

**RADIATION SHIELDING PARAMETERS FOR
COMPOSITE PARTICLEBOARD ADDED BaSO_4
AND Bi_2O_3 AT ORTHOVOLTAGE ENERGY
RANGE**

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AND Bi₂O₃ AT ORTHOVOLTAGE ENERGY
RANGE**

by

SITI NOR AZIZAH BINTI ABDULLAH

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LIST OF SYMBOLS

%	Percentage
°	Degree
°C	Degree in Celcius
μ	Linear Attenuation Coefficient
μ/ρ	Mass Attenuation Coefficient
μm	micrometre
^{133}Ba	Barium-133
^{241}Am	Americium-241
^{57}Co	Cobalt-57
$^{99\text{m}}\text{Tc}$	Metastable Nuclear Isomer of Technetium-99
D_0	Average Particle Size
N_e	Effective Electron Number
nm	nanometer
Z	Atomic Number
Z_{eff}	Effective Atomic Number

LIST OF ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
B ₂ O ₃	Boron Trioxide
BaO	Barium Oxide
BaSO ₄	Barium Sulphate
Bi ₂ O ₃	Bismuth (III) Oxide
B-UHPC	Barite Ultra High-Performance Concrete
CT	Computed Tomography
Cu ₂ S	Copper Sulphate
DSC	Differential Scanning Calorimetