



Gamma-Ray Attenuation Characteristics and Shielding Performance of BaTiO₃ Nanomaterial: An Experimental and Theoretical Investigation

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Abstract

The increasing use of ionizing radiation in medicine, industry, and nuclear technology has intensified the search for efficient radiation shielding materials. Among the promising candidates, barium titanate (BaTiO₃) nanomaterials have attracted considerable attention owing to their excellent dielectric, ferroelectric, and structural properties. In this study, the gamma-ray attenuation and shielding performance of BaTiO₃ nanomaterial were investigated experimentally using a NaI(Tl) detector with radioisotope sources covering the energy range of 122–1330 keV and theoretically using the Win-XCOM database. The shielding performance was evaluated by determining the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), total atomic cross section (σ_t), electronic cross section (σ_e), molar extinction coefficient (ϵ), effective atomic number (Z_{eff}), effective electron density (N_{eff}), transmission factor (TF), and radiation protection efficiency (RPE). The experimental results showed excellent agreement with the theoretical predictions, with deviations not exceeding 6%, confirming the reliability and accuracy of the measurements. The values of MAC, LAC, σ_t , σ_e , and ϵ decreased with increasing photon energy before approaching nearly constant values at higher energies, whereas Z_{eff} and N_{eff} remained almost independent of photon energy throughout the investigated range. BaTiO₃ exhibited its highest attenuation capability at 122 keV, with attenuation gradually decreasing as photon energy increased to 1330 keV. The radiation protection efficiency reached approximately 100% at 122 keV, indicating excellent shielding performance against low-energy gamma rays. These findings demonstrate that BaTiO₃ nanomaterial is a promising and effective candidate for gamma-ray shielding, particularly in low-energy radiation protection applications.

Keywords: Barium titanate, MFP, shielding, XCOM, gamma-ray, RPE.

المخلص: أدى التوسع المتزايد في استخدام الإشعاعات المؤينة في المجالات الطبية والصناعية والنووية إلى تكثيف الجهود الرامية إلى تطوير مواد فعالة للوقاية من الإشعاع. وتعد مادة تيتانات الباريوم (BaTiO₃) النانوية من المواد الواعدة في هذا المجال، نظراً لما تتمتع به من خصائص عازلية وكهرو ضغطية وبنائية متميزة. في هذه الدراسة، تم تقييم خصائص توهين أشعة جاما وكفاءة الحماية الإشعاعية لمادة تيتانات الباريوم النانوية عملياً باستخدام كاشف يوديد الصوديوم المنشط بالثاليوم NaI(Tl) ومصادر إشعاعية تغطي مدى طاقة يتراوح بين 122 و1330 كيلو إلكترون فولت، كما أجريت دراسة نظرية باستخدام قاعدة بيانات Win-XCOM. وقد تم تقييم أداء المادة من خلال حساب معامل التوهين الكتلي (MAC) ومعامل التوهين الخطي (LAC) والمقطع العرضي الذري الكلي (σ_t) والمقطع العرضي الإلكتروني (σ_e) ومعامل الانقراض المولي (ϵ) والعدد الذري الفعال (Z_{eff}) والكثافة الإلكترونية الفعالة (N_{eff}) ومعامل النفاذية (TF) وكفاءة الحماية الإشعاعية (RPE). أظهرت النتائج العملية توافقاً ممتازاً مع النتائج النظرية، حيث لم تتجاوز نسبة الانحراف 6%، مما يؤكد دقة وموثوقية القياسات. كما بينت النتائج أن قيم كل من معامل التوهين الكتلي، ومعامل التوهين الخطي، والمقطع العرضي الذري الكلي، والمقطع العرضي الإلكتروني، ومعامل الانقراض المولي تتخفص مع زيادة طاقة الفوتونات قبل أن تستقر تقريباً عند الطاقات المرتفعة، في حين ظل كل من العدد الذري الفعال والكثافة الإلكترونية الفعالة شبه ثابتين عبر مدى الطاقات المدروسة. وسجلت مادة تيتانات الباريوم أعلى قدرة على توهين أشعة جاما عند طاقة 122 كيلو إلكترون فولت، ثم انخفضت كفاءة التوهين تدريجياً مع زيادة الطاقة حتى 1330 كيلو إلكترون فولت. كما بلغت كفاءة الحماية الإشعاعية نحو 100% عند طاقة 122 كيلو إلكترون فولت، مما يدل على قدرة المادة العالية على حجب أشعة جاما منخفضة الطاقة. وتؤكد هذه النتائج أن مادة تيتانات الباريوم النانوية تعد مرشحاً واعداً وفعالاً لتطبيقات الحماية من أشعة جاما، ولا سيما في تطبيقات الوقاية من الإشعاعات منخفضة الطاقة.

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1. Introduction

The application of gamma (γ) radiation has expanded significantly in medicine, industry, agriculture, nuclear technology, radiation dosimetry, and energy production. Despite its wide range of beneficial applications, prolonged exposure to γ -rays poses serious risks to human health and electronic systems due to their high penetration capability and ionizing nature [1, 2]. Gamma radiation is a form of electromagnetic radiation that is commonly emitted by radionuclide sources during radioactive decay. The interaction of γ -rays with matter occurs primarily through three mechanisms: the photoelectric effect, Compton scattering, and pair production. Owing to their high penetrating power, γ -rays can pass through most materials [3]. They can also penetrate biological tissues, including the skin, teeth, and bones, causing cellular damage and genetic mutations that may ultimately lead to cancer [4]. Consequently, investigating the γ -ray attenuation characteristics of different materials remains an important area of research for the development of effective radiation shielding and protection materials.

The reduction in γ -ray intensity as it passes through a shielding material results from the combined effects of attenuation and scattering. Gamma radiation poses significant risks to biological tissues and organs; therefore, the use of appropriate shielding materials is essential to minimize radiation exposure and ensure safety. The mass attenuation coefficient is an important parameter for calculating the gamma-ray absorbed dose and absorption build-up factors, highlighting its significance in the field of radiation dosimetry [5]. Nanotechnology is one of the fastest-growing scientific disciplines, with applications spanning numerous fields, including electronics. Nanoelectronics involve the use of nanomaterials in electronic devices with characteristic dimensions ranging from 1 to 100 nm [6]. Electronic devices are continuously exposed to various forms of radiation during their operation. Moreover, the ongoing trend toward device miniaturization and the increasing integration density of electronic components may further increase their susceptibility to radiation-induced damage [7].

