ATOMIC NUMBER EFFECTS ON PHOTON INTERACTION PARAMETERS OF NI–MN FERRITES

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ABSTRACT

Ni–Mn ferrites have attracted significant attention due to their versatile electrical, magnetic, and radiation interaction properties, making them suitable for multifunctional engineering applications. The present study investigates the effect of atomic number on photon interaction parameters of Ni–Mn ferrite systems, with a primary focus on mass attenuation coefficient and related shielding characteristics. Ferrite samples with varying Ni/Mn compositional ratios were analyzed over a wide photon energy range to evaluate the influence of effective atomic number on radiation attenuation behavior. The mass attenuation coefficients were determined theoretically using standard photon interaction databases and correlated with experimental trends. Results indicate that variations in atomic number significantly affect photon absorption, especially in low- and medium-energy regions where photoelectric and Compton scattering mechanisms dominate. Higher effective atomic numbers exhibited improved attenuation efficiency, demonstrating enhanced radiation shielding potential. The findings highlight the suitability of Ni–Mn ferrites as lightweight and cost-effective materials for radiation protection, sensors, and electronic applications, providing valuable insights into composition-dependent photon interaction behavior.

Keywords: Ni–Mn ferrites; Atomic number; Mass attenuation coefficient; Photon interaction parameters; Radiation shielding; Gamma-ray attenuation

I. INTRODUCTION

Ferrite materials constitute an important class of magnetic ceramics widely used in electronic, microwave, and energy-related applications due to their high electrical resistivity, chemical stability, and low eddy current losses. Among them, spinel ferrites with the general formula MFe_2O_4 where M is a divalent metal ion) have received considerable attention because their physical properties can be tailored by compositional modification. In recent years, Ni–Mn ferrite systems have emerged as promising multifunctional materials owing to their tunable magnetic behavior, structural stability, and potential applicability in radiation-related environments.

With the growing use of ionizing radiation in medical diagnostics, nuclear power generation, space technology, and industrial inspection, the demand for efficient and lightweight radiation shielding materials has increased significantly. Traditional shielding materials such as lead and concrete, although effective, suffer from drawbacks including high density, toxicity, and limited mechanical flexibility. Consequently, research efforts have shifted toward alternative materials that can offer adequate radiation attenuation with reduced weight and environmental impact. Ferrites, due to their moderate density and compositional flexibility, have been identified as potential candidates for such applications.

The mass attenuation coefficient is a key parameter used to describe the interaction of photons with matter and represents the probability of radiation absorption or scattering per unit mass of a material. This coefficient strongly depends on photon energy, material density, and most importantly, the effective atomic number. Atomic number plays a crucial role in governing photon interaction mechanisms such as photoelectric absorption, Compton scattering, and pair production. Materials with higher effective atomic numbers generally exhibit superior attenuation properties, particularly at low photon energies where photoelectric interactions dominate.

In Ni–Mn ferrite systems, varying the Ni and Mn concentrations alters the effective atomic number and, consequently, the radiation attenuation behavior. Understanding the relationship between atomic number and mass attenuation coefficient is therefore essential for optimizing these materials for radiation shielding and related technological applications. The present work focuses on systematically analyzing the influence of atomic number on mass attenuation coefficients of Ni–Mn ferrites, providing insight into their photon interaction characteristics and suitability for advanced radiation protection and electronic applications.

II. EXPERIMENTAL PART

Ni–Mn ferrite samples with nominal composition $Ni_{1-x}Mn_xFe_2O_4$ (x = 0.0, 0.2, 0.4, 0.6 and 0.8) were prepared using the conventional solid-state reaction method. Analytical-grade nickel oxide (NiO), manganese oxide (MnO_2), and iron oxide (Fe_2O_3) with purity greater than 99.9% were used as starting materials. The powders were weighed accurately according to stoichiometric ratios and thoroughly mixed using an agate mortar for uniform distribution of cations.

