eff} and μm . Magnesium level rises due to zinc, effectively blocking gamma rays. Mansy et al. [15] examined the attenuation properties of gamma rays and fast neutrons from $\text{Ni}_x\text{Co}_{1-x}\text{Fe}_2\text{O}_4$ nickel ferrites.

Here, the tried-and-true methods such as the sol-gel method yield a homogeneous product with small particles and a wide surface area; moreover, the method is less expensive and takes less time to process. Many efforts have been made to create ferrite nanoparticles that are suitable for use as gamma-ray shielding material; it has been found that the ferrite nanoparticles in $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ exhibit structural, mechanical, and chemical stability; furthermore, they should work well as gamma and X-ray absorbers. Accordingly, we created $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ ferrite nanoparticles and in the current work, we examined their gamma radiation shielding capabilities. To our knowledge, the synthesis of $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ ferrite nanoparticles using the sol-gel method has proven to be a flexible and energy-efficient technique. The fabricated nanoparticles were analyzed using X-ray diffraction (XRD), UV-visible absorption spectroscopy, and Fourier transmission infrared spectroscopy (FTIR). Further research is done on the production of ferrite nanoparticles, $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$, and their gamma-ray shielding capabilities. This research opens up a new path for the simple, economical, and effective production of nanomaterials for gamma-ray shielding.

2) Materials and Method:

Materials for the synthesis of $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ were prepared ferrite nanoparticles according to this given content of 99.9% pure AR grade ferric nitrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$), nickel nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), Copper (III) nitrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$) and magnesium nitrate ($\text{Mg}(\text{NO}_3)_2$), were used as starting materials to prepare $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$. Urea [$\text{CH}_4\text{N}_2\text{O}$] was used as fuel because of its better complexing ability and low ignition temperature (200–250 °C) than other fuels used in wet-chemical methods. Metal nitrate to urea was maintained in a molar ratio of 1:3. A minimum amount of deionized water was mixed with a stoichiometric proportion of metal nitrates to create a homogenous solution. To keep the pH of the combined nitrate solution at 7, it was vigorously agitated using liquid ammonium hydroxide (NH_4OH), drop by drop. For three to four hours, the mixed solution was heated simultaneously at 70 °C to form a sol. To eliminate the water, the transparent sol was heated for one hour at 110 °C. Sol becomes a thick brown gel as the temperature rises. The viscous brown gel turns into a dried gel when it is constantly stirred and heated.

When the gel reached an appropriate temperature, ignition started, and it burned in a self-propagating manner until it was completely burned, forming a fluffy, loose powder that was $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$. After drying, the powder was annealed for 5 hours at 700°C . The prepared powder of loose $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ ferrite was grinded in a planetary ball mill for 40 minutes, samples were characterized by XRD, FTIR, UV-Vis, and Radiation parameters by using NaI-(Tl) Scintillation detector [16-20].

3) Result and Discussion

3.1) X-ray Diffraction Analysis

The structural properties of the synthesized ferrite samples, namely S1 (Nickel Copper Ferrite) and S2 (Nickel Magnesium Ferrite), prepared via the sol–gel method, were investigated using X-ray diffraction (XRD). The diffraction patterns of both samples exhibited well-defined peaks at 2θ values of 30.26° , 35.64° , 43.33° , 57.31° , and 62.94° , which are characteristic of spinel ferrite structures. These reflections correspond to the crystallographic planes (220), (311), (400), (511), and (440), respectively, and are in good agreement with the standard JCPDS card No. 22–1086 for cubic spinel ferrites, confirming the successful formation of a single-phase spinel structure without any detectable impurity phases[21]. The lattice parameter (a) for both samples was calculated using the relation for cubic systems[22, 23].

$$\frac{1}{d^2} = (h^2 + k^2 + l^2) \frac{1}{a^2}$$

The obtained values were found to be nearly identical, around $a = 6.92 \text{ \AA}$, which matches well with the reported values for spinel ferrites. This consistency in lattice parameter indicates that the substitution of Cu^{2+} and Mg^{2+} ions in the nickel ferrite lattice does not significantly distort the cubic structure, suggesting successful incorporation of dopant ions within the spinel framework[24]. The average crystallite size (D) was determined using the Debye–Scherrer equation from the most intense diffraction peak (311)[25-27].