Barium titanate (BaTiO_3) is a well-known ferroelectric inorganic compound with a wide range of technological applications. It has attracted considerable attention because of its excellent chemical stability, low dielectric loss, ferroelectric and piezoelectric properties, high electrical resistivity, and environmentally friendly nature [8, 9]. These characteristics make BaTiO_3 suitable for numerous applications, particularly in the medical, electronic, and sensor industries. In medical applications, a thorough understanding of radiation interactions with materials is essential for evaluating radiation absorption and attenuation processes. Consequently, several studies have investigated the radiation shielding performance of BaTiO_3 [10, 11]. The reported findings generally demonstrate that BaTiO_3 is a promising material for radiation shielding applications. Fundamental shielding parameters, including the linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), and mean free path (MFP), are commonly used to characterize the interaction of gamma radiation with shielding materials. In addition, previous studies have reported the γ -ray attenuation characteristics of various ceramics, polymer composites, glasses, and granites [12–15].

The shielding performance of a material is determined by its ability to attenuate or absorb incident radiation. Materials with higher mass attenuation coefficient generally exhibit superior radiation shielding performance. The primary objective of the present study is to evaluate the gamma-ray shielding performance of BaTiO_3 nanomaterial by determining several key shielding parameters, including the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), mean free path (MFP), effective atomic number (Z_{eff}), effective electron density (N_{eff}), transmission factor (TF), and radiation protection efficiency (RPE). To achieve this objective, the shielding properties of BaTiO_3 nanomaterial were investigated experimentally using a sodium iodide [NaI(Tl)] detector system and theoretically using the NIST-XCOM database. The experimentally determined MAC values

were used to calculate the total atomic cross-section (σ_t), electronic cross-section (σ_e), molar extinction coefficient (ϵ), Z_{eff} , and N_{eff} , whereas the LAC values were used to determine the HVL, MFP, TF, and RPE. The findings of this study provide valuable data for researchers investigating gamma-ray shielding materials and contribute to the development of effective radiation protection technologies.

2. Experimental and Theoretical Approaches

The gamma-ray attenuation measurements were performed using a well-designed gamma-ray transmission setup incorporating a NaI(Tl) gamma spectrometry system coupled to an 8K multichannel analyzer (MCA), as shown in Figure 1. The system provides an energy resolution of approximately 8% at 662 keV for the γ -rays emitted by the ^{137}Cs source. High quality and high-purity BaTiO_3 nanomaterial (99.9%, Sigma-Aldrich, India) was used in this study as shielding material. The weight of the BaTiO_3 sample was measured using a digital electronic balance, and each measurement was repeated three times to ensure the reliability of the recorded values. The sample thickness was determined using a digital micrometer with an accuracy of ± 0.01 mm. The measured thickness ranged from 0.5 to 3.0 cm, and these values were subsequently used in the attenuation coefficient calculations.

The attenuation characteristics of the BaTiO_3 nanomaterial were investigated over the photon energy range of 122–1330 keV using standard point gamma-ray sources. Namely the BaTiO_3 nanomaterial sample was irradiated using: ^{57}Co (122 keV), ^{133}Ba (356 keV), ^{137}Cs (662 keV), ^{54}Mn (840 keV), ^{22}Na (511 and 1275 keV), and ^{60}Co (1170 and 1330 keV). To minimize background radiation and scattered photons, both the detector and the experimental setup were enclosed within a 5-cm-thick lead (Pb) shield. This shielding effectively reduced the contribution of scattered and background radiation originating from external sources and the surrounding environment.

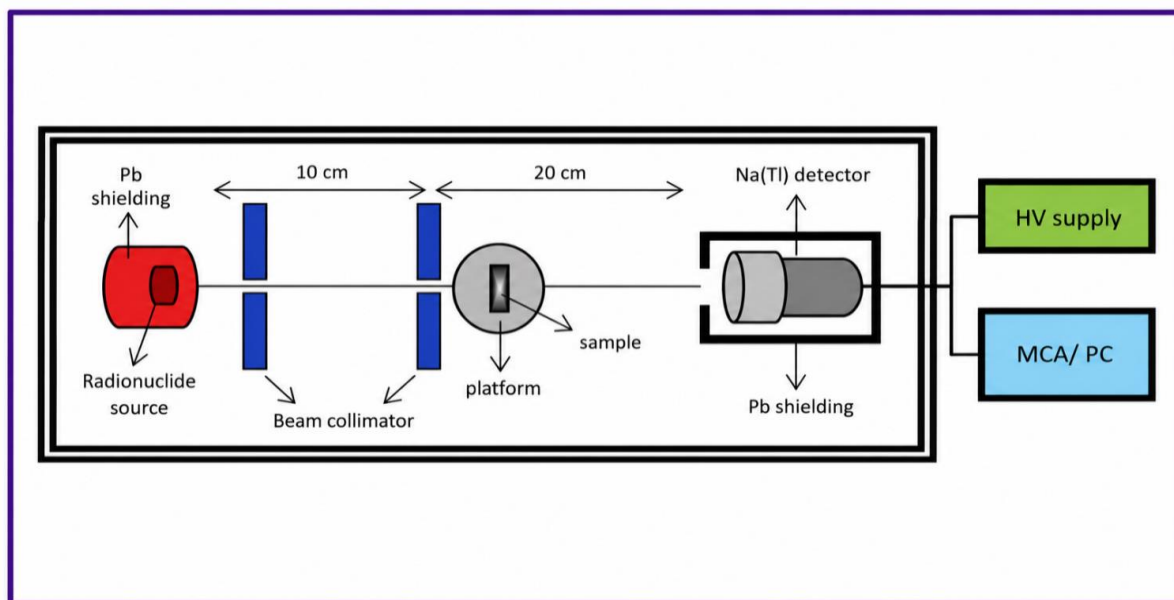


Figure 1. Gamma ray geometry setup of the attenuation measurements used in this study.

A BaTiO_3 nanomaterial sample with thicknesses ranging from 0.5 to 3.0 cm was positioned between the radionuclide source and the detector to measure the intensity of the transmitted photons. The distance between the γ -ray source and the detector was maintained between 30–50 cm throughout the measurements. The detector output signals were amplified and analyzed using an 8K multichannel analyzer (MCA). An empty plastic container, identical to that used for the sample, served as the sample holder during the measurements. Preliminary measurements confirmed that the attenuation of the gamma-ray beam by the empty container was negligible and was therefore ignored in the calculations. The relationship between the

gamma-ray energies and the recorded counts was established by identifying the full-energy photopeaks using the full width at half maximum (FWHM) and the corresponding channel numbers of the 8K MCA. The sample thicknesses were carefully selected to provide reliable attenuation measurements over the investigated energy range. All experiments were conducted under temperature-controlled laboratory conditions to minimize any potential drift in the gamma-ray peak positions during data acquisition.

