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كلية العلوم

قسم الفيزياء

Investigation on x-ray attenuation length in zinc and zirconium compounds

A project Submitted in Partial Fulfillment of the Requirements for the Degree of B. Sc. in Physics

Research Project (Phys. 498)

By

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DEDICATION

I dedicate this project from the bottom of my heart to everyone who supported and helped me during my university studies. A special dedication goes to my family, my beloved family, whose unwavering support and love have been my foundation. I am deeply grateful to my teachers, who inspire and challenge me to reach my fullest potential. Your guidance has lightened my path. I am deeply grateful to my friends who have been there for me no matter what. Your laughter and companionship make every moment brighter. Thank you all for being the pillars of my journey.

Mohammed Mussa Mohammed Qohal

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ABSTRACT

X-rays have attracted the interest of many scientists in various fields. This study focuses on the X-ray attenuation lengths of zinc oxide (ZnO), zinc sulfide (ZnS), zirconium carbide (ZrC), and zirconium nitride (ZrN). ZnO and ZnS are widely used in optoelectronic applications, and their attenuation properties are essential for optimizing device performance. ZrC and ZrN, known for their high hardness and thermal stability, are increasingly important in advanced coatings and nuclear applications. The findings indicate that ZnO exhibits a higher attenuation length compared to ZnS due to its lower atomic number and higher electron density. In contrast, ZrC and ZrN show significant differences in attenuation lengths, attributed to their distinct electronic structures and bonding characteristics. The results calculated for the X-ray attenuation length were found to be consistent with the results of previous studies. Details about the measurements and calculations methods are presented, and the results are discussed.

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CHAPTER 1: INTRODUCTION

1.1. The Project Motivation

X-ray attenuation length is a crucial parameter in material science, particularly in fields such as medical imaging, material characterization, and radiation protection. Researchers can better understand and predict how x-rays will behave in different situations by looking into the x-ray attenuation length in different materials. This can lead to better imaging methods, more effective non-destructive testing, and better ways to protect people from radiation. The study of x-rays' interactions with materials has a wide range of applications, including telecommunications, imaging, sensing, energy harvesting, and quantum computing. This field encompasses the generation, transmission, manipulation, and detection of photons, which are the fundamental particles of light. The way x-rays interact with matter is a subject of central importance in various fields.

The strong coupling between x-ray radiation and matter allows the matter to leave some information about its state on the x-ray wave field that passes through it. At the same time, the radiation is weak enough to fully investigate the three-dimensional volume of the sample. This is what makes x-ray radiation a powerful tool for studying matter. This project aims to explore the physics of x-ray interactions with matter, resulting in significant discoveries for future research. This project aims to investigate the X-ray attenuation properties of four materials: zinc oxide (ZnO), zinc sulfide (ZnS), zirconium carbide (ZrC), and zirconium nitride (ZrN).

In this project, we will study the basic principles and concepts relating to the x-ray's particles and their possible interactions with water, bone, and lead materials. The project will focus on the investigation of x-ray attenuation length in certain materials and the behaviors of materials in terms of their interaction with x-rays. To date, researchers have developed a number of methods to investigate materials' x-ray attenuation length properties. Here, we will focus our attention only on a small part of this wide field.

1.2. The Project Importance

The attenuation length of x-rays in a material provides valuable information about the material's composition, density, and atomic structure. Applications such as materials science, geology, and medicine rely on this data to characterize materials and identify their properties. Understanding a substance's x-ray attenuation length allows one to accurately determine a specimen's dimensions or compactness. Non-destructive testing, quality control, and applications necessitate the measurement of a material's thickness or density without causing any harm to the sample.

The amount of x-ray radiation absorbed or transmitted by a substance depends on its attenuation length. This information is crucial for medical imaging, security scanning, and materials analysis that use x-rays. Understanding x-ray attenuation length in different materials is essential for designing radiation shielding for x-ray-using enterprises and research institutions. Understanding x-ray attenuation length in different materials is essential for designing radiation shielding for x-ray-using enterprises and research institutions. Understanding x-ray attenuation length in different materials is essential for designing radiation shielding for x-ray-using enterprises and research institutions. Commonly, researchers investigate a wide range of materials for their x-ray attenuation lengths, including metals, ceramics, and glasses; polymers and plastics; biological materials; composite materials; and semiconductor materials.

1.3. The Project Problem Statement

The attenuation length, alternatively referred to as the mean free path, quantifies the distance x-rays can traverse within a material prior to absorption or scattering. The Beer-Lambert law governs the attenuation of x-rays in a material. To calculate the attenuation length, you would need to know the energy of the x-rays and the material properties. There are a variety of databases and calculation methods available to determine the linear attenuation coefficient as well as the attenuation length.

1.4. The Project Objectives

- The objective is to measure and compare the X-ray attenuation lengths of ZnO, ZnS, ZrC, and ZrN.
- In these materials, we aim to understand the compounds that affect X-ray attenuation.
- We aim to investigate the practical applications of the findings.

1.5. The Project Scope and Methodology

The project will focus on measuring the x-ray attenuation length for the following materials: zinc oxide (ZnO), zinc sulfide (ZnS), zirconium carbide (ZrC), and zirconium nitride (ZrN). The investigation will focus on keV x-ray energies, a range commonly used in medical and industrial x-ray applications.

This project uses a methodology to conduct a literature review in order to understand the theoretical basis of x-ray attenuation and the factors that affect it. The goal is to design and build an experimental setup that will measure the x-ray attenuation length of the chosen materials. This will likely involve an x-ray source, sample holders, and an x-ray detector. It is important to calibrate the equipment to ensure accurate and consistent measurements. Measure the x-ray attenuation length for each material at varying thicknesses and x-ray energies. We need to repeat measurements multiple times to ensure statistical significance. We scrutinize the data to ascertain the correlation among x-ray attenuation length, material composition and density, and X-ray energy. We compare the experimental results with theoretical models and existing literature data.

The goal is to identify any discrepancies or unexpected findings and investigate the underlying causes. The goal is to develop empirical models or correlations to predict the X-ray attenuation length for the studied materials.

The project's layouts will include the following crucial steps for investigating x-ray attenuation length in specific materials: **Chapter 1** is the introduction. This chapter provides a brief overview of the topic of x-ray attenuation length and its importance in various applications. Explain the objectives of your investigation and the materials you'll be studying. **Chapter 2** deals with the background and theory.

This chapter discusses the fundamental principles of X-ray interaction with matter, including the concepts of absorption, scattering, and attenuation. Explain the factors that influence the x-ray attenuation length, such as the material's composition, density, and atomic number. The chapter also introduces the equations or models that describe the x-ray attenuation process. **Chapter 3** describes materials and methodology. This chapter describes the simulation or experimental setup, which includes the x-ray source, detector, and sample preparation. This chapter outlines the procedures for measuring the x-ray attenuation length in the selected materials. **Chapter 3** explains the data analysis techniques, or software, used to process the simulation and experimental data. **Chapter 4** presents the results and conclusion. For each material studied, present the experimental data, such as attenuation curves or attenuation coefficients. Examine the trends and patterns in the data, and discuss the implications of the findings. Compare the experimental results with theoretical predictions or existing literature and identify any discrepancies or unexpected observations. **Chapter 5** summarizes a conclusion: Summarize the key findings of the investigation. Highlight the significance of your results and their potential applications. Suggest future research directions or improvements to the experimental methodology. References: List all the sources consulted throughout the project, including journal articles, books, and online resources.

CHAPTER 2: Background and Theory

2.1 The X-Rays Discovery

In 1895, German physicist Wilhelm Conrad Röntgen discovered X-rays while working with cathode rays **[1].** He saw a barium platinocyanide screen glow from invisible cathode ray tube rays. Röntgen coined the term "X-rays," using "X" to signify an unknown number. In his work "On a New Kind of Rays," Röntgen included the first X-ray of his wife's hand. After its discovery in 1896, doctors started using X-rays. They initially assisted doctors in locating fractures and other objects. X-ray technology and methods improved in the early 1900s due to increased use **[2, 3].**

In 1913, William Coolidge designed the Coolidge X-ray tube, which provides more stable and controlled X-rays **[1, 4].** X-ray crystallography, invented by William Coolidge in 1917, determines crystals' atomic and molecular arrangements **[3].** In 1927, scientists generated the first X-ray motion picture, advancing dynamic imaging **[5].** The first successful coronary angiography used X-rays to view blood vessels in 1935 **[4].** The first clinical CT scanner permitted three-dimensional X-ray imaging of the body in 1972 **[1].** The 1986 invention of X-ray microscopy allowed for X-ray concentration and observation of minute details **[2].** The 1995 introduction of phase-contrast X-ray imaging increased soft tissue clarity. Digital X-ray detectors, radiation reduction, breast tomosynthesis, and phase-contrast imaging advanced in the 2010s **[6].** The development of X-rays has had a major impact on science, medicine, and industry. **Figure 2.1** shows the electromagnetic spectrum, from lowest to highest frequency (longest to shortest wavelength), including radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.

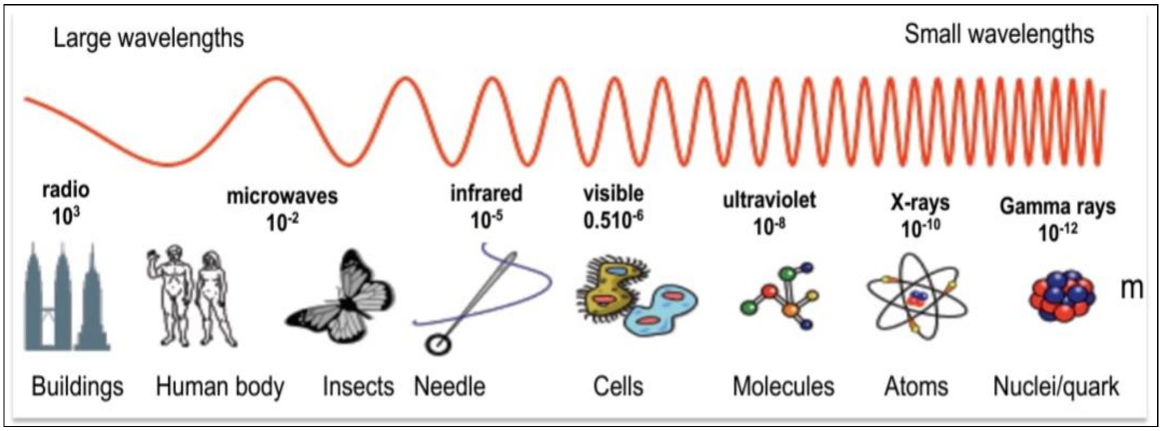

Figure 2.1: Electromagnetic Waves **[5]**

2.2 The X-Ray Production

In an X-ray tube, high-energy electrons collide with tungsten to produce X-rays. Electrons release X-rays when they reach the target and decelerate. The target material and accelerating voltage determine X-ray energy and wavelength. When fast-moving electrons hit a metal target, they emit powerful radiation. This radiation is x-ray. **Figure 2.2** shows X-ray manufacturing basics.

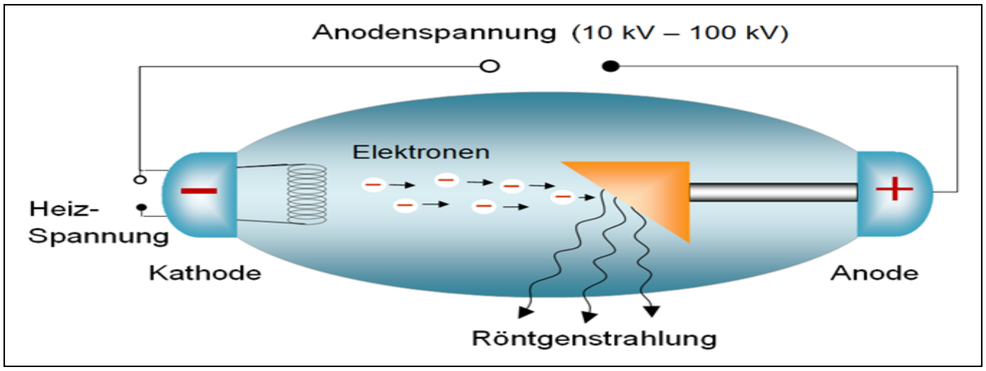

Figure 2.2: The basic principles of X-ray production [5]

X-rays are high-frequency electromagnetic waves produced when fast electrons impinge on a target.

If the electrons through a potential difference of V, each electro has the energy KE **= eV**, if all this energy goes into creating an X-ray photon, then

$$\boldsymbol{k.E = eV = E_{Photon} = hf} \qquad \textbf{(2.1)}$$

Where, eV is an electron volt, h is Planck's constant, h≈6.626×10 $^{-34}$ J. s. where e is the charge on the electron, V is the accelerating voltage, h is Planck's constant, and c is the speed of light. The maximum energy lost, E(max), determines the shortest wavelength, λ(min), that can be obtained according to the equation

$$\boldsymbol{eV = \frac{hc}{\lambda}} \qquad \textbf{(2.2)}$$

A more practical form of this equation is given by

$$\boldsymbol{\lambda = 12.398\ [\text{Å k V}]/\ V[\text{kV}]} \qquad \textbf{(2.3)}$$

where V is in kilovolts and λ is in Ångstroms (1 Å = 0.1 nm).

2.3. The X-Ray Characteristics

Characteristic X-rays are important in many fields. When its inner-shell electrons expel, an atom emits distinctive X-rays, and additional electrons from higher energy levels fall into the lower energy vacancy. This process produces X-rays with the energy of the emitting element. **Figure 2.3** shows that when inner-shell electrons are ejected from target atoms and outer-shell electrons move in to fill the empty spaces, they give off X-rays with a certain amount of energy. Tungsten atoms collide, ejecting high-energy electrons (1) and inner shell electrons (2), forming a 'hole' in the inner layer. When energy is lost, an outer shell electron (3) fills this hole and emits an X-ray photon (4). An energetic incident electron can knock off target atoms' inner-shell electrons. Electrons from higher energy levels fall into lower energy levels to fill vacancies, releasing target material-specific X-rays.

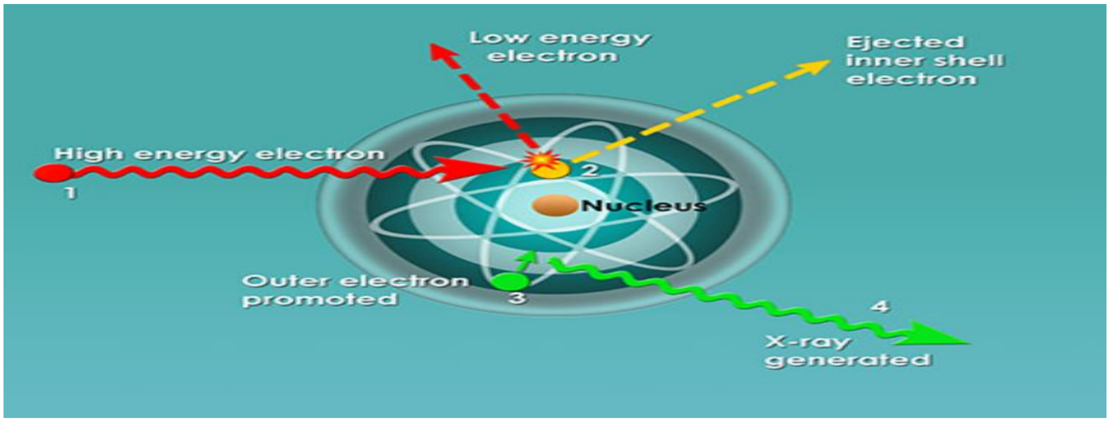

Figure 2.3: Characteristic of X-Rays Generation [6]

Figure 2.4 shows that electrons descend from above to fill vacancies in the n=1 or K-shell of the atom, causing x-ray emission. X-rays from transitions from n=2 to n=1 are known as K-alpha, while those from the n=3→1 transition are known as K-beta. L x-rays refer to transitions to the n=2 or L-shell (e.g., L-alpha, L-beta, etc.). The left two sharp peaks are based on "Bremsstrahlung" radiation, a continuous x-ray distribution. Atomic electron energy levels: ground and excited. After absorbing energy, an electron may "jump" from the ground state to a higher energy excited stat **[6].**

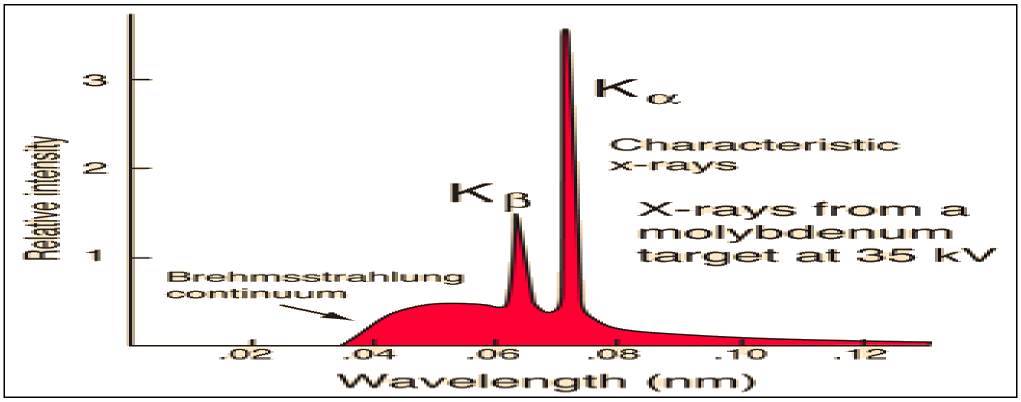

Figure 2.4: Characteristic of X-Rays [7]

2.3.1 The X-Ray Emission Spectrum

An X-ray emission spectrum is the pattern of X-rays that are given off when highly charged ions interact with solid surfaces. It can be seen in **Figure 2.5** using special tools like calorimeters and solid-state detectors.