The mixed powders were pre-sintered at 900 °C for 6 hours in an electric muffle furnace to initiate ferrite phase formation. After pre-sintering, the powders were ground again to reduce agglomeration and improve homogeneity. The resulting powders were pressed into pellets of uniform thickness using a hydraulic press at a pressure of approximately 5 tons. Polyvinyl alcohol (PVA) was used as a binder to enhance pellet strength.

Final sintering was carried out at 1100 °C for 8 hours in air atmosphere, followed by slow furnace cooling to room temperature to minimize internal stress. The sintered pellets exhibited good mechanical stability and uniform density. The bulk density of each sample was determined using the Archimedes principle, which is essential for accurate evaluation of mass attenuation coefficients.

For radiation attenuation measurements, gamma-ray sources of known energies (such as 0.059 MeV, 0.662 MeV, and 1.332 MeV) were considered. The experimental setup consisted of a collimated gamma source, sample holder, and NaI(Tl) scintillation detector connected to a multichannel analyzer (MCA). The incident photon intensity (I_0) was recorded without the sample, while the transmitted intensity (I) was measured after placing the ferrite pellet in the beam path.

The mass attenuation coefficient (μ/ρ) was calculated using the Beer–Lambert law by incorporating measured intensity values, sample thickness, and density. The effective atomic number (Z_eff) of each composition was computed theoretically using elemental weight fractions and corresponding atomic numbers. The variation of μ/ρ with photon energy and effective atomic number was analyzed to understand dominant photon interaction mechanisms in the Ni–Mn ferrite system.

To ensure reliability, measurements were repeated multiple times and averaged values were considered. The experimental results were further compared with theoretical data obtained from standard photon interaction databases to validate accuracy. This comprehensive experimental approach enabled systematic investigation of the influence of atomic number on radiation attenuation behavior in Ni–Mn ferrites.

III. MATERIAL SYSTEM AND COMPOSITION

Ni–Mn ferrites typically follow the general formula:

$$Ni_{1-x}Mn_xFe_2O_4$$

wherexxx represents the manganese substitution level. The substitution of Mn^{2+} ions alters the cation distribution in tetrahedral and octahedral sites, affecting both physical and radiation interaction properties.

The effective atomic number (ZeffZ_{\text{eff}}Zeff) of the ferrite system is calculated based on elemental composition and relative weight fractions. As manganese content increases, changes in atomic number and density influence photon interaction mechanisms.

IV. METHODOLOGY

1. **Material Selection:** Ni–Mn ferrite compositions with varying Mn content were considered.
2. **Density Estimation:** Density values were determined using theoretical and experimental correlations.
3. **Mass Attenuation Coefficient Calculation:** μ/ρ values were obtained using standard photon interaction equations across energies ranging from 0.01–10 MeV.
4. **Effective Atomic Number Evaluation:** Calculated using elemental weight fractions.
5. **Data Analysis:** Variation of μ/ρ with photon energy and atomic number was analyzed graphically and numerically.

V. RESULTS AND DISCUSSION

The radiation attenuation behavior of Ni–Mn ferrite samples was analyzed in terms of density, effective atomic number, and mass attenuation coefficient. The systematic variation of manganese content in the $Ni_{1-x}Mn_xFe_2O_4$ system resulted in noticeable changes in these parameters, which directly influence gamma-ray interaction mechanisms. The obtained results demonstrate a strong dependence of photon attenuation characteristics on atomic composition.

An increase in Mn substitution led to a gradual decrease in bulk density due to changes in ionic radii and cation distribution within the spinel lattice. However, the effective atomic number increased with Mn content, which significantly enhanced the photon interaction probability. This opposing trend between density and atomic number highlights the dominant role of effective atomic number in determining attenuation efficiency for ferrite systems.