The attenuation coefficients were determined experimentally by measuring the count rates obtained from the gamma-ray source without the sample and then with the BaTiO₃ sample placed between the source and detector. Photon spectra were collected for a fixed counting time of 180 s for each measurement. Each measurement was repeated three times to reduce statistical uncertainty and improve reproducibility. The recorded counts, with and without the BaTiO₃ sample, were subsequently used to calculate the relevant radiation shielding parameters of the investigated material. The main sources of uncertainty in the measured mass attenuation coefficient were associated with counting statistics, which contributed less than 6% to the total uncertainty of the investigated BaTiO₃ sample. These uncertainties may arise from several factors, including sample impurities, variations in the measured transmitted and incident photon intensities, mass measurement errors, sample non-uniformity, thickness variations, and background radiation effects.

Table 1. The parameters of gamma-ray attenuation and shielding features, along with associated equations used in the present study.

No.	Radiation shielding parameters	Equations	Descriptions
1	Linear attenuation coefficient	$LAC = \ln\left(\frac{I_0}{I}\right) \frac{1}{t}$	I_0 is the original γ intensity (absent the sample), I is the transmitted intensity (present the BaTiO ₃ sample), and t is the BaTiO ₃ thickness.
2	Mass attenuation coefficient	$MAC = \frac{LAC}{\rho}$	LAC is the linear absorption coefficient, and ρ represents the BaTiO ₃ density.
3	Relative deviation	$RD = \left[\frac{\text{Theo.} - \text{Exp.}}{\text{Theo.}} \right] * 100\%$	Exp. is the experimental values and Theo. is the theoretical values obtained from XCOM.
4	Total atomic cross-section	$\sigma_t = \frac{1}{N_A} \sum f_i A_i MAC$	N_A is Avogadro's constant, f_i abundance of the element, and A_i is the atomic weight of the BaTiO ₃ .
5	Electronic cross-section	$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} MAC$	Z_i is the atomic number of elements in the BaTiO ₃ sample.
6	Molar extinction coefficient	$\epsilon = 0.4343 N_A \sigma_t$	σ_t is the total atomic cross section.
7	Effective atomic number	$Z_{eff} = \frac{\sigma_t}{\sigma_e}$	σ_t is the total atomic cross section, and σ_e is the electronic cross section.
8	Effective electronic densities	$N_{eff} = \frac{Z_{eff} N_A}{M} \sum n_i$	M is the molar mass of the BaTiO ₃ sample.
9	Half-value layer	$HVL = \frac{\ln 2}{LAC}$	LAC is the linear absorption coefficient.
10	Mean free path	$MFP = \frac{1}{LAC}$	LAC is the linear attenuation coefficient.
11	Transmission factor	$TF\% = (e^{-LAC.t}) * 100$	t is the BaTiO ₃ thickness.
12	Radiation protection efficiency	$RPE\% = (100 - TF)$	TF is the transmission factor.

For theoretical analysis, the attenuation coefficients of BaTiO₃ were calculated using the Win-XCOM database over the same energy range investigated experimentally. The theoretical values of the mass attenuation coefficient (MAC) were employed to calculate the total atomic cross section (σ_t), electronic cross section (σ_e), molar extinction coefficient (ϵ), effective atomic number (Z_{eff}), and effective electron density (N_{eff}). Similarly, the linear attenuation coefficient (LAC) was used to determine the half-value layer (HVL), mean free path (MFP), transmission factor (TF), and radiation protection efficiency (RPE). The mathematical expressions used to calculate all shielding parameters are summarized in Table 1 [16–19].

3. Results and Discussions

The chemical formula, density, atomic number, and molecular weight of the investigated sample are presented in Table 2. The fundamental experimental and theoretical parameters related to radiation interactions, including the mass attenuation coefficient, linear attenuation coefficient, total atomic cross section, electronic cross section, effective atomic number, effective electron density, transmission factor, and radiation protection efficiency of BaTiO₃ nanomaterial, were determined experimentally using a NaI(Tl) sodium iodide detector system and theoretically using the Win-XCOM software program.

Table 2. Some properties of the investigated barium titanate BaTiO₃ nanomaterial.

Sample name	Chemical formula	Density g/cm ³	Mean atomic number, $\bar{Z}$	Molecular weight (M) (g/mol)	Effective atomic number (A_{eff})
Barium Titanate	BaTiO ₃	6.02	20.4	233.191	46.6382

3.1 Mass and Linear Attenuation Coefficients

The experimental and theoretical values of the mass attenuation coefficient (MAC) and linear attenuation coefficient (LAC) at eight selected gamma-ray energies are presented in Table 3. The selected energies were chosen to represent a broad range of the calculated values. As shown in Table 3, both experimental and theoretical MAC values decrease with increasing photon energy at the low-and intermediate-energy, followed by a gradual stabilization at higher energy levels. The comparison between experimental and theoretical results indicates that all deviations are $\leq 6\%$. The maximum deviation in the MAC values was 6%, observed at 122 and 1330 keV, whereas the minimum deviation was 1.74% at 511 keV. The close agreement between the experimental and theoretical MAC values across the entire investigated energy range confirms the reliability of the experimental measurements and demonstrates the suitability of BaTiO₃ nanomaterial for radiation shielding applications.

The variation of the MAC values of the BaTiO₃ nanomaterial sample as a function of photon energy is illustrated in Figure 2. The MAC exhibits a general decreasing trend with increasing energy, except in the higher energy region where the variation becomes less pronounced. Specifically, the MAC decreases from 0.7934 cm²/g at 122 keV to 0.0474 cm²/g at 1330 keV. This behavior can be attributed to the increased penetration capability of high-energy photons, which reduces the probability of photon absorption within the material and consequently leads to lower MAC values. The results indicate that the MAC strongly depends on the incident photon energy, as well as the chemical composition and physical properties of the investigated sample. Therefore, BaTiO₃ exhibits favorable MAC values over the investigated energy range, which can be associated with its relatively high molecular weight (233.191 g/mol), indicating its potential as an effective radiation shielding material. The significant variation in MAC values with increasing photon energy suggests that BaTiO₃ nanomaterial has enhanced photon attenuation capability compared with its bulk counterpart.

Figure 3 shows that, the LAC values exhibit an exponential decrease with increasing photon energy from 122 to 662 keV, followed by a slight reduction at energies above 662 keV. This behavior can be explained based on the fundamental principles of photon-matter interactions.

The rapid decrease in LAC within the low-energy region is mainly attributed to the dominance of the photoelectric effect, whereas the relatively gradual variation at higher energies is associated with the contribution of Compton scattering [20]. The highest LAC value was observed at 122 keV, reaching 4.7763 cm^{-1} , while the lowest value was recorded at 1330 keV, with a value of 0.2853 cm^{-1} .