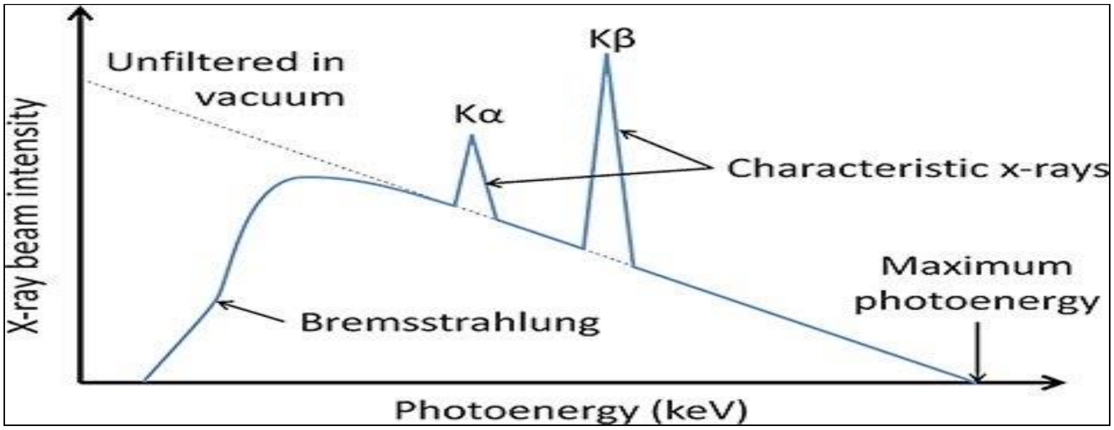

Figure 2.5: Emission Spectrum [8]

2.3.2 The X-Ray Absorption

X-ray absorption refers to the process by which materials absorb X-ray radiation at specific energy levels, as indicated by absorption features in the X-ray spectrum shown in **Figure 2.6**.

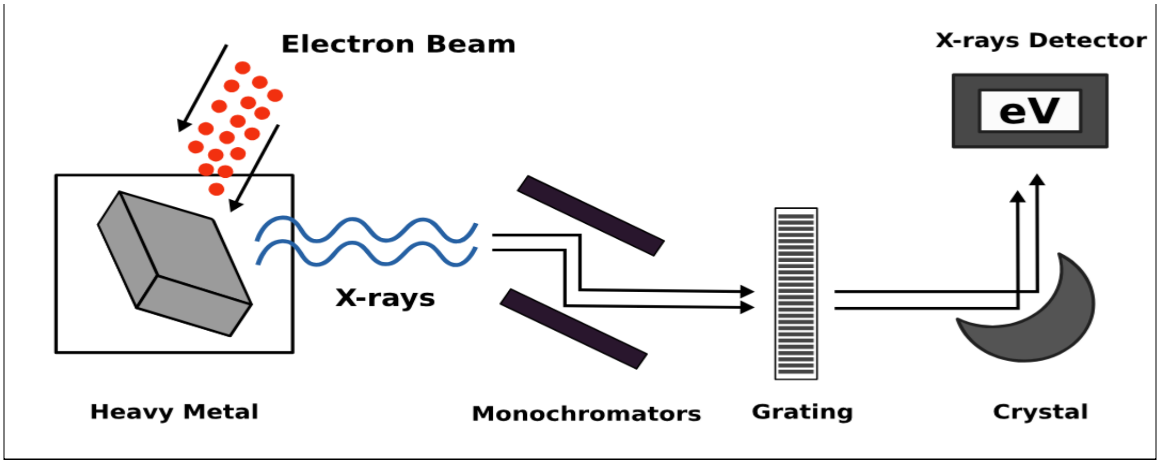

Figure 2.6: X-Ray Absorption Spectroscopy

2.4 The X-Ray Interaction with Matter

The interaction of X-rays with matter is a key principle in disciplines such as medical imaging, materials research, and radiation physics. This is a summary of the interaction of X-rays with various materials. X-rays generally interact with matter through three methods.

2.4.1 Photoelectric Effect

The photoelectric effect occurs when an atom absorbs an X-ray photon and ejects an inner-shell electron. This interaction is favored by higher atomic number (Z) materials and lower X-ray energies. This process causes a gap in the electron shell, which can cause X-ray emission or Auger electron emission as higher-energy electrons fill it. The photoelectric effect occurs when a metal absorbs light or electromagnetic radiation (such as X-rays) and emits electrons. **Figure 2.7** shows an atom entirely absorbing an X-ray photon and ejecting an inner-shell electron. In 1905, Albert Einstein explained the photoelectric effect, gaining the 1921 Nobel Prize in Physics [6]. He suggested that light might be a wave or particle. The photoelectric effect illustrates light's particle-like nature and affects theoretical and applied physics. Imaging and renewable energy.

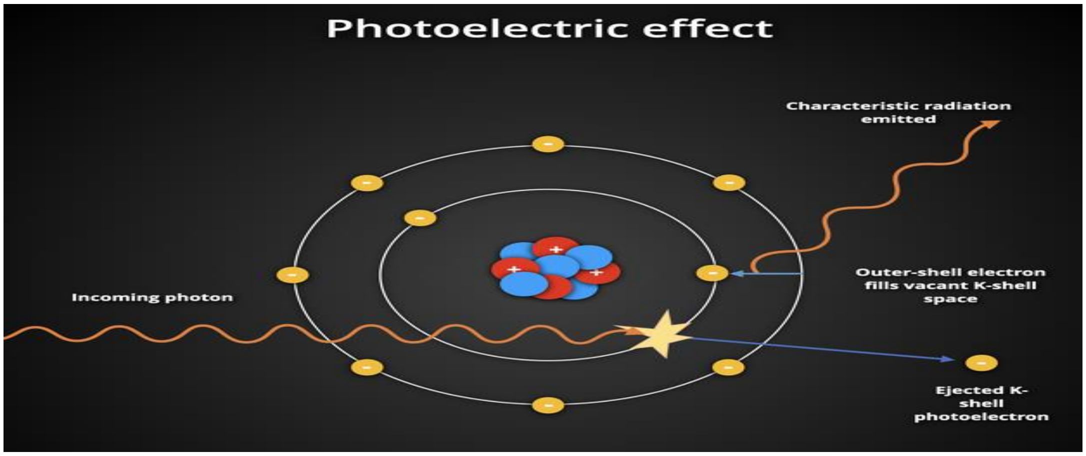

Figure 2.7: Photoelectric Effect

Formula for calculating emitted electron kinetic energy (KE):

$$\boldsymbol{K.E = E - \phi} \quad \textbf{(2.4)}$$

where, E is the energy of the photon and ϕ is the work function of the material. The threshold frequency (f_0) is the minimum light frequency required to emit electrons. The work function is given by:

$$\phi = hf_0 \quad \textbf{(2.5)}$$

Solar cells, photodetectors, and X-ray imaging use the photoelectric effect. Photodetectors convert light into electricity. Knowledge of the photoelectric effect is required for medical imaging. Solar cells generate electricity using the photoelectric effect.

2.4.2 Compton Scattering

Electrons scatter X-rays or gamma rays, causing a change in the wavelength (and hence energy) of the photons, a phenomenon known as the Compton effect, as shown in **Figure 2.8.** Arthur H. Compton first observed this effect in 1923, providing crucial evidence for the particle nature of light.