$$D = \frac{K\lambda}{\beta \cos\theta}$$

The crystallite size of the S1 (Ni–Cu ferrite) sample was estimated to be **33.93 nm**, whereas the S2 (Ni–Mg ferrite) sample showed a smaller size of **20.50 nm**. The observed decrease in crystallite size upon magnesium substitution could be attributed to differences in ionic radii and bonding preferences of Mg^{2+} compared to Cu^{2+} , which influences the nucleation and growth process during the sol–gel synthesis[28]. Thus, the XRD results confirm the formation of nanocrystalline spinel ferrite structures with controlled crystallite sizes, which may strongly influence their physical and functional properties for potential applications.

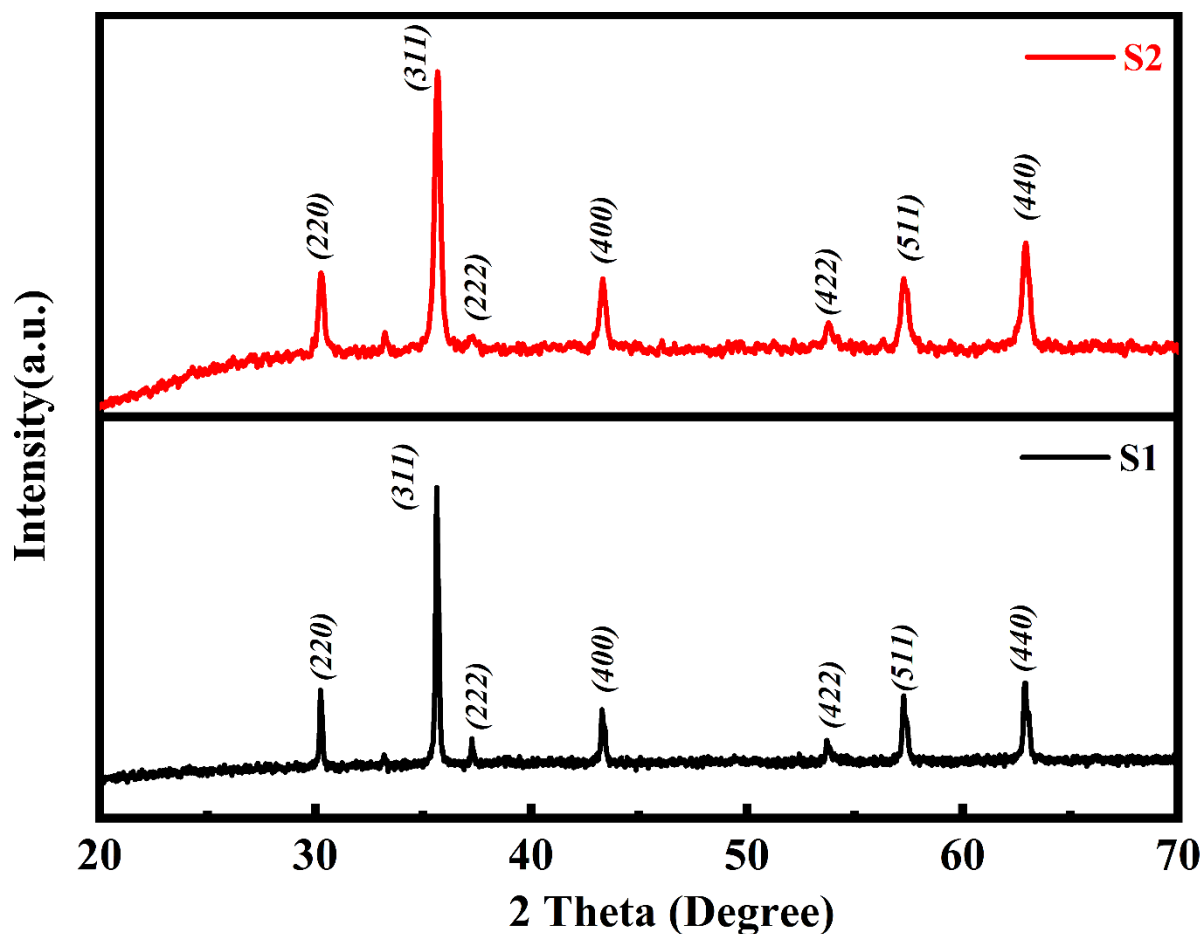


Figure 1 XRD spectra of synthesized samples.

