

Gamma-Ray Shielding Effectiveness Of Ni-Cu-Zn Ferrite Ceramics: An Alternative To Conventional Shielding Materials

V. K. Barote*, R. R. Magar

Sant Dnyaneshwar Mahavidyalya, Soegaon, Maharashtra, India 431120

ABSTRACT

This study investigates the photon attenuation capabilities of Ni–Cu–Zn ferrites in the energy range 0.360–1.33 MeV, with particular emphasis on their potential for gamma-ray shielding applications. We synthesized ferrite samples with varying compositions based on $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ were synthesized using the solid-state reaction method. Their structural, morphological, and radiation-shielding properties were systematically evaluated. The experimental results were compared with theoretical calculations obtained using the XCOM software. The findings indicate that Ni–Cu–Zn ferrites exhibit competitive linear attenuation coefficients, mass attenuation coefficient, total photon interaction cross-section and total electronic cross section which are strongly influenced by their chemical composition and density. The attenuation behavior is primarily governed by Compton scattering within the investigated energy range. These results demonstrate that Ni–Cu–Zn ferrites are promising, eco-friendly, and potentially cost-effective alternatives to conventional shielding materials such as lead.

Keywords: Synthesis of Ni–Cu–Zn ferrites; XRD; Photoelectric Cross-Section; Linear attenuation coefficient; Total electronic cross-section.

INTRODUCTION

The escalating use of ionizing radiation in medical imaging, nuclear power, and industrial radiography has intensified the need for efficient, non-toxic radiation shielding materials. Traditionally, lead (Pb) and concrete have been the materials of choice. However, lead poses significant environmental and health risks due to its toxicity, while concrete is bulky and requires significant volume for effective attenuation [1]. With ever-increasing use of gamma rays in various fields such as industry, medicine and agriculture etc, the study of photon interaction with different composite materials has become a topic of prime importance for radiation physicists. Some parameters of dosimetric interest are the mass attenuation coefficient, effective atomic number, total photon interaction cross-section and total electronic cross-section. These parameters help in basic understanding of photon interaction with composite materials. The mass attenuation coefficient (μ/ρ) is a measure of number of photons interacting (scattered/absorbed) with target material. It is the

fundamental tool to derive many other parameters for dosimetric interests such as mass energy absorption coefficient, molecular, atomic and electronic cross-sections, effective atomic number and density of the materials. Berger and Hubbell have developed a computer program XCOM [2], which is useful for calculation of mass attenuation coefficient and photon interaction cross-section for pure elements and their mixture theoretically in the energy range 1 keV to 100 GeV. Even then, the measurement of mass attenuation coefficient and other parameter is the subject of large interest for many researchers. The theoretical and experimental values of mass attenuation coefficient may or may not agree with each other because of the experimental procedure and conditions. Several researchers have used different composite materials such as Bakelite, cement high Tc superconductor etc, biologically important materials such as plant leaves, bones, proteins etc, for attenuation coefficient of photon [3-4].

Ferrite materials, specifically spinel ferrites (MFe_2O_4 , where M = Ni, Cu, Zn), have emerged as promising

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Materials due to their high density, chemical stability, and cost-effectiveness. This study investigates the photon absorption capabilities of $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ synthesized via solid-state reaction. By evaluating their performance within the 0.360-1.33 MeV energy range-relevant to commonly used isotopes like Ba^{133} , ^{137}Cs and ^{60}Co we analyze the relationship between composition, morphology, and attenuation effectiveness [5]. Among these magnetic materials, soft magnetic materials are used as inductive components in electromagnetic devices viz, transformers of large and small size, telecommunication systems, field sensors in magnetic recording, etc. would determine their suitability of applications in specific electromagnetic devices. For the low magnetic loss, the high resistivity of the material is needed for various applications. In this regard, spinel ferrite is highly suited for their applications as soft magnetic materials because of low coercive field, high resistivity and low production cost [6]. Therefore, spinel ferrites are considered as a composite material in the present study. Recently, many researchers [7-9] have used the mixture rule in order to provide mass attenuation coefficients for multi-elements. To our knowledge very few researchers [10] have studied mass attenuation coefficient and effective atomic numbers for their use in shielding purpose, Hubbell [11] provided theoretical values of mass attenuation coefficients for various elements.