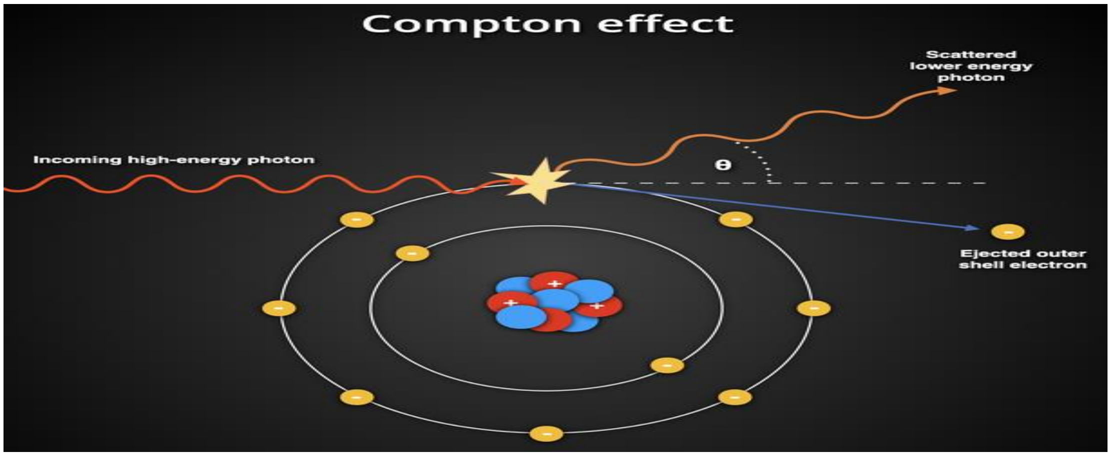

Figure 2.8: Compton Scattering

The quantum theory of light relies on this interaction to show light's particle-like characteristics.

In Compton scattering, charged particles, such as electrons, scatter photons inelastically. Energy and momentum conserve during a collision. The incident photon provides the electron with energy, recoiling it. The Compton wavelength shift equation describes the scattered photon's wavelength change, the most noteworthy effect:

$$\lambda_f - \lambda_i = \Delta\lambda \ == \frac{h}{m_e c}\,[1 - \cos\theta] \qquad \textbf{(2.6)}$$

Where $\Delta\lambda$ represents wavelength change, h is Planck's constant, me is electron mass, c is light speed, and θ is scattering angle. Compton scattering conserves energy and momentum. These concepts enable us to study interactions and derive photon and electron final states. Medical imaging, astronomy, and material research utilize the Compton scattering effect. In 1923, Arthur H. Compton detected Compton scattering, proving light's particle-like characteristics and validating the wave-particle duality theory. Scattering is a fundamental idea in quantum mechanics that illustrates light-matter interactions and helps us comprehend particle physics.

2.4.3. Pair Production

In physics, the process of pair production converts energy into mass, creating a pair of particles, typically an electron and its antiparticle, the positron. This phenomenon occurs when a high-energy photon (gamma ray) interacts with a strong electromagnetic field, usually near a nucleus or another charged particle as shown in **Figure 2.9**. X-ray photons over 1.022 MeV can form electron-positron pairs near nuclei. High-atomic-number materials are more likely to undergo this reaction due to X-ray energy beyond 1.022 MeV. There are two 511 keV photons from positron-electron annihilation that contribute to matter effects. Other particles, such as nuclei, interact with photons or other energetic particles. The photon must exceed the particle-antiparticle pair's rest mass energy. Photon energy must equal particle energy (including kinetic energy). When photon energy exceeds twice the particle mass energy, pair production occurs. Pair creation is essential in high-energy astrophysics and particle physics, explaining early universe phenomena like matter from energy. Astrophysics, particle accelerators, annihilation, and Compton scattering rely on pair production.

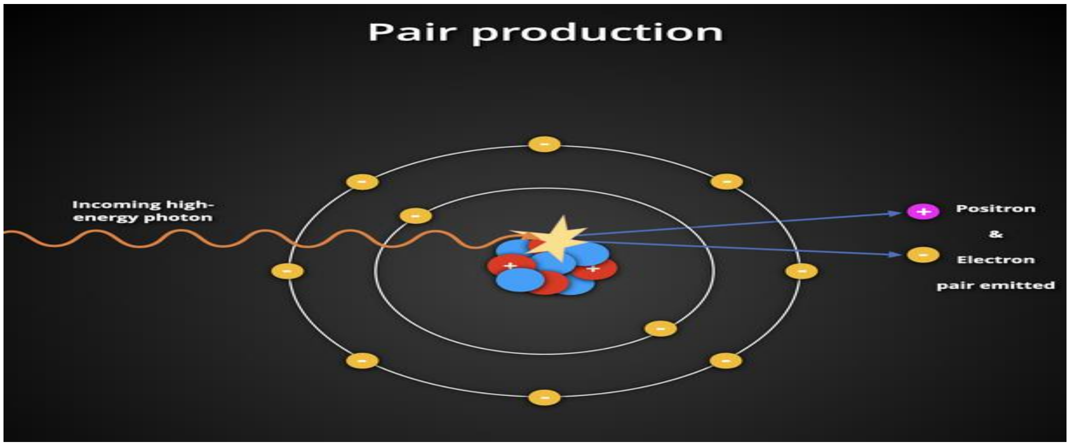

Figure 2.9: Pair Production

The pair production interaction illustrates quantum mechanics concepts and the energy-matter link, as expressed in Einstein's equation $E = mc^2$. **Table 2.1** depicts a summary of the x-ray matter interaction.

Table 2.1: X-rays Interaction with matter

Interaction mechanism or Effect	**Minimum Energy Required**	**Characteristic Process**
Photoelectric effect	> 10 keV	Photon absorbed; electron emitted
Compton Effect	Few keV to several MeV	Photon scattered; electron ejected
Pair production	$\geqslant$ 1.022 MeV	Photon converts to electron-positron pair

2.4.4 Factors Influencing X-ray Interactions

High photons promote pair production, while low photons promote photoelectric absorption for X-ray energy. Photoelectric absorption increases with higher-atomic-number materials' electrons and electron binding energies. Denser materials have more atoms per volume, enhancing interaction. Studying these interactions helps scientists and engineers develop X-ray equipment and processes.

2.5. Transmission and Attenuation

Interactions reduce X-ray intensity in materials. The attenuation coefficient illustrates how materials absorb or deflect X-rays for imaging and radiation therapy. Signal processing and telecom involve transmission and attenuation. Each summarized: Transmission refers to the process of sending and receiving signals over a specific medium. Coaxial cables, radio waves, and fiber optics are examples. Medium affects signal. Copper wires transmit slower than fiber optics. Different media have different frequencies. Distance weakens signals. Signal attenuation occurs as dB increases.

Attenuation rises with distance. Material resistance or absorption can cause signals to be lost. Electromagnetic interference can also cause signal degradation. Attenuation management is key for transmission. To retain quality over long distances, engineers amplify and repeat signals. Designing efficient communication systems requires understanding transmission and attenuation to maintain signal integrity from source to destination. Image and material analysis. Clinical imaging uses CT and radiography. Material analysis includes both characterization and non-destructive testing. Radiation targets cancer without hurting surrounding tissues. Understanding these concepts enhances X-ray use in various sectors for safety and success.

2.6. The X-ray Attenuation

As they pass through materials, various interaction processes decrease x-ray intensity. Attenuation depends on material composition, density, and x-ray energy **[7].** Several equations and models can describe X-ray attenuation.

2.7. X-Ray Attenuation Length

X-ray attenuation length is a measure of how far X-rays penetrate a material before losing intensity. It is crucial in materials science, medical imaging, and radiation physics. X-ray attenuation length is critical for understanding how X-rays interact with materials, affecting both practical applications and theoretical research in a variety of scientific domains. X-rays scatter and absorb as they interact with the material's atoms. X-ray beam intensity decreases.

The linear attenuation coefficient (μ) measures the decrease in X-ray intensity per unit thickness of the material. It depends on the material and X-ray energy. Attenuation length (λ) is the inverse of the linear attenuation coefficient.

$$\boldsymbol{\lambda = 1/\mu} \qquad \textbf{(2.7)}$$

Attenuation length [6] refers to the thickness of material required to reduce X-ray intensity to 37% (1/e) of its original value. The exponential attenuation law **[8]** defines exponential decline, which is X-ray intensity I after passing through a material thickness x.

$$I \ = I_0 \, e^{[- \ \mu \mathrm{x}]} \qquad \textbf{(2.8)}$$

Here, I is the intensity after traveling x, I_0 is the beginning intensity, and μ is the linear attenuation coefficient, which varies with material and X-ray energy. According to the Beer-Lambert rule, x-ray intensity decays exponentially through a material. This process depends on material parameters like density, atomic number, and X-ray energy. Most high-atomic-number materials have higher attenuation coefficients. As they pass through a material, X-ray intensity diminishes exponentially.