3.2) FTIR Analysis

Fourier Transform Infrared (FTIR) spectroscopy is a powerful tool to confirm the formation of spinel ferrite structures by analysing the characteristic metal–oxygen vibrational bands. In the present study, FTIR spectra of NiFe_2O_4 samples are recorded in the wavenumber region of $4000\text{--}300\text{ cm}^{-1}$. This range is particularly important for ferrite systems, as it reveals the fundamental vibrational modes of metal–oxygen bonds in the crystal lattice. The spectra display two distinct broad absorption bands that are typical features of spinel ferrites. The first absorption band (ν_1), appearing in the range of $600\text{--}550\text{ cm}^{-1}$, is attributed to the stretching vibrations of metal–oxygen bonds located at the tetrahedral sites of the spinel structure[29]. The second band (ν_2), generally observed in the range of $450\text{--}385\text{ cm}^{-1}$, corresponds to the vibrations of metal–oxygen bonds at the octahedral sites[30]. The presence of these two well-defined absorption bands in all investigated samples confirms the formation of the spinel phase, as they reflect the characteristic distribution of cations over tetrahedral and octahedral interstitial positions. Thus, FTIR analysis not only verifies the spinel structure of NiFe_2O_4 but also provides insight into the bonding nature and cationic environment within the lattice, supporting the structural results obtained from XRD analysis.