In the present work, we report our results on linear, mass attenuation coefficient, total atomic cross-section and total electronic cross-section of $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ ferrite composite. The results are verified by Hubble's mixture rule formula.

2. EXPERIMENTAL PROCEDURE

2.1 Synthesis

The Polycrystalline $\text{Ni}_{0.3}\text{Cu}_{0.5}\text{Zn}_{0.2}\text{Fe}_2\text{O}_4$ ferrite powders were synthesized using the conventional solid-state reaction method [12]. High-purity oxide powders AR grade (NiO , CuO , ZnO , and Fe_2O_3) were stoichiometrically weighed and the constituent oxides of the respective ferrite were, mixed thoroughly. The mixture was well grinded for 3 hours using agate mortar and pestle. The homogeneous mixture is then pressed into a circular pellet of 10 mm diameter and about 2 mm thickness using a hydraulic press. The

sample in the pellet form was pre-sintered at 950°C for 12 hour in a programmable furnace. The samples are then slowly cooled to room temperature at the rate 2°C per minute. The pre-sintered pellets were again crushed and reground to improve the homogeneity for 2 hours. The dried mixture is compressed in circular pellet form. The polyvinyl alcohol (PVA) was used as a binder. The pellet was then sintered at 1100°C for 24 hour and finally cooled slow to room temperature at the rate of 2°C per minute. The final product obtained in the form of pellet is hard, flat and crack free. The bulk density of prepared spinel ferrite composite $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ is obtained by using mass volume relation is 4.070 gm cm^{-3} , and the molecular weight of the prepared sample is 238.66. At room temperature, X-ray diffraction (XRD) patterns of sample were obtained by using Philips X-ray diffractometer (Model PW 3710) using $\text{Cu-K}\alpha$ radiations ($\lambda = 1.5405\text{ \AA}$). The sample is taken in the form of right circular cylindrical pellets of uniform thickness. These pellets of uniform thicknesses were used to find the linear attenuation coefficient, mass attenuation coefficient of gamma radiation and related parameter for various energies. A narrow beam geometry technique was used to obtain the absorption of gamma radiations. All observations were taken on similar assembly using Scintillation counter and Na(Tl) detector. The linear attenuation coefficient (μ) was measured using a gamma-ray spectrometer equipped. Standard gamma sources (^{137}Cs at 0.662 MeV and ^{60}Co at 1.17 and 1.33 MeV) were used. The intensity of the transmitted radiation was measured both with and without the sample.

3. RESULTS AND DISCUSSION

3.1 X-ray diffraction

The single phase cubic spinel structure of the spinel ferrite composite with the chemical formula $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ has been confirmed by the powder X-ray diffraction technique (XRD). The phase purity and crystallinity were determined using X-ray Diffraction (XRD).

The XRD pattern was recorded on Philips X-ray diffractometer (Model-3710). The X-ray diffraction patterns were recorded using $\text{Cu-K}\alpha$ range, at room temperature. The XRD pattern was recorded in the 2θ range of 20° to 80° with scanning rate 1° per minute.