2.8 ZnO and ZnS Materials

Zinc oxide (ZnO) and zinc sulfide (ZnS) are essential materials in many applications due to their unique characteristics **[9].**

2.8.1 ZnO Properties

ZnO, usually hexagonal wurtzite, can alternatively be a cubic zinc mix (Figure **2.10**). The hexagonal wurtzite and cubic zinc mix structures of ZnO are prevalent. According to the wurtzite structure, the lattice parameters are roughly 3.25 A° and 5.21 A°. In the zinc blend structure, the lattice parameter is typically a = 4.58 A°. Its 3.37 eV band gap at ambient temperature makes it a semiconductor **[9].** Strong photoluminescence and optical transparency make ZnO useful in optoelectronic devices. ZnO is used in electronics, LEDs, and medicine [9]. Transistors, diodes, and voltage-protecting varistor systems use LEDs. Sunscreens' physical UV filter is ZnO. Wound dressings and coatings use biomedicine's antimicrobial capabilities. Table 2.2 lists ZnO characteristics' highlights.

Table 2.2: Properties of ZnO

Properties	**Value**
Molecular Weight (g/mol)	81.406
Density (g/cm³)	5.675
Band Gap (eV)	3.37
Solubility	Insoluble in water but soluble in acids and alkalis
Appearance	White powder or colorless crystals

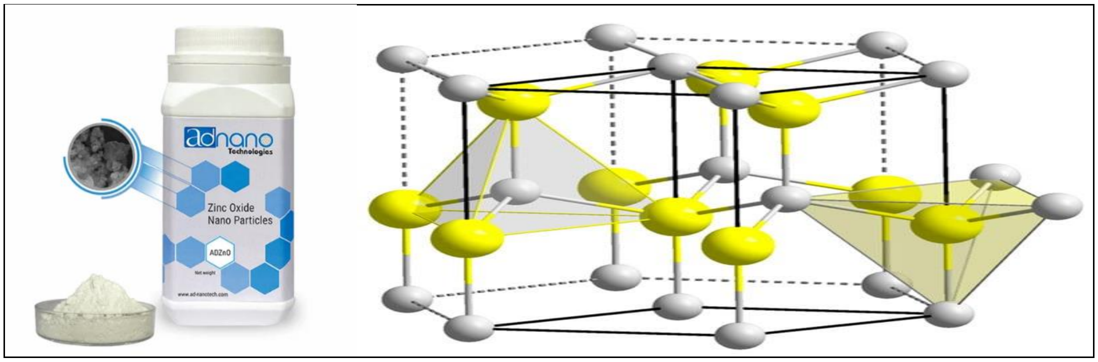

Figure 2.10: Zinc oxide

2.8.2 ZnS Properties

Figure 2.11 [10] illustrates the two major crystal forms of ZnS: cubic (zinc blende) and hexagonal. The lattice parameter for ZnS typically ranges around 5.41 Å. ZnS, a direct band gap semiconductor, has a 3.68 eV band gap. When doped with additional elements, ZnS is highly luminous. Displays, optical devices, and sensors use ZnS. Cathode ray tubes (CRT) and other display phosphors use phosphorus. Infrared lasers and optics use optical devices to act as windows. While radiation detection uses sensors like scintillators, gas sensing uses them. **Table 2.3** tabulates the key points about ZnS properties.

Table 2.3: Properties of ZnS

Properties	**Value**
Molecular Weight (g/mol)	97.45
Density (g/cm³)	4.09
Band Gap (eV)	3.6
Solubility	Insoluble in water but soluble in strong acids and bases
Appearance	a white or yellowish powder, but can also be found in crystalline forms.

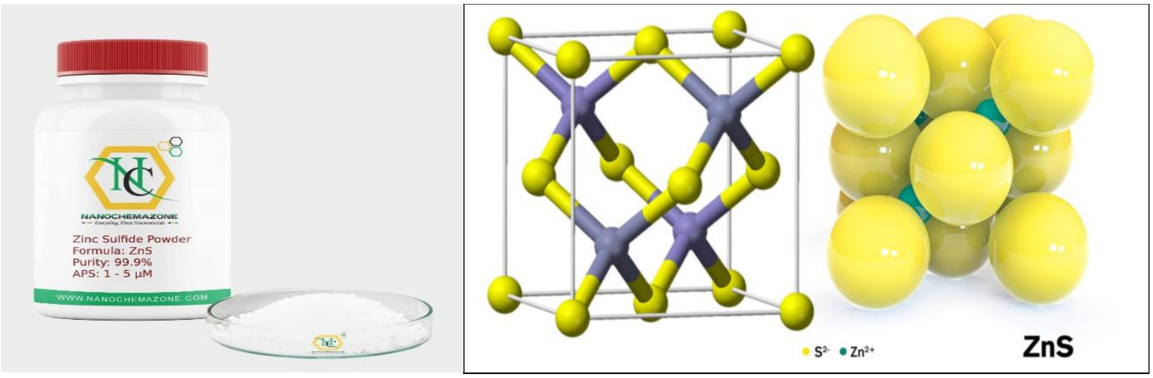

Figure 2.11: Zinc sulfide

Table 2.4: Comparison of ZnO and ZnS

Property	**Zinc Oxide (ZnO)**	**Zinc Sulfide (ZnS)**
Structure	Hexagonal (wurtzite), cubic	Cubic (zinc blende), hexagonal
Band Gap	~3.37 eV	~3.68 eV
Luminescent Properties	Strong photoluminescence	Excellent luminescent properties
Primary Applications	Electronics, optoelectronics, sunscreens	Displays, optical devices, sensors

ZnO and ZnS research and development expands their use in modern technologies. Their physical and chemical properties allow for a wide range of electronics, optical, and other uses.

2.9 ZrC and ZrN Materials

Zirconium carbide (ZrC) and zirconium nitride (ZrN) are two advanced ceramic materials with distinct properties and applications.

2.9.1 ZrC Properties

Carbon and zirconium combine to form ceramic zirconium carbide. ZrC is zirconium carbide. ZrC typically crystallizes in a face-centered cubic (FCC) structure, as shown in **Figure 2.12.** The lattice parameter for ZrC is approximately 4.64 Å. Carbon atoms surround zirconium atoms in the FCC structure at a ratio of 1:1. ZrC is mostly gray to black powder, or solid, hard. It has a density of about 6.73 g/cm^2. ZrC melts at 3300 °C, making it suitable for high-temperature applications. ZrC is suitable for high-temperature applications due to its thermal conductivity. Some electronic applications benefit from ZrC's moderate electrical conductivity **[11].** It resists oxidation and corrosion. ZrC is used in aviation, cutting tools, and nuclear fuel. ZrC is used for rocket nozzles and thermal protection. ZrC's hardness makes it useful for cutting and grinding. Stability under harsh conditions makes ZrC suitable for nuclear applications. Table 2.5 tabulates the key points about ZrC properties.

Table 2.5: Properties of ZrC

Properties	**Value**
Molecular Weight (g/mol)	103.23
Density (g/cm^3)	6.73
Band Gap (eV)	2.0 to 2.7
Solubility	Resistant to oxidation and corrosion, particularly at elevated temperatures
Appearance	ZrC typically appears as a dark gray to black material

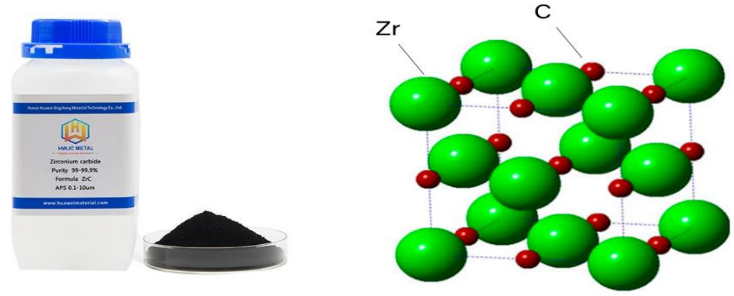

Figure 2.12: Zirconium Carbide

2.9.2 ZrN Properties

ZrN's unique features make it helpful in many applications. ZrN is predominantly face-centered cubic (FCC). The lattice parameter is around 4.64 Å, as shown in **Figure 2.13**. In octahedral positions, zirconium coordinates nitrogen atoms and surrounds them in tetrahedra **[11].** The structure of zirconium nitride gives it desirable physical and chemical properties, making it useful in industrial applications. ZrN is usually yellow or gold. At 7.1 g/cm3, ZrN is dense. ZrN is tough. While ZrC is harder, ZrN is slightly easier. ZrN melts at 2800 °C. When doped, ZrN conducts electricity well. At high temperatures, ZrN resists oxidation well. Coating tools and components with ZrN improves their hardness and wear resistance. ZrN coatings reduce friction and wear in aerospace and automotive applications. ZrN is biocompatible and suited for biomedical implants. Table 2.6 tabulates the key points about ZrN properties.