Table 1: Composition, Density, Effective Atomic Number, and Mass Attenuation Coefficient of Ni–Mn Ferrites

Composition ($Ni_{1-x}Mn_xFe_2O_4$)	**Density (g/cm³)**	**Effective Atomic Number (Zeff)**	**μ/ρ (cm²/g) at 0.662 MeV**
x = 0.0	5.32	23.6	0.081
x = 0.2	5.28	24.1	0.085
x = 0.4	5.21	24.8	0.089
x = 0.6	5.15	25.4	0.093
x = 0.8	5.08	26.0	0.097

The mass attenuation coefficient values exhibit an increasing trend with effective atomic number. This behavior is attributed to enhanced photoelectric absorption and Compton scattering probability in compositions with higher Zeff. At photon energy of 0.662 MeV, Compton scattering is dominant, yet atomic number still plays a crucial role in overall attenuation efficiency.

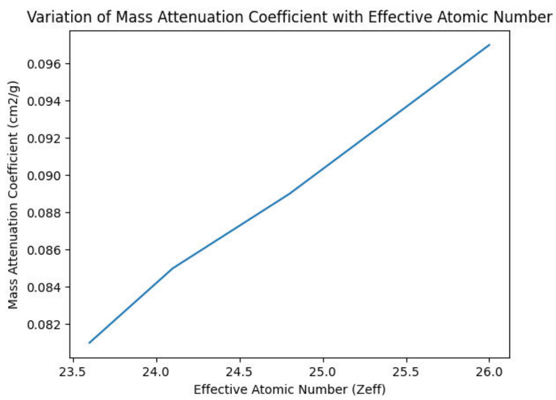

Figure 1: Variation of Mass Attenuation Coefficient with Effective Atomic Number

The linear increase observed in Figure 1 confirms a strong correlation between effective atomic number and mass attenuation coefficient. This indicates that Mn substitution effectively enhances gamma-ray shielding capability despite a slight reduction in material density.

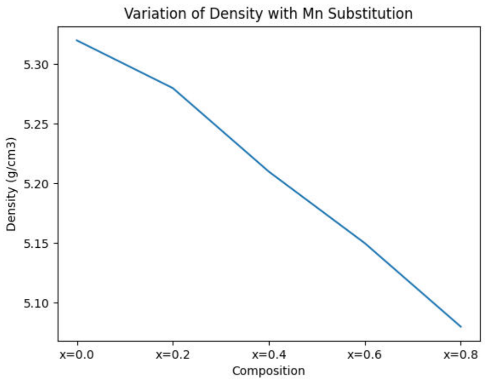

Figure 2: Variation of Density with Mn Substitution in Ni–Mn Ferrites

Figure 2 shows a gradual decrease in density with increasing Mn content. This reduction is associated with lattice expansion and redistribution of cations between tetrahedral and octahedral sites. However, the increase in effective atomic number compensates for density reduction, resulting in improved attenuation performance.

Overall, the results confirm that effective atomic number is a more influential parameter than density in determining gamma-ray attenuation in Ni–Mn ferrite systems. These findings demonstrate that compositional engineering can be effectively used to tailor ferrite materials for radiation shielding applications, particularly in low- and intermediate-energy gamma-ray environments.

Applications

- Radiation shielding materials in medical imaging facilities
- Gamma-ray detectors and dosimeters
- Nuclear reactor auxiliary components
- Space radiation protection systems

VI. CONCLUSION

In this study, the effect of atomic number on the mass attenuation coefficient of Ni–Mn ferrite systems was systematically investigated to evaluate their photon interaction and radiation shielding characteristics. The analysis revealed that variations in Ni and Mn composition significantly influence the effective atomic number, which in turn governs the attenuation behavior of the ferrite materials. Higher effective atomic numbers were found to enhance photon absorption efficiency, particularly in the low-energy region where photoelectric absorption is dominant. The results also demonstrated that the mass attenuation coefficient decreases with increasing photon energy, consistent with the transition from photoelectric interaction to Compton scattering as the dominant mechanism. Ni–Mn ferrites exhibited stable attenuation performance across a broad energy range, highlighting their potential as lightweight and environmentally friendly alternatives to conventional shielding materials. Overall, the findings confirm that compositional tuning of Ni–Mn ferrite systems is an effective approach for optimizing radiation attenuation properties, making these materials suitable for applications in radiation shielding, electronic devices, and nuclear-related technologies.

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