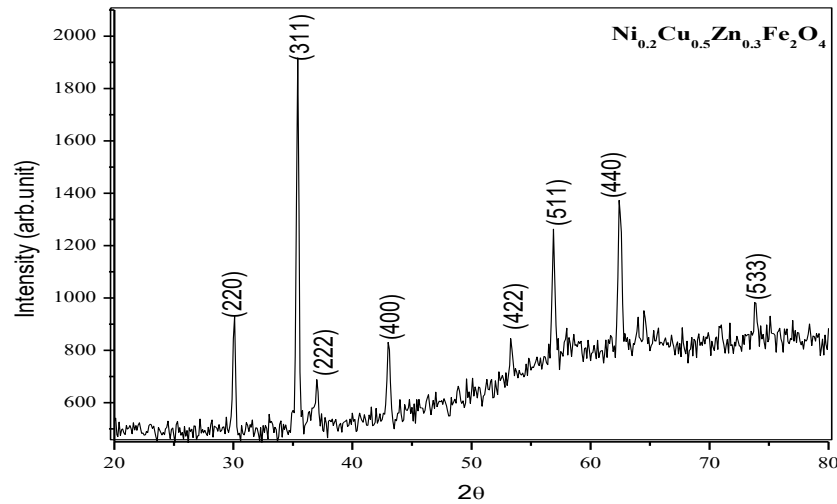


Fig-1 X-ray diffraction patterns of spinel ferrite composite $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$

$$I = I_0 e^{-\mu t}$$

1

All the peaks in the recorded X-ray diffraction pattern are sharp intensive and diffraction patterns reflects (220), (311), (222), (400), (422), (511), (440) and (533) planes belonging to cubic spinel structure. Fig-1 represents X-ray diffraction pattern of $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ of spinel ferrite composite.

Where, t- thickness of absorber

The values of I_0 and I were obtained for different thickness of absorbers using a scintillation counter. The variation of $\ln(I_0/I)$ with thickness has been studied for various energies.

3.2 Linear Attenuation Coefficients

The prepared $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ spinel ferrite sample in the form of circular pellets of uniform thickness has been used as an absorber. A narrow beam technique has been used to determine the linear attenuation coefficient for different energies in the present investigation. The thickness of the absorber was varied by staging the absorber. The linear attenuation coefficient (μ) for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ for various energies 0.360 MeV to 1.33 MeV were calculated using the following relation,

Table 1

Experimentally measured values of linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), total photon interaction cross-section (σ_{total}), total electronic cross-section (σ_{ele}) and effective atomic number (Z_{eff}) for collimated photon beam of 0.2cm diameter in the energy range (0.360 MeV-1.33 MeV) for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ ferrite composite.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2/gm)		% Devi.	σ_{total} (barn/atom)	σ_{ele}
		XCOM.	Expt.			
0.360	2.742	0.7067	0.6750	4.0	38.21	2.363
0.511	2.245	0.5938	0.5518	3.7	31.24	1.931
0.662	1.928	0.5014	0.4738	5.0	26.82	1.658
1.170	1.568	0.4128	0.3855	6.0	21.82	1.349

1.280	1.442	0.3824	0.3545	7.0	20.07	1.241
1.330	1.365	0.3675	0.3355	8.7	18.99	1.174

The linear attenuation coefficient values were obtained from the slope of $\ln(I_0/I)$ versus t for different collimator diameter 0.2 cm to 0.4 cm in the steps of 0.1 cm and the measured value of linear attenuation coefficient are shown in tables 1, 2, 3 and the exponential order of linear attenuation coefficient (μ) is decreases. The Similar results were reported in the literature [13].

3.3 Mass attenuation Coefficient

The mass attenuation coefficient was calculated by measuring the sample density using mass-volume relation. The mass attenuation coefficient was calculated using the relation:

$$\mu_m = \mu/\rho \quad 2$$

where, μ_m - mass absorption coefficient, ρ – density of the material

The calculated values of mass attenuation coefficient from the above relation are listed in tables 1, 2, 3. The variation of mass attenuation coefficients for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ is shown in table 2 for all collimator diameters. From table 2, it is observed that, the mass attenuation coefficient (μ_m) decreases with increasing photon energies.

Table 2

Experimentally measured values of linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), total photon interaction cross-section (σ_{total}), total electronic cross-section (σ_{ele}) and effective atomic number (Z_{eff}) for collimated photon beam of 0.3cm diameter in the energy range (0.360 MeV-1.33 MeV) for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ ferrite composite.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2/gm)		% Devi.	σ_{total} (barn/atom)	σ_{ele}
		XCOM.	Expt.			
0.360	2.840	0.7067	0.6980	1.2	39.51	2.443
0.511	2.408	0.5938	0.5918	0.3	33.50	2.071
0.662	2.029	0.5014	0.4987	0.5	28.23	1.745
1.170	1.668	0.4128	0.4099	0.7	23.20	1.435
1.280	1.564	0.3824	0.3845	0.5	21.26	1.346
1.330	1.494	0.3675	0.3672	0.08	20.80	1.285