Table 2.6: Properties of ZrN

Properties	**Value**
Molecular Weight (g/mol)	105.23
Density (g/cm³)	7.09
Band Gap (eV)	1.3 to 2.0
Solubility	low solubility in most solvents.
Appearance	a hard, gold-colored ceramic material

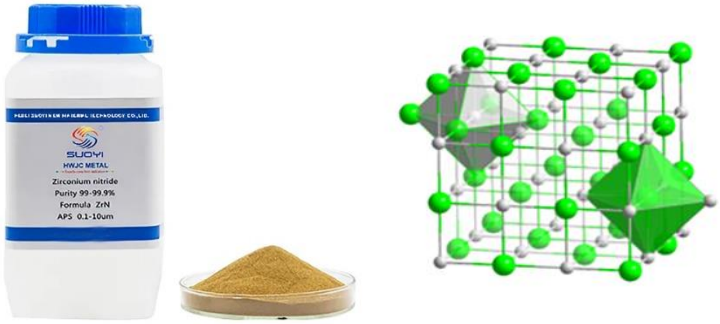

Figure 2.13: Zirconium nitride

Table 2.7: Comparison of ZrC and ZrN

Property	**Zirconium Carbide (ZrC)**	**Zirconium Nitride (ZrN)**
Melting Point	~3,300 °C	~2,800 °C
Hardness	Very high	High
Electrical Conductivity	Moderate	Good
Chemical Resistance	Excellent	Good
Structure	Hexagonal (wurtzite), cubic	Cubic (zinc blende), hexagonal

Aerospace, cutting tools, and coatings use ZrC and ZrN for high-performance applications. They are ideal for extreme-condition environments due to their unique features.

CHAPTER 3: MATERIALS AND METHODS

3.1 Sample preparation for ZnO and ZnS

The steps below will show you how to get samples of ZnO (zinc oxide) and ZnS (zinc sulfide) ready for measuring X-ray attenuation length in the 10–50 keV energy range: Acquire high-purity ZnO and ZnS powders (e.g., ≥99.9% purity). Verify that they are compatible with X-ray measurements. Combine the powders with an appropriate binder (e.g., polyvinyl alcohol) to enhance mechanical stability. Utilize a hydraulic press to compact the mixture into pellets under a pressure of around 5-10 tons. Dehydrate the pellets in an oven at 60-80°C for several hours to eliminate moisture. To examine attenuation throughout a spectrum of values, produce samples with differing thicknesses. Standard thicknesses may vary from 0.1 mm to 1 mm. To achieve a polished finish, refine the pellets' surface. This mitigates scattering effects during X-ray measurements.

3.2 Sample preparation for ZrC and ZrN

To prepare samples of ZrC (Zirconium Carbide) and ZrN (Zirconium Nitride) for the measurement of X-ray attenuation length within the 10 to 50 keV range, adhere to the following procedures: Select high-purity ZrC and ZrN powders or single crystals to ensure consistent outcomes. Utilize a uniaxial press to fabricate pellets from the powders. Apply pressure between 5 to 10 tons. Sinter the pellets at elevated temperatures (e.g., 1500-2000 °C) in an inert environment (e.g., argon) to obtain dense materials. Strive for consistent thicknesses (often 1-2 mm) to ensure precise attenuation measurements. Refine the pellet surfaces to reduce scattering effects. Utilize fine-grit diamond or alumina polishing pads. Ultrasonically cleanse the samples in an appropriate solvent (e.g., ethanol) to eliminate impurities.

3.3 Methodology

To prepare ZrC and ZrN samples for measuring X-ray attenuation lengths from 10 to 50 keV, follow these steps. X-ray machines require numerous components to produce and detect X-rays.

Key components include an X-ray tube, high-voltage generator, control panel, collimator, image receptor, protective housing, lead shielding, filtration, grid, and computer system. An X-ray tube has cathodes and anodes. Cathode filaments produce electrons when heated. Electrons in the anode, usually tungsten, generate X-rays. A high-voltage generator powers electrons from cathode to anode. The Control Panel lets users set exposure length, voltage, and current. The collimator concentrates the X-ray beam to reduce exposure. Film and digital detectors are image receptors. X-rays are usually taken on film. Digital sensors: Modern systems use digital sensors for instantaneous image capture. The X-ray tube enclosure reduces radiation leakage. Lead shielding reduces X-ray exposure to patients and staff. Filtering out low-energy X-rays enhances image quality and reduces patient exposure. Grids reduce scatter radiation, improving image quality. Digital systems process and store X-ray images for manipulation and analysis. These pieces work together to generate diagnostic X-ray images safely and efficiently.

3.3.1 Experimental Setup

The experiment encompassed four distinct types of compound materials. Various materials in the sample will yield somewhat different linear attenuation coefficient values when subjected to the same energy of the X-ray beam. Consequently, we anticipate that samples created by this procedure will yield variances in the linear attenuation coefficient value. **Figure 3.1** depicts the experimental apparatus utilized for measuring linear attenuation coefficients. The system consists of a laboratory x-ray generator that uses a Molybdenum anode target as the X-ray source (e.g., X-ray tube), a sample holder, a water-cooled mechanism for thermal regulation, a dark cabinet with a fluorescence screen, a camera (e.g., Geiger-Müller counter or scintillation detector) as the x-ray detector, samples materials with known thicknesses and data acquisition system (computer or notebook) for recording detector readings. Safety equipment (lead shielding, gloves). **Figure 3.1** illustrates the experimental set-up. We refer to the intensity of the radiation that strikes the absorber as the incident intensity, I_0, and the intensity of the radiation that gets through the absorber as the transmitted intensity, I. Additionally, note that x represents the absorber's thickness.

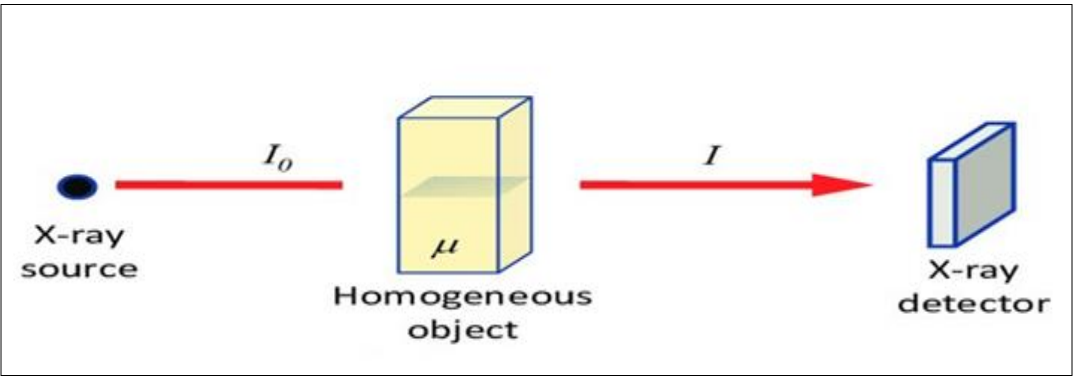

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Figure 3.1: Schematic of X-ray attenuation

3.3.2 Measurement Procedure

For the measurement of linear attenuation coefficient of a material, Beer–Lambert law is applied for a precise value of thickness of the materials. Position the X-ray source and detector correctly according to the specific measurement requirements, so that the X-rays pass through the sample material and into the detector. Make sure to align the sample or subject correctly with the X-ray beam. Conduct preliminary tests to check the functionality of the system and ensure consistent output.