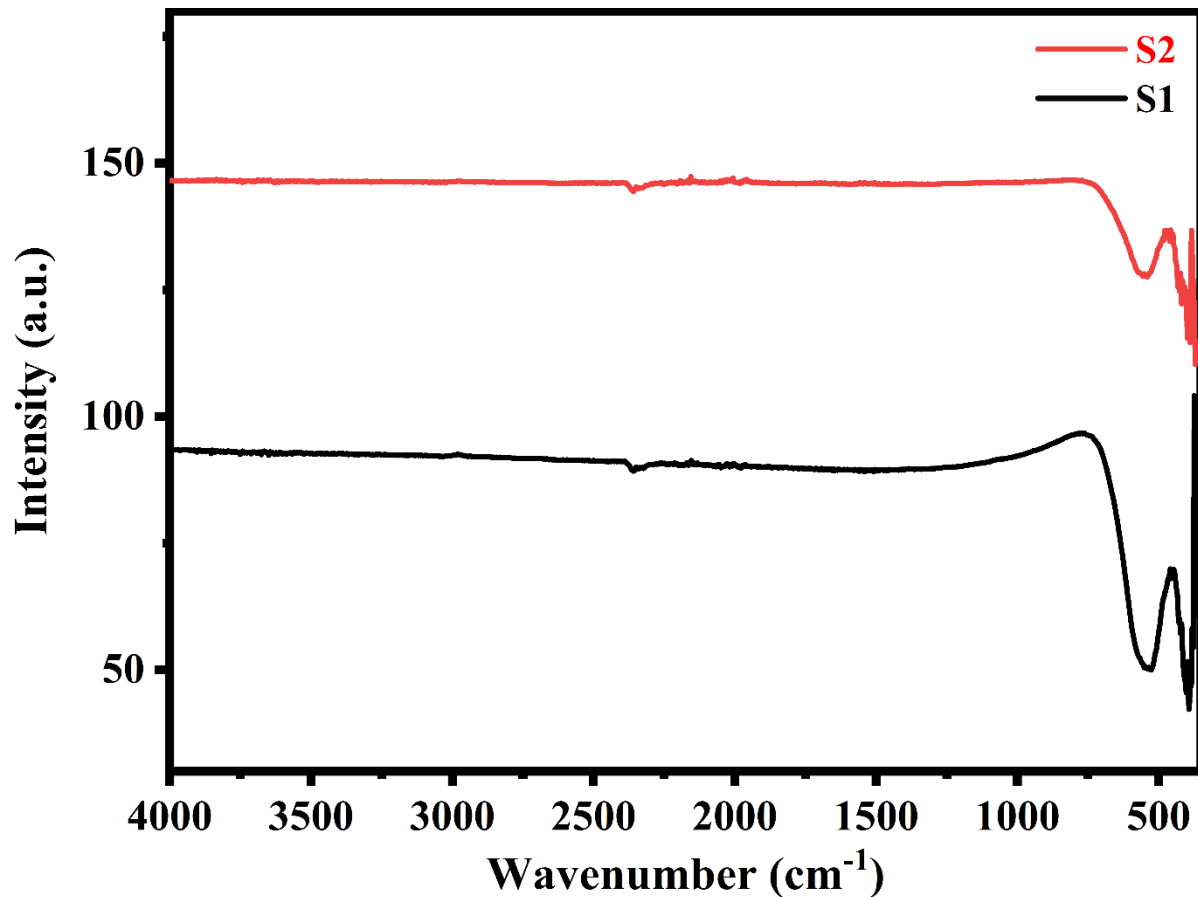


Figure 2 FTIR spectra of synthesized samples.

3.3 Optical Property Study

The optical properties of ferrite nanoparticles can be studied using UV–Vis spectroscopy, which provides insight into their electronic band structure shown[31]. Figure 3 shows the absorption spectra of the prepared S1 (Nickel Copper Ferrite) and S2 (Nickel Magnesium Ferrite) samples. The band gap energies were determined using the Tauc plot method[32, 33].

$$\alpha h\nu = A(h\nu - E_g)^n$$

For S1, the estimated optical band gap is 2.84 eV, while for S2 it is 3.24 eV. The difference in band gap values can be attributed to the nature of the substituted cations (Cu^{2+} in S1 and Mg^{2+} in S2) and their influence on the electronic structure of the spinel ferrite lattice.

In Nickel Copper Ferrite (S1), the incorporation of Cu^{2+} ions, which possess partially filled d-orbitals, introduces localized electronic states within the band structure[34]. These states effectively reduce the energy difference between the valence and conduction bands, leading to a narrower band gap (2.84 eV). Such a reduced band gap enhances visible-light absorption and can improve photocatalytic and optoelectronic properties[35]. In contrast, Nickel Magnesium Ferrite (S2) exhibits a larger band gap of 3.24 eV. This is because Mg^{2+} ions are non-transition metal cations with no d-electrons, and their substitution does not create

additional localized states in the band structure[36]. As a result, the material maintains a wider separation between the valence and conduction bands. The larger band gap makes S2 more suitable for applications requiring higher-energy photon absorption, such as UV-light-driven processes. Thus, the observed band gap variation between S1 and S2 highlights the role of cation substitution in tuning the optical properties of ferrite nanomaterials for specific applications[37-43].