The values of total mass attenuation coefficient as a function of photon energy and collimator size were calculated from the Hubbell's mixture rule. The total mass attenuation coefficient for the different materials and energies are determined by the transmission. This process is described by the following equation:

$$I = I_0 e^{-\mu t} \quad 3$$

where I_0 - photon intensity with energy E , without attenuation, I -photon with energy

E , intensity after attenuation

$\mu_m = \mu/\rho$ (cm^2/gm) i.e. mass attenuation coefficient and t (gm/cm^2) sample mass thickness (mass per unit area). The total mass attenuation values for materials that are composed of multi elements is the sum of

$(\mu_m)_i$, values of each constituents element by the following mixture rule [14]:

$$\mu_m = \sum w_i (\mu_m)_i \quad 4$$

where, w_i is the weight fraction of i^{th} element and $(\mu_m)_i$ is mass attenuation coefficient of the i^{th} element. For a material composed of multi-elements, the fraction by weight is given by:

$$w_i = \frac{n_i A_i}{\sum n_j A_j} \quad 5$$

where, A_i is the atomic weight of the i^{th} element and n_i is the number of formula units [15].

The theoretically obtained values of mass attenuation coefficient are given in tables 1, 2, 3. A comparison of theoretical and experimental values shows good agreement for the collimator diameter 0.3 cm. The

results indicate a clear decrease in μ as photon energy increases, which is consistent with the predominance of the Compton scattering effect in this energy range (0.36–1.33 MeV). The synthesized Ni-Cu-Zn ferrite samples show good agreement with XCOM theoretical values, validating the experimental setup. The attenuation is density-dependent; samples with higher sintering temperatures showed higher density and, consequently, higher μ values.

Table 3

Experimentally measured values of linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), total photon interaction cross-section (σ_{total}), total electronic cross-section (σ_{ele}) and effective atomic number (Z_{eff}) for collimated photon beam of 0.4 cm diameter in the energy range (0.360 MeV-1.33 MeV) for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ ferrite composite.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2/gm)		%Devi.	σ_{total} (barn/atom)	σ_{ele}
		XCOM	Expt.			
0.360	2.666	0.7067	0.6551	7.3	37.08	2.293
0.511	2.227	0.5938	0.5473	7.7	30.98	1.916
0.662	1.944	0.5014	0.4778	4.7	27.05	1.672
1.170	1.591	0.4128	0.3910	5.2	22.13	1.368
1.280	1.469	0.3824	0.3610	5.5	20.43	1.263
1.330	1.444	0.3675	0.3550	3.4	20.09	1.242

There is small variation of 1 to 12 % in theoretical and experimental values of total mass attenuation for different collimator sizes. It is observed that, the deviation in experimental and theoretical values of mass attenuation coefficient increases with collimator diameter (0.2 cm to 0.4 cm). Similar observations of mass attenuation coefficient are reported in the literature [14].

3.4 Total photon interaction cross-section

The values of mass attenuation coefficient were used to calculate the total photon interaction cross-section (σ_{tot}) for the prepared $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ composite

material. Following relation was used to calculate the total photon interaction cross-section:

$$\sigma_{\text{tot}} = \frac{\mu_m \times A \times 10^{24}}{N_A} \text{ (barn/atom)} \quad 6$$

where, μ_m - mass absorption coefficient

A- Atomic weight of sample

N_A - Avogadro's number

The values of total photon interaction cross-section for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ composite spinel ferrite with varying collimator diameter are given in tables 1, 2, 3, and the variation of total photon interaction versus

photon energy for collimator diameter 0.2 cm to 0.4 cm is shown in Tables. It is evident that as photon energy increases, the total photon interaction cross-section decreases.