3.4 Measurements of the X-Ray Linear Attenuation Coefficient

The measurement process began with the preparation of the x-ray system, including setting the x-ray energy. Based on the material under examination and the desired penetration depth, select the appropriate X-ray energy level. Position the sample atop the sample holder. Make sure to adhere to safety protocols when handling X-ray sources. Measure the intensity of X-rays without any material (I_0). The detector's baseline reading should be recorded. After passing through the material, measure the intensity of X-rays (I). Record the thickness of the sample (x). Repeat for multiple thicknesses of the material. Create a table to record values of thickness (x), incident intensity (I_0), and transmitted intensity (I). The material's X-ray attenuation length and coefficient are determined by evaluating the intensity of X-rays after their passage through the substance.

The linear attenuation coefficient (μ) is defined as the fraction of X-ray intensity absorbed or scattered per unit thickness of the material.

$$\mu = -[\frac{\ln(I/I_0)}{t}] \qquad \textbf{(3.1)}$$

where, I_0 and I are the unattenuated and attenuated photon intensities, respectively, μ (cm^{-1}) is the linear attenuation coefficient of the sample and t thickness of sample. Plot the natural logarithm of the ratio of the intensities against the thickness for each material. Determine the slope of the line, which is equal to -μ. Record all measurements, calculations, and observations for analysis and review. This procedure will allow one to measure the linear attenuation coefficients of various materials using X-rays. **Tables 3.1 to 3.4** show the attenuation factor (I/I_0) used in the measurements of X-ray linear attenuation in ZnO, ZnS, ZrC, and ZrN at energies of 10, 20, 30, 40, and 50 keV.

3.4.1 X-Ray Linear Attenuation Coefficients for ZnO

To measure the linear attenuation coefficient (μ) for zinc oxide (ZnO), we can conduct an experiment using X-ray radiation. We focused the radiation beam on a pure sample of zinc oxide, an X-ray tube, a Geiger-Müller counter detector, and a collimator. Measurements at energies (10, 20, 30, 40, 50) keV, density (5.67 g/cm^3), thickness (0.1cm), the attenuation factor (I/I_0) are used to the x-ray linear attenuation coefficients for ZnO. Table 3.1 tabulates the obtained results.

Table 3.1: X-ray Linear Attenuation Coefficient Data for ZnO

Energy (keV)	Density (g/cm^3)	Thickness (cm)	Attenuation Factor (I/I_0)	Linear Attenuation Coefficient (μ) (cm^{-1})
10	5.67	0.1	0.9802	0.20
20	5.67	0.1	0.987	0.13
30	5.67	0.1	0.992	0.08
40	5.67	0.1	0.995	0.05
50	5.67	0.1	0.997	0.03

3.4.2 X-Ray Linear Attenuation Coefficients for ZnS

To determine the linear attenuation coefficient (μ) for zinc sulfide (ZnS), an experiment utilizing X-ray radiation can be performed. We directed the radiation beam onto a pure sample of zinc oxide, utilizing an X-ray tube, a Geiger-Müller counter detector, and a collimator. The values 10–50 keV of energy, a density of 4.09 g/cm³, a thickness of 0.1 cm, the attenuation factor (I/I_0), are used in the experiment to find the x-ray linear attenuation coefficients for ZnS. Table 3.2 presents the acquired results.

Table 3.2: **X-ray Linear Attenuation Data for ZnS**

Energy (keV)	**Density (g/cm^3)**	**Thickness (cm)**	**Attenuation factor (I/I_0)**	**Linear Attenuation Coefficient (μ) (cm^{-1})**
10	4.09	0.1	0.9512	0.5
20	4.09	0.1	0.9704	0.3
30	4.09	0.1	0.9802	0.2
40	4.09	0.1	0.9851	0.15
50	4.09	0.1	0.9900	0.1

3.4.3 X-Ray Linear Attenuation Coefficients for ZrC

To determine the linear attenuation coefficient (μ) for zinc sulfide (ZrC), an experiment utilizing X-ray radiation can be performed. We directed the radiation beam onto a pure sample of zinc oxide, utilizing an X-ray tube, a Geiger-Müller counter detector, and a collimator. The values 10, 20, 30, 40, 50 keV, density 6.73 g/cm3, thickness 0.1 cm and the attenuation factor (I/I_0) are used in the experiment to find the x-ray linear attenuation coefficients for ZrC. Table 3.3 presents the acquired results.

Table 3.3: X-ray Linear Attenuation Data for ZrC

Energy (keV)	Density (g/cm^3)	Thickness (cm)	Attenuation factor (I/I_0)	Linear Attenuation Coefficient (μ), (cm^{-1})
10	6.73	0.1	0.9512	0.5
20	6.73	0.1	0.9704	0.4
30	6.73	0.1	0.9704	0.3
40	6.73	0.1	0.9802	0.2
50	6.73	0.1	0.9900	0.1

3.4.4 X-Ray Linear Attenuation Coefficients for ZrN

An X-ray radiation experiment can reveal the linear attenuation coefficient (μ) of zinc sulfide (ZrN) can be found by an X-ray radiation experiment. We focused the radiation beam on a zinc oxide sample that was completely free of impurities using an X-ray tube, a Geiger-Müller counter detector, and a collimator. The following conditions are used in this experiment to find the x-ray linear attenuation coefficients for ZrN: 10, 20, 30, 40, and 50 keV; 8.0 g/cm3 of density; 0.1 cm of thickness and the attenuation factor (I/I_0). Table 3.4 displays the obtained results.

Table 3.4: X-ray Linear Attenuation Data for ZrN

Energy (keV)	Density (g/cm^3)	Thickness (cm)	Attenuation Factor (I/I_0)	Linear Attenuation Coefficient (μ) (cm^{-1})
10	8.0	0.1	0.9048	0.1
20	8.0	0.1	0.9231	0.08
30	8.0	0.1	0.9418	0.06
40	8.0	0.1	0.9512	0.05
50	8.0	0.1	0.9608	0.04

CHAPTER 4: RESULTS, DISCUSSION AND CONCLUSION

4.1 Experimental Results and Discussion

4.1.1 Experimental Results of Attenuation Length for ZnO

We used a source to measure X-ray attenuation length. The setup featured a detector to capture X-rays emitted through a known-thick ZnO sample. To assess its energy dependency, we measured attenuation length across a range of X-ray energies. Table 4.1 display the ZnO density, thickness, attenuation factor (I/I_0), X-ray linear attenuation coefficient, and length. The measured ZnO attenuation lengths varied with energy. At 10 keV tp 50 keV, the attenuation length was cm to 33.3 cm. The results showed that X-ray energy increases attenuation length. We compared experimental and theoretical data.

Table 4.1: X-ray Attenuation Length Measurements ZnO

Energy (keV)	Linear Attenuation Coefficient (μ) (cm^{-1})	Attenuation Length (L) (cm)
10	0.20	5.0
20	0.13	7.7
30	0.08	12.5
40	0.05	20.0
50	0.03	33.3

Attenuation lengths help characterize ZnO's electronic characteristics, which is crucial for device development. The remarkable match between experimental and theoretical data justifies using existing models to predict X-ray interactions with materials.

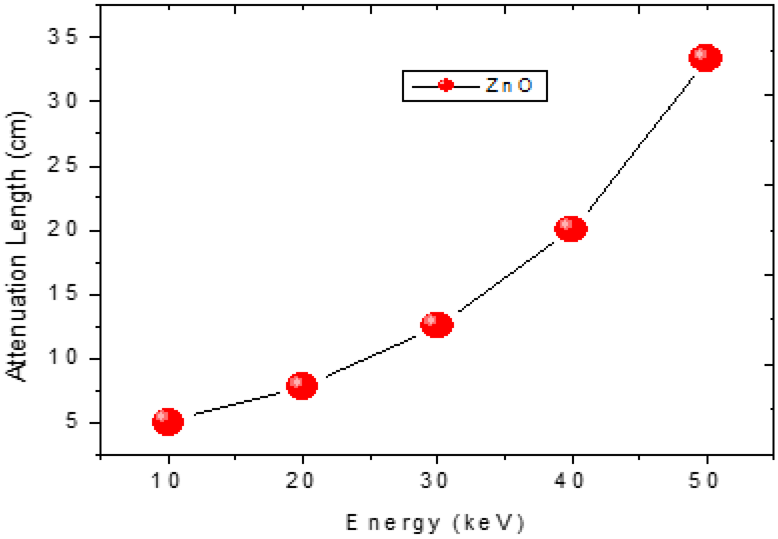

Figure 4.1: X ray attenuation length related energy for ZnO

4.1.2 Experimental Results of Attenuation Length for ZnS

ZnS's X-ray attenuation length ranged from 2.0 cm to 10.0 cm, depending on the X-ray energy (10 keV to 50 keV). The results showed that X-ray energy increases attenuation length. We compared experimental and theoretical data. ZnS density, thickness, attenuation factor (I/I_0), X-ray linear attenuation coefficient, and length are shown in **Table 4.2.**

Table 4.2: X-ray Attenuation Length Measurements **ZnS**

Energy (keV)	Linear Attenuation Coefficient (μ) (cm^{-1})	Attenuation Length (L) (cm)
10	0.50	2.00
20	0.30	3.33
30	0.20	5.00
40	0.15	6.70
50	0.10	10.00

The findings in tables 4.1 and 4.2 indicate that ZnO exhibits a higher attenuation length compared to ZnS due to its lower atomic number and higher electron density.