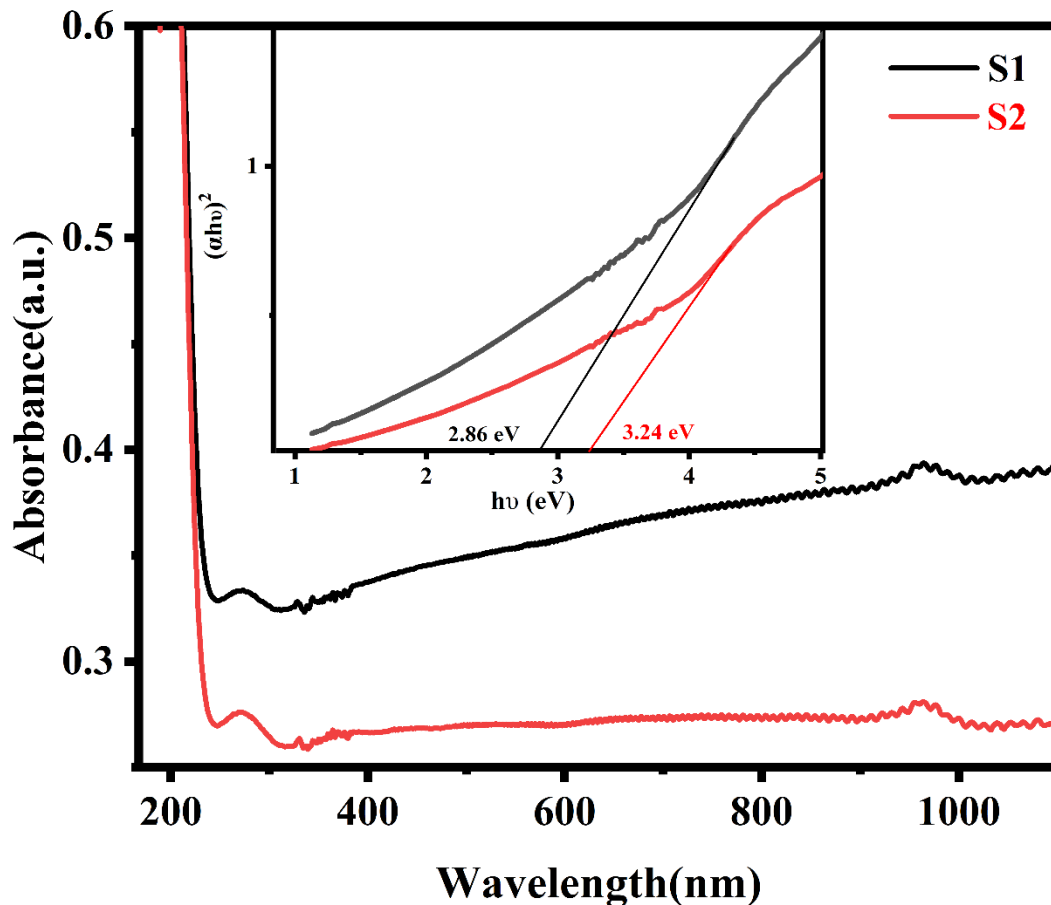


Figure 3 UV-Vis absorption spectra and Tauc plot of synthesized samples.

3.4) Radiation Shielding Properties:

The theoretical MAC was computed using the Phy-X/PSD algorithm, and the results were compared to the experimental data. Phy-X/PSD software was used to estimate additional properties. Several researchers used this software to assess the radiation shielding capabilities of various materials, such as glasses [38]. Linear attenuation coefficients (LAC), Mass attenuation coefficients (MAC), half-value length (HVL), tenth-value length (TVL), and mean free path (MFP).

3.4.1. Linear Attenuation Coefficient (LAC)

Figure 4 shows the linear attenuation coefficient (μ) of a particular ferrite nanoparticle to energy. It is possible to see how the linear attenuation coefficient for all created samples drops exponentially as energy is increased. Sample S2 has the lowest LAC value, whereas Sample S1 has the highest. Furthermore, the S2 ferrite decays

faster than the spinel ferrites selected in the energy range of 122 to 356 keV, after which it drops linearly with energy. A linear attenuation coefficient is a key factor when evaluating a material's shielding performance [39].

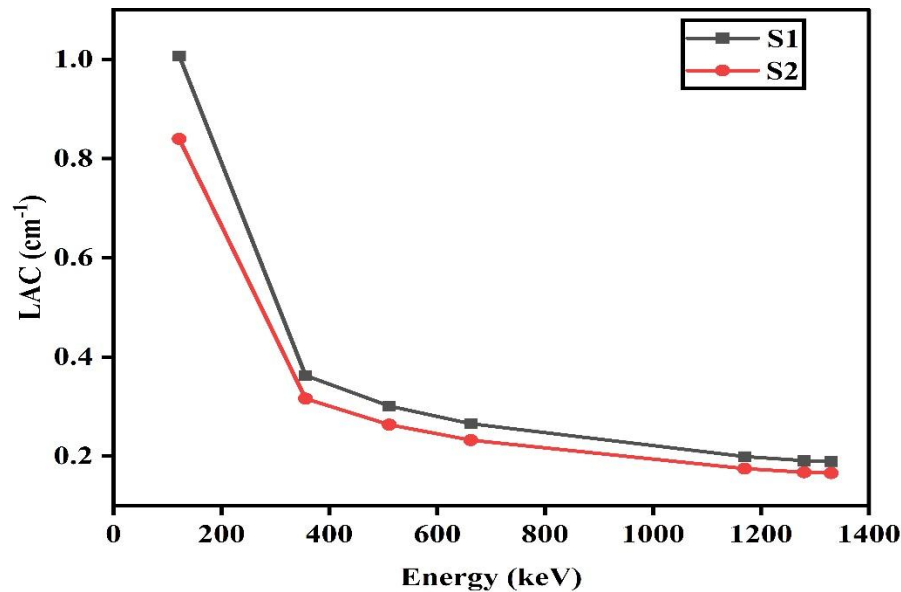


Figure. 4. Linear Attenuation Coefficient (LAC) of the synthesized sample.