3.5 Total electronic cross-section

The total electronic cross-section for $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ composite spinel ferrite was calculated by using the following relation [16]:

$$\sigma_{ele} = \frac{1}{N_A} \sum \frac{f_i A_i \times \mu}{Z_i \times \rho} \quad 7$$

where, f_i – denotes the fractional abundance of i^{th} element with respect to number of atoms such that, $f_1 + f_2 + f_3 + \dots + f_i$

Z_i – atomic number of i^{th} element.

The values of atomic mass of $\text{Ni}_{0.3}\text{Zn}_{0.5}\text{Cu}_{0.2}\text{Fe}_2\text{O}_4$ composite spinel ferrite was used to calculate the total electronic cross-section (σ_{ele}) and are listed in tables 1, 2, and 3 for varying diameter of collimator.

CONCLUSION

This study successfully synthesized $\text{Ni}_{0.3}\text{Cu}_{0.5}\text{Zn}_{0.2}\text{Fe}_2\text{O}_4$ ferrites using the solid-state reaction method. The evaluation of their radiation shielding properties reveals that these ferrites are effective attenuators of gamma radiation within the 0.360–1.33 MeV range. The close agreement between experimental findings and XCOM theoretical data for collimator diameter 0.3 confirms the validity of the synthesis process. Given their eco-friendly nature and performance, Ni-Cu-Zn ferrites represent a viable, sustainable alternative to lead-based shielding in specific industrial and medical applications where toxicity is a concern.

Ni-Cu-Zn ferrites demonstrate promising photon absorption; particularly $\text{Ni}_{0.3}\text{Cu}_{0.5}\text{Zn}_{0.2}\text{Fe}_2\text{O}_4$ their tunable composition and structural stability make them viable for lightweight shielding in medical and aerospace applications. Future work will explore neutron shielding and mechanical durability.

REFERENCES

1. Kumar, R., & Sharma, S. (2022). Comparative analysis of lead-free shielding materials. *Materials Science in Semiconductor Processing*.
2. D.R. White, L. H. J. Peaple, and T. J. Crosby, *Rad. Res.*84, (1980) 239.
3. E storm and H I Israel, *At.Data Tables A7* (1970) 565
4. V Manjunathaguru and T K Umesh, *Pramana J.Phys.* 72(2009)375.
5. Srivastava, A., et al. (2020). Synthesis and magnetic properties of Ni-Cu-Zn ferrites. *Journal of Magnetism and Magnetic Materials*.
6. S. Modak. M. Ammar, F. Mazaleyrat, S. Das, P.K. Chakrabarti *J. Alloys compds*, 473(2009) 15.
7. M.T. Teli and L.M. Chaudhari, *Rad. Phys.Chem.* 47(1996)531.
8. G. A. Battiston, S. Degetto, R. Gerbasi, G. Sbrignadello and L.Tosotti, *Nucl. Inst.Meth. Phys. B* 28 (1987) 438.
9. R. H. Millar and J. R. Greening, *J. Phys. B*7(1974) 2332.
10. K. Singh, R. Kerur, Vandana, V. Kumar, *Rad. Phys chem.*47(1996) 535.
11. J.H. Hubell, S.M. Seltzer, *NISTIR* 5632 (1995).
12. Singh, V. P., et al. (2018). Assessment of gamma-ray shielding properties of various ferrites. *Radiation Physics and Chemistry*.
13. Berger, M. J., & Hubbell, J. H. (1987). *XCOM: Photon Cross Sections Database*. National Institute of Standards and Technology.
14. I. Han, L.Demir, *Nucle. Instru. And Method in phys. Rese. B* 267 (2009) 3.
15. Orhan Icellia, Saliah Erzeneoglu, *J.of Quantitative Soectro. & Radiative Transf.* 85 (2004) 115-124.
16. Wang Da-Chun, Luo ping-An and yang Hua, *Nucl. Instrum. Methods B*95 (1995) 161.

HOW TO CITE: V. K. Barote*, R. R. Magar, Gamma-Ray Shielding Effectiveness Of Ni-Cu-Zn Ferrite Ceramics: An Alternative To Conventional Shielding Materials, *Int. J. Sci. R. Tech.*, 2026, 3 (10), 328-333. <https://doi.org/10.5281/zenodo.23162366>