Table 3. The experimental and theoretical values of mass and linear attenuation coefficients (MAC, LAC) of the investigated BaTiO₃ nanomaterial at energy 122-1330 keV.

Radioactive source	Energy keV	MAC (cm^2/g)		RD%	LAC (cm^{-1})		RD%
		Exp.	Theo. (XCOM)		Exp.	Theo. (XCOM)	
Co-57	122	0.7934	0.8439	6	4.7763	5.0803	6
Ba-133	356	0.1197	0.1269	5.67	0.7206	0.7639	5.67
Na-22	511	0.0901	0.0917	1.74	0.5424	0.5520	1.74
Cs-137	662	0.0750	0.0764	1.83	0.4515	0.4599	1.83
Mn-54	840	0.0635	0.0658	3.49	0.3823	0.3961	3.48
Co-60	1170	0.0526	0.0542	2.95	0.3167	0.3263	2.94
Na-22	1275	0.0502	0.0518	3.08	0.3022	0.3118	3.08
Co-60	1330	0.0474	0.0506	6.32	0.2853	0.3046	6.34

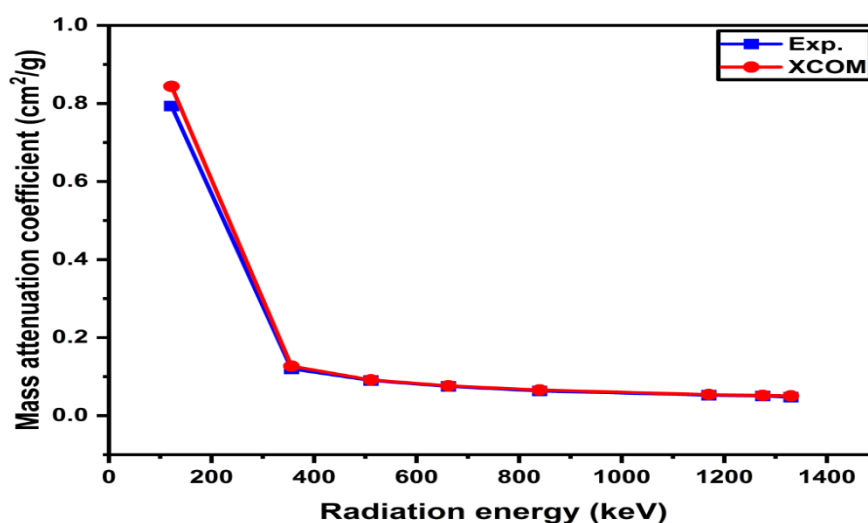


Figure 2. Experimental and theoretical variations of MAC against radiation energies for the BaTiO₃ nanomaterial.

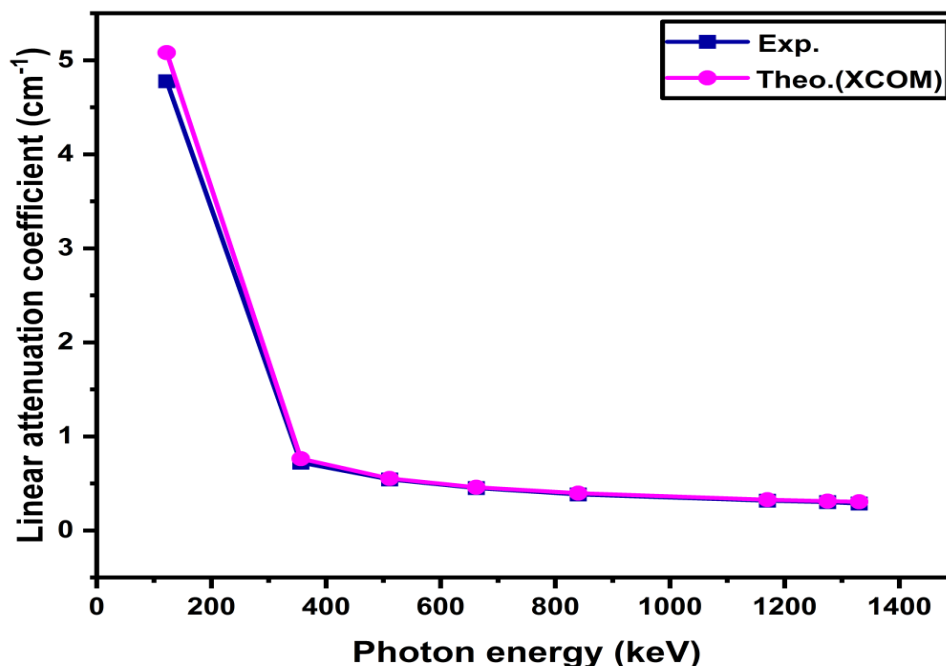


Figure 3. The experimental and theoretical variations of LAC as function of photon energies for the BaTiO₃ sample.

3.2 Total Atomic Cross Section, Electronic Cross Section, and Molar Extinction Coefficient

Using the measured and theoretical MAC values, the total atomic cross section (σ_t), electronic cross section (σ_e), and molar extinction coefficient (ϵ) of the BaTiO₃ sample were calculated and are presented in Table 4. The experimental values of σ_t , σ_e , and ϵ show good agreement with the theoretical values obtained from the XCOM database. Figures 4 and 5 illustrate the variations of σ_t and σ_e as a function of photon energy. Both parameters exhibit a decreasing trend with increasing photon energy, following a behavior similar to that observed for the mass attenuation coefficient (MAC).

Table 4. The experimental and theoretical values of total atomic cross section σ_t , electronic cross section σ_e and molar extinction coefficient ϵ of the BaTiO₃ sample at energy 122-1330 keV.