3.4.2. Mass Attenuation Coefficient (MAC)

Figure 5 and Table 1 display mass-attenuation coefficients for nano and micro-sized $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ ferrites Nanoparticles. The results from experimental measurements and Phy-X are nearly equivalent, with tiny variation values not exceeding 4.0%. This finding shows that the size of the nickel magnesium ferrite has little effect on the attenuation qualities. The S1 composition had the largest mass-attenuation coefficients at different energies because to its high $\text{NiCuFe}_2\text{O}_4$ content, while $\text{NiMgFe}_2\text{O}_4$ had the lowest due to its high Mg content. The accuracy and consistency of the results obtained by Phy-X are notable, confirming the validation of its application in computing the mass-attenuation coefficient for micro-sized materials [44]

Table 1. Comparison of Theoretical (Phy-X) and Experimental Mass Attenuation Coefficient.

Energy	Phy-X S1	Exp	% Dev	Phy-X S2	Exp	% Dev
122	0.2799	0.2764	1.263199318	0.2678	0.2636	1.564052437
356	0.1016	0.0978	3.701091942	0.1008	0.0962	4.519178853
511	0.0836	0.0818	2.18304748	0.0839	0.0822	2.055994396
662	0.0737	0.0722	2.011775266	0.0740	0.0729	1.54595148
1170	0.0553	0.0539	2.582160106	0.0557	0.0541	2.820999791
1280	0.0530	0.0512	3.459772736	0.0534	0.0517	3.116982282
1330	0.0525	0.0507	3.496832703	0.0529	0.0511	3.333798104

The MAC of S1 and S2 ferrites can be determined using its assistance. To demonstrate how the findings in Table 1 differ in percentage. This figure validates the experiment that was used to produce the MAC values. Figure 7 depicts the mass attenuation coefficient values for various samples in the energy range of 122 keV to 1330 keV. At 122 keV, MAC is $0.2799 \text{ cm}^2/\text{g}$ for S1 and $0.2496 \text{ cm}^2/\text{g}$ for S2, while at 1330 keV, it is $0.0525 \text{ cm}^2/\text{g}$, and $0.0529 \text{ cm}^2/\text{g}$, respectively.

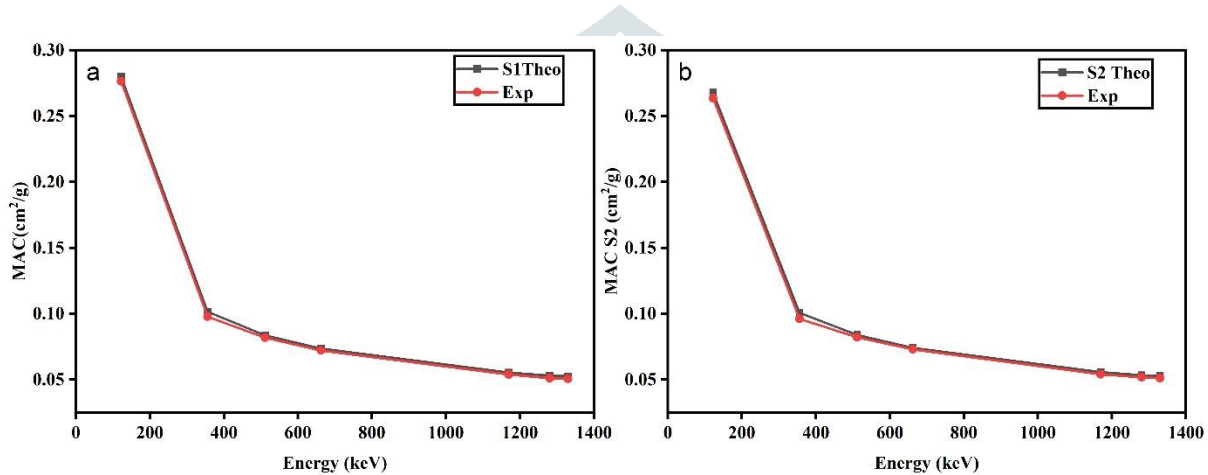


Figure. 5. Comparison of theoretical and experimental results of Mass Attenuation Coefficient (MAC) synthesized sample.