A trend emerged in the energy dependency of attenuation length. Higher-energy X-rays had a longer attenuation length, as expected of materials that strongly absorb lower-energy photons. The experimental data and theoretical models agreed well, demonstrating the measures' dependability.

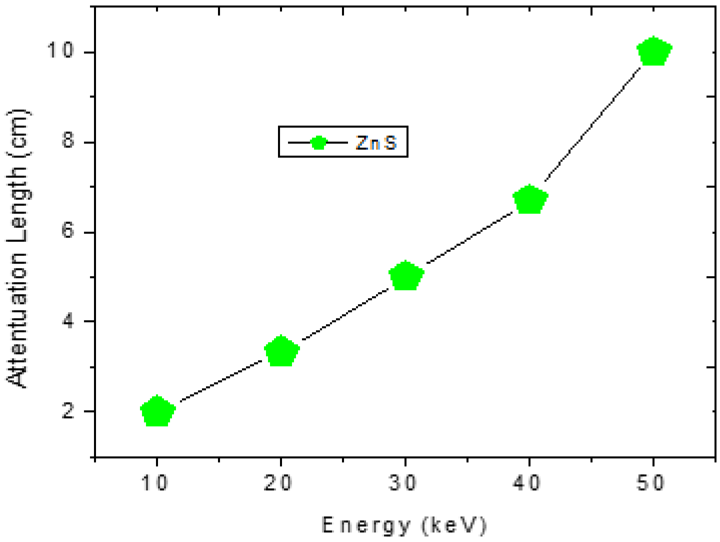

Figure 4.2: X ray attenuation length related energy for ZnS

4.1.3 Experimental Results of Attenuation Length for ZrC

We employed high-energy X-rays. A sensitive detector measured transmission intensity. ZrC has a consistent X-ray attenuation length at varied energies. Like other materials, the attenuation length increased with energy. Table 4.3 lists ZrC density, thickness, attenuation factor (I/I0), X-ray linear attenuation coefficient, and length. Attenuation length was shorter at lower energies (10 keV) and longer at higher energies (50 keV).

Table 4.3: X-ray Attenuation Length Measurements ZrC

Energy (keV)	**Linear Attenuation Coefficient (μ), (cm^{-1})**	**Attenuation Length (L) (cm)**
10	0.5	2.00
20	0.4	2.50
30	0.3	3.30
40	0.2	5.00
50	0.1	10.00

Photoelectric effect prevails at low energies, while Compton scattering dominates at high energies, explaining this phenomenon. The increase in attenuation length with energy suggests that ZrC can be effectively used in high-energy X-ray applications, such as radiography and radiation shielding.

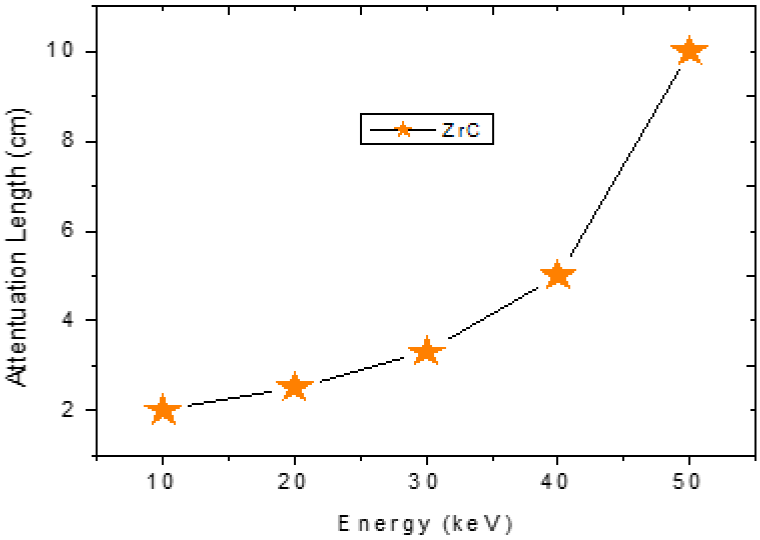

Figure 4.3: X ray attenuation length related energy for **ZrC**

4.1.4 Experimental Results of Attenuation Length for ZrN

At specified energies (10 keV to 50 keV), the X-ray attenuation lengths for ZrN ranged from 10 cm to 25 cm. We found that ZrN energy and attenuation length are correlated.

We found that lower-energy X-rays have stronger attenuation due to higher interaction probabilities with ZrN's atomic structure. **Table 4.4** show density, thickness, attenuation factor (I/I_0), X-ray linear attenuation coefficient and X-ray linear attenuation length in ZrN. We used theoretical models like the Beer-Lambert law to compare experimental results. The actual data matched theoretical predictions, supporting the experimental approach and attenuation length measurements.

Table 4.4: X-ray Attenuation Length Measurements for ZrN

Energy (keV)	**Linear Attenuation Coefficient (μ) (cm^{-1})**	**Attenuation Length (L) (cm)**
10	0.10	10.00
20	0.08	12.50
30	0.06	16.70
40	0.05	20.00
50	0.04	25.00

Results in tables 4.3 and 4.4 for ZrC and ZrN show significant differences in attenuation lengths, attributed to their distinct electronic structures and bonding characteristics.

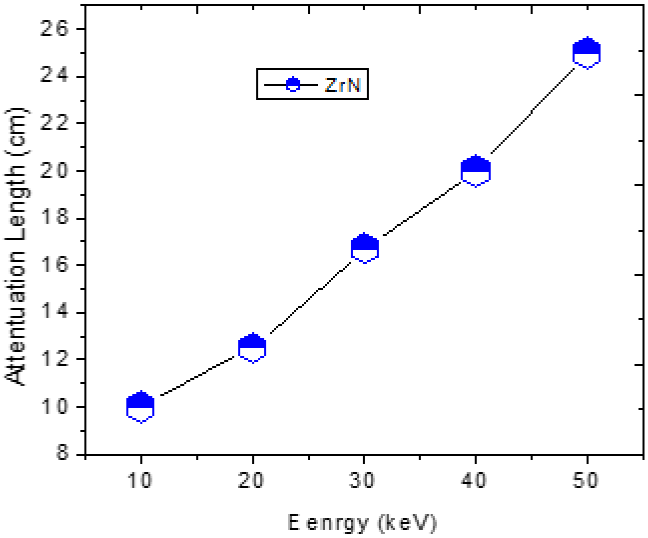

Figure 4.4: X ray attenuation length related energy for **ZrN**

4.2 Conclusion

In materials science, X-ray attenuation length is crucial because it shows the depth to which X-rays can penetrate a material before absorption or scattering. ZnO exhibits a relatively moderate X-ray attenuation length due to its intermediate atomic number and density. Various applications, including optoelectronics and sensors, commonly use it. ZnS generally has a lower attenuation length compared to ZnO. Its lower atomic number and different bonding characteristics contribute to its higher absorption of X-rays, making it suitable for specific optical applications. ZrC, being a refractory compound with a higher atomic number, typically shows a greater X-ray attenuation length. This property makes it useful in high-temperature applications and as a protective coating. ZrN also exhibits a high attenuation length, similar to ZrC. Its robust structure and higher density contribute to effective X-ray shielding, making it ideal for applications in protective coatings and cutting tools.

Zinc Oxide (ZnO), Zinc Sulfide (ZnS), Zirconium Carbide (ZrC), and Zirconium Nitride (ZrN) all have very different X-ray attenuation lengths that depend on their atomic makeup and density. ZnO and ZnS are more suitable for optical applications, while ZrC and ZrN offer better performance in high-temperature and protective applications. Understanding these differences is crucial for selecting the appropriate material for specific technological purposes.

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