Energy keV	σ_t (barn/atom)		RD%	σ_e (barn/atom)		RD%	ϵ (cm ² mol ⁻¹)		RD%
	Exp.	Theo. (XCOM)		Exp.	Theo. (XCOM)		Exp.	Theo. (XCOM)	
122	307.2227	326.7774	6	15.0599	16.0185	6	80.3387	85.4523	6
356	46.3506	49.1386	5.67	2.2721	2.4088	5.67	12.1207	12.8497	5.67
511	34.8888	35.5083	1.74	1.7102	1.7406	1.75	9.1234	9.2854	1.74
662	29.0417	29.5838	1.83	1.4236	1.4502	1.83	7.5944	7.7362	1.83
840	24.5887	25.4793	3.49	1.2053	1.2489	3.49	6.4299	6.6628	3.49
1170	20.3679	20.9875	2.95	0.9984	1.0288	2.95	5.3262	5.4882	2.95
1275	19.4386	20.0581	3.08	0.9529	0.9832	3.08	5.0832	5.2452	3.09
1330	18.3544	19.5935	6.32	0.8997	0.9605	6.33	4.7997	5.1237	6.32

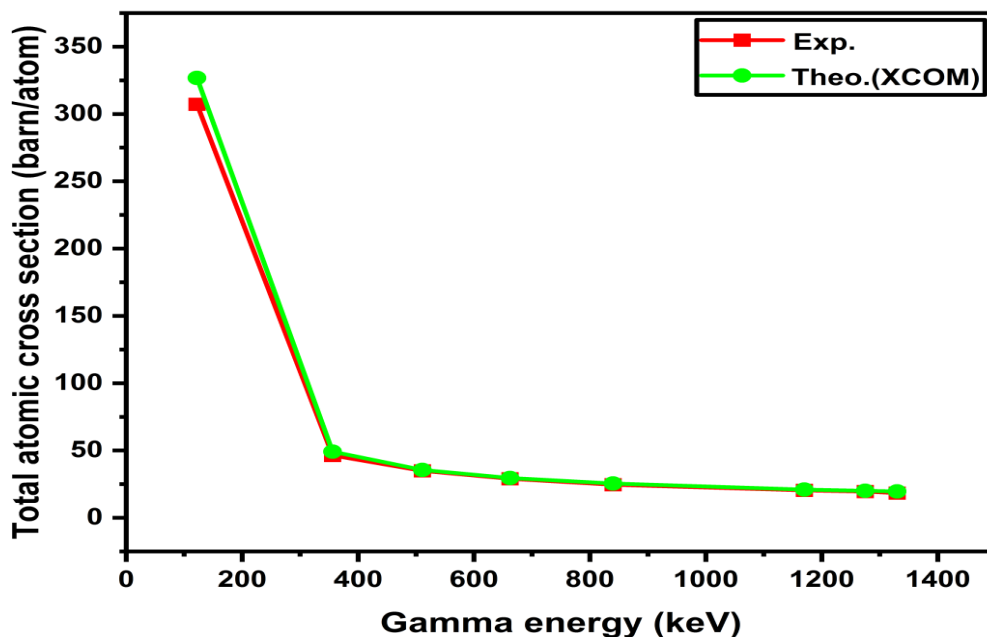


Figure 4. Variation of σ_t as function of the incident γ -photon energies.

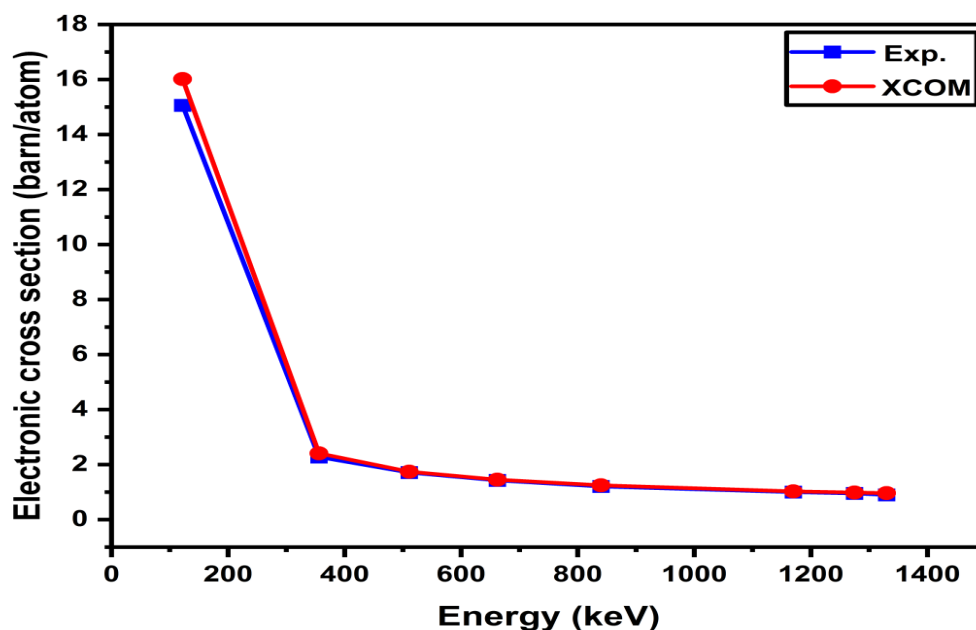


Figure 5. Variation of σ_e as function of the incident γ -photon energies.

3.3 Effective Atomic Number and Effective Electron Density

Using the experimental and theoretical values of σ_t and σ_e , the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of BaTiO₃ nanomaterial were calculated and are presented in Table 5. The corresponding experimental and theoretical results are illustrated in Figures 6 and 7, respectively, demonstrating that Z_{eff} and N_{eff} remain nearly independent of photon energy over the investigated energy range. The relatively constant behavior of Z_{eff} as a function of γ -ray energy can be mainly attributed to the dominance of Compton (incoherent) scattering at the studied energy levels, which exhibits a linear dependence on the atomic number. A similar trend

was observed for N_{eff} . The effective atomic number depends strongly on the atomic numbers of the constituent elements forming the compound. The calculated Z_{eff} values for BaTiO_3 were found to be close to the average atomic number ($Z = 20.4$) of the material. Furthermore, N_{eff} is affected by both the effective atomic number and the number of interacting electrons within the investigated material.

Table 5. The values of effective atomic number (Z_{eff}) and effective electronic densities (N_{eff}) of the BaTiO_3 sample at energy 122-1330 keV.

Energy keV	Z_{eff}		RD%	$N_{\text{eff}} (10^{24} \text{ electrons/g})$		RD%
	Exp.	Theo. (XCOM)		Exp.	Theo. (XCOM)	
122	20.40005	20.40000	-0.0003	0.26341	0.26341	0
356	20.39989	20.39962	-0.0013	0.26341	0.26341	0
511	20.40042	20.40003	-0.0019	0.26342	0.26341	-0.0038
662	20.40018	20.39981	-0.0018	0.26341	0.26341	0
840	20.40048	20.40139	0.0045	0.26342	0.26343	0.0038
1170	20.40054	20.39998	-0.0027	0.26342	0.26341	-0.0038
1275	20.39941	20.40083	0.0069	0.26340	0.26342	0.0076
1330	20.40058	20.39927	-0.0064	0.26342	0.26340	-0.0076