3.4.3 Mean Free Path (MFP)

Figure 6 depicts the ferrite nanoparticles' mean free path (MFP). The MFP value is found at the lowest tested energy, 122 keV, and ranges from 1.1908 to 0.9928 cm. At 1330 keV, the largest MFP is discovered to be between 5.2899 and 6.0324 cm. Because higher intensity radiation can easily flow through the damaged material, there is a growing tendency in the MFP. At higher energies, the Compton interaction replaces the photoelectric effect [45-47]. Since this alteration, photon attenuation has decreased because the Compton interaction, which is generally independent of atomic number and energy, happens mostly between incoming photons and the outer shell electron of an atom within ferrite nanoparticles.

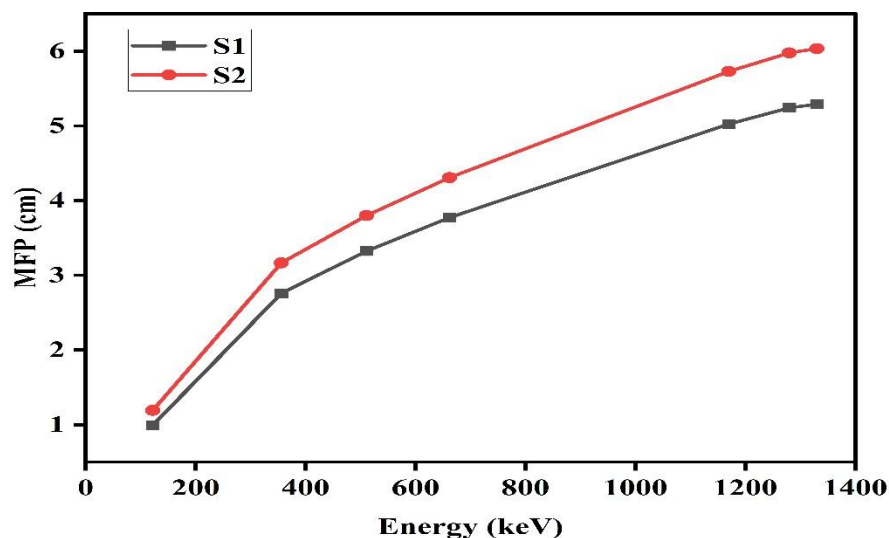


Figure. 6. Mean Free Path (MFP) of the synthesized sample.

3.4.4 Half Value Layer (HVL) and Tenth Value Layer (TVL)

Figures 7 and 8 depict the Half Value Layer and Tenth Value Layer, respectively. The HVL values for a given energy are organized in the following order, and they rise when energy levels $S2 > S1$. In other words, the S1 sample has the lowest HVL and the best shielding ability, whereas the S2 sample has the highest HVL but the lowest acceptable shielding capacity. In addition, the influence of energy on HVL was investigated. There is evidence that HVL increases with higher energy levels. The HVL of the S1 sample grew from 0.6881 to 1.9119, 2.3036, 2.6144, 3.4817, 3.6323, and 3.6667 cm at energies of 122, 356, 511, 662, 1170, 1275, and 1330 keV, respectively. Higher energy photons are more likely to pass through nanoparticles and impact with material atoms less frequently, causing HVL to rise and remain. As a result, the space efficiency of nanoferrites increases at lower energies while decreasing at higher energies [48-51]. Similar results show the TVL outcomes as the HVL