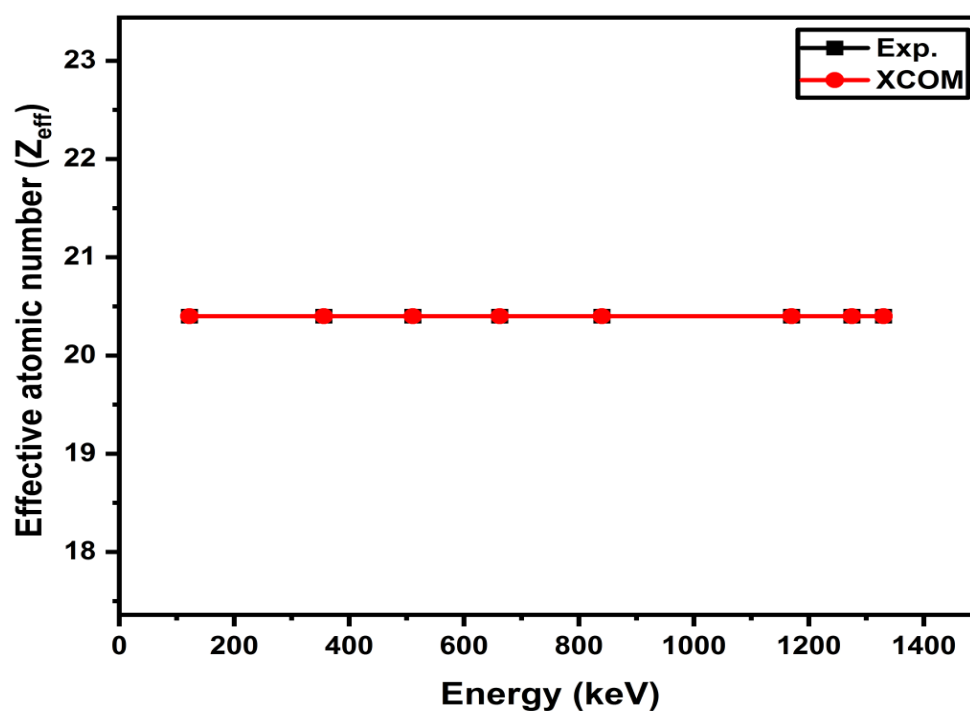


Figure 6. The effective atomic number of the BaTiO_3 versus incident radiation energies.

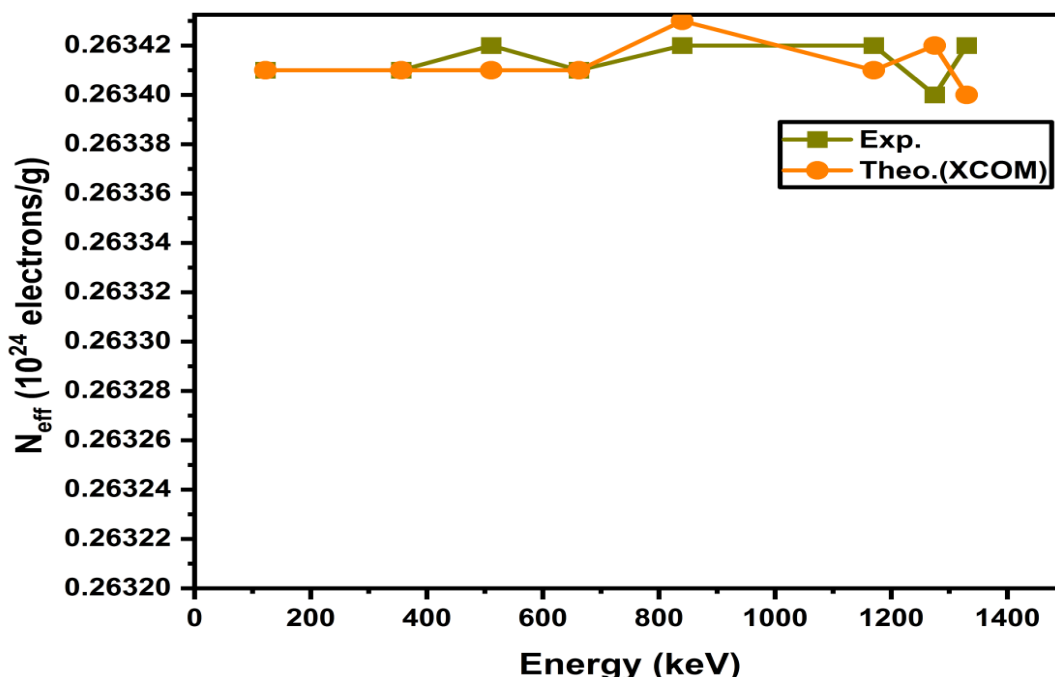


Figure 7. The effective electronic densities (N_{eff}) of the BaTiO₃ sample against energy.

3.4 Half-Value Layer and Mean Free Path

Table 6 presents the calculated values of the half-value layer (HVL), mean free path (MFP), transmission factor (TF%), and radiation protection efficiency (RPE%) for the BaTiO₃ nanomaterial sample. The HVL is defined as the thickness of an absorber required to reduce the intensity of incident radiation to 50% of its initial value [21]. Figure 8 illustrates the variation of HVL for BaTiO₃ nanomaterial as a function of incident gamma-ray energy. As shown in Figure 8, the HVL increases with increasing photon energy, indicating that a greater absorber thickness is required to attenuate the same fraction of high-energy photons. The HVL value increased significantly from 0.1451 cm at 122 keV to 2.4290 cm at 1330 keV. The experimental and theoretical HVL values exhibit good agreement across almost all investigated energy levels.

Table 6. Half-value layer (HVL), mean free path (MFP), transmission factor (TF%), and radiation protection efficiency (RPE%) of the BaTiO₃ nanomaterial.

Energy keV	HVL (cm)		MFP (cm)		TF%	RPE%
	Exp.	Theo. (XCOM)	Exp.	Theo. (XCOM)		
122	0.1451	0.1364	0.2094	0.1968	0.0001	99.9999
356	0.9617	0.9072	1.3877	1.3091	11.5118	88.4882
511	1.2777	1.2554	1.8437	1.8116	19.6479	80.3521
662	1.5349	1.5068	2.2148	2.1744	25.8076	74.1924
840	1.8127	1.7496	2.6157	2.5246	31.7619	68.2380
1170	2.1882	2.1238	3.1576	3.0647	38.6702	61.3298
1275	2.2932	2.2226	3.3091	3.2072	40.3895	59.6105
1330	2.4290	2.2751	3.5051	3.2829	42.4901	57.5099

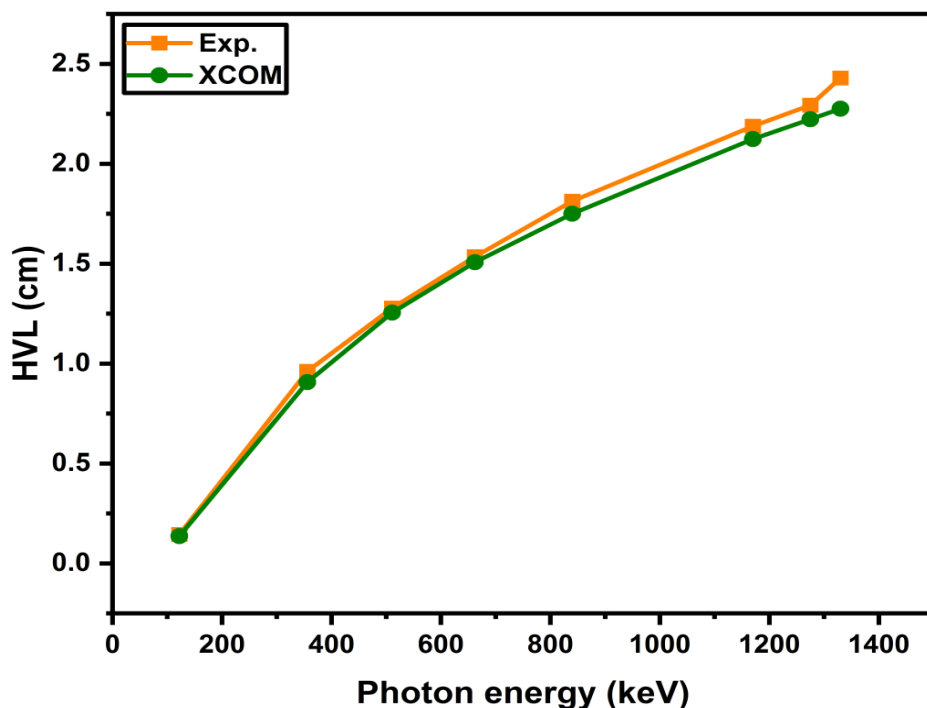


Figure 8. Dependence of the half-value layer of the BaTiO₃ sample on γ -photon energies.

The mean free path (MFP) values of the BaTiO₃ sample as a function of incident photon energy are presented in Figure 9. The MFP represents the average distance traveled by photons between successive interactions within the material; therefore, a smaller MFP value indicates a higher probability of photon interactions, stronger attenuation, and improved shielding capability [22]. The variation of MFP follows a trend similar to that observed for HVL with increasing radiation energy. The MFP of the BaTiO₃ sample increases with increasing γ -ray energy, ranging from 0.2094 cm at 122 keV to 3.5051 cm at 1330 keV. This increase can be attributed to the lower probability of high-energy photons interacting with the sample, resulting in fewer interactions and consequently longer photon travel distances before attenuation. At higher photon energies, the reduced attenuation efficiency leads to an increase in MFP values due to the greater contribution of Compton scattering and the reduced probability of photoelectric absorption. In general, materials with higher atomic numbers exhibit greater interaction probabilities with incident radiation, leading to lower MFP values. Therefore, BaTiO₃ demonstrates relatively low MFP values over the investigated energy range, indicating its potential effectiveness as a radiation shielding material. Furthermore, the mean free path (MFP) is strongly dependent on the incident photon energy. Higher energy levels, such as 1330 keV, result in larger MFP values due to the reduced probability of photon interactions and lower interaction cross sections. Similarly, both HVL and MFP increase with increasing γ -ray energy. This behavior indicates that the penetration capability of radiation through the BaTiO₃ nanomaterial is strongly influenced by the incident photon energy.

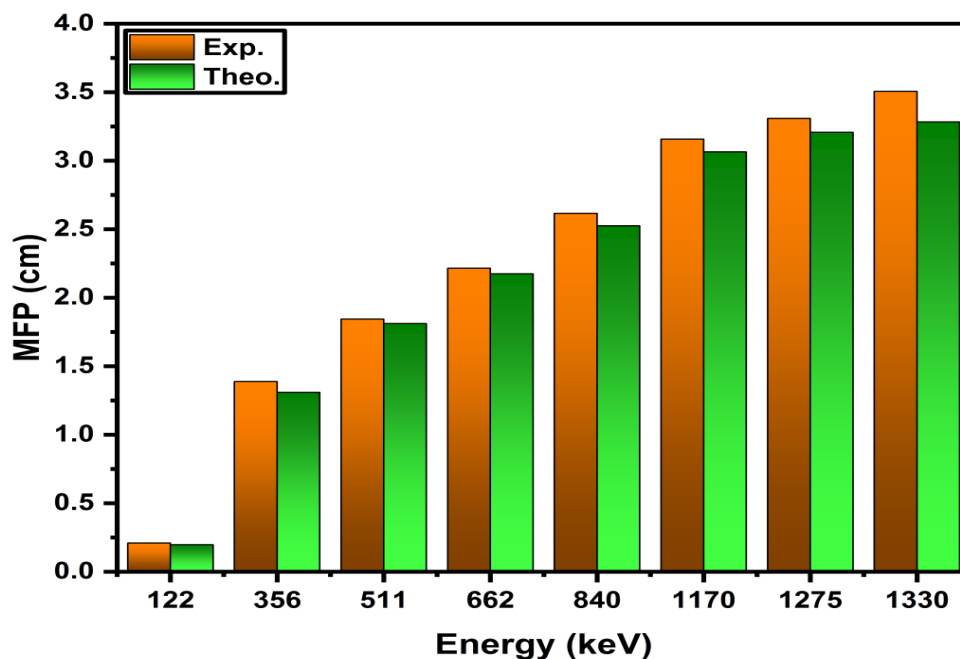


Figure 9. The mean free path (MFP) of the BaTiO₃ sample versus incoming photon energies.

3.5 Transmission Factor and Radiation Protection Efficiency

To evaluate the shielding effectiveness of the investigated BaTiO₃ nanomaterial against incident γ -rays, the transmission factor (TF%) and radiation protection efficiency (RPE%) were calculated and presented in Table 6. These parameters were determined based on the measured incident and transmitted photon intensities. With increasing gamma-ray energy, the penetration ability of incident photons increases due to the reduction in photon interaction probability and interaction cross section, resulting in fewer interactions between γ -rays and the electrons of the BaTiO₃ sample.