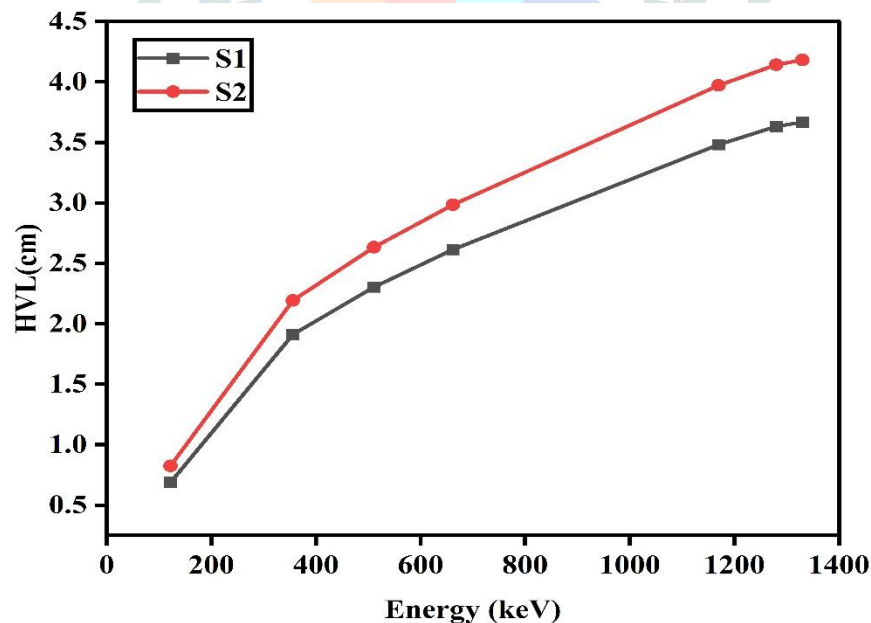


Figure. 7. Half Value Layer (TVL) of the synthesized sample.

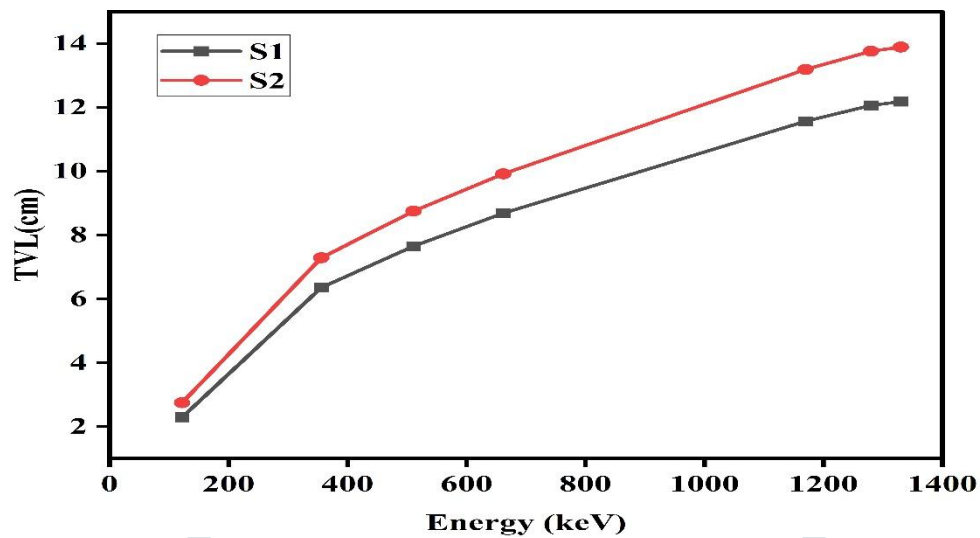


Figure. 8. Experimental Tenth Value Layer (TVL) of the synthesized sample.

4) Conclusion:

This study looked at the radiation shielding properties of $\text{NiCuFe}_2\text{O}_4$ and $\text{NiMgFe}_2\text{O}_4$ nanoparticles. to determine how effective photon protection is. The computations in the study were done using Phy-X/PSD. LAC, MAC, TVL, and HVL. The mass attenuation coefficient was experimentally determined for each ferrite nanoparticle sample using the Phy-X/PSD program and the NaI (Tl) scintillation detector. Furthermore, HVL values for a given energy are grouped in the following order, and they increase when energy levels $S2 > S1$. These numbers rise in lockstep with the energy levels. Alternatively, the S1 sample has the lowest HVL and the best shielding capacity, whereas the S2 sample has the highest HVL and the least effective shielding capacity. This shows how ferrite nanoparticle samples can be employed in radiation-safe applications. Future research could lead to the development of more effective radiation barrier materials. The study results can be used as a first approximation and as the foundation for future investigations.

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