Since the transmission factor represents the fraction of photons transmitted through the material relative to the incident photon intensity, a lower TF value indicates stronger photon absorption, particularly at lower energies. Therefore, as the γ -ray energy increased from 122 to 1330 keV, the TF values increased, whereas the RPE values decreased, as illustrated in Figures 10 and 11. As shown in Table 6, the TF values increased from 0.0001% to 42.4901% over the investigated energy range (122–1330 keV) for the BaTiO₃ sample. Additionally, increasing the γ -ray energy from 122 to 1330 keV resulted in a decrease in the RPE values, which declined from 99.9999% to 57.5099% for the investigated BaTiO₃ sample. The RPE results indicate that BaTiO₃ can act as an effective shielding material, particularly at photon energies below 840 keV. Therefore, a greater thickness of BaTiO₃ may be required when it is exposed to higher-energy radiation fields or increased radiation intensities. The enhanced shielding performance of BaTiO₃ can be attributed to its ability to attenuate radiation through photon absorption and scattering mechanisms. Furthermore, the intrinsic properties of the material, including its relatively high atomic number and density, contribute significantly to its radiation attenuation and shielding capability.

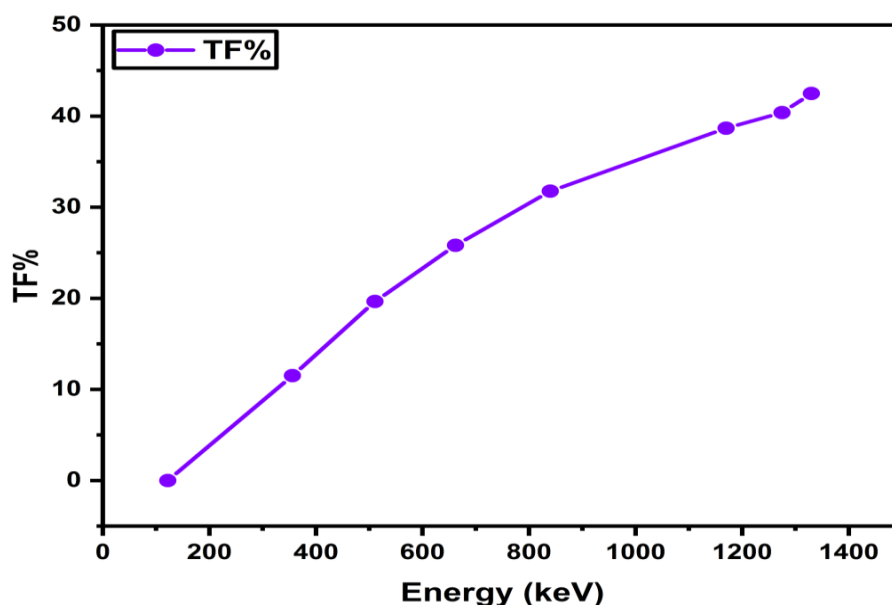


Figure 10. Effect of incident γ energy on transmission factor (TF%) of the BaTiO₃ sample.

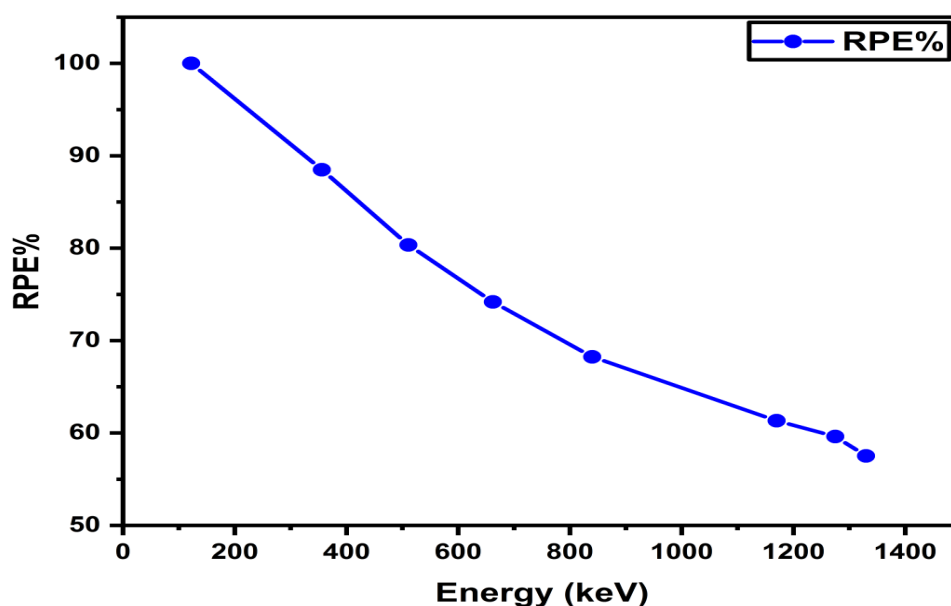


Figure 11. Impact of incident γ energy on radiation protection efficiency (RPE%) of the BaTiO₃ sample.

4. Conclusions

In the present study, BaTiO₃ nanomaterial was investigated under γ -ray irradiation within the energy range of 122–1330 keV to evaluate its attenuation and shielding properties. The mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), total atomic cross section (σ_t), electronic cross section (σ_e), molar extinction coefficient (ϵ), effective atomic number (Z_{eff}), effective electron density (N_{eff}), half-value layer (HVL), mean free path (MFP), transmission factor (TF%), and radiation protection efficiency (RPE%) were determined experimentally and theoretically. The experimental results of these parameters were compared with the theoretical values obtained from the XCOM program, showing good agreement with deviations of $\leq 6\%$, which confirms the reliability and accuracy of the measured radiation

shielding parameters. The MAC, LAC, RPE, σ_t , σ_e , and ε values decreased with increasing photon energy, whereas the HVL, MFP, and TF values increased as the γ -ray energy increased. The effective atomic number (Z_{eff}) of BaTiO₃ depends on the atomic numbers of its constituent elements and remains nearly independent of γ -ray energy within the investigated energy range. The effective electron density (N_{eff}) is closely related to Z_{eff} and exhibits a similar stable behavior across the selected energy domain. The observed decrease in MAC and LAC values with increasing γ -ray energy, together with the corresponding increase in HVL and MFP values, reflects the energy-dependent photon attenuation behavior of BaTiO₃.

The experimental evaluation of MAC, LAC, HVL, MFP, TF, and RPE demonstrates that BaTiO₃ nanomaterial possesses promising gamma-ray shielding capability. The obtained results emphasize the important role of material structure and nanoscale characteristics in enhancing radiation attenuation performance, suggesting BaTiO₃ nanomaterial as a potential candidate for radiation protection and shielding applications. The generated data on radiation interaction parameters may provide valuable information for applications in radiation dosimetry, medical and nuclear technologies, radiation shielding, and related fields of radiation physics and chemistry.

Data availability statement

No new data were created or analyzed in this research work.

Conflicts of interest

The authors of this article declare that they have no known competing financial interests or personal relationships that could have appeared to affect the data documented in this research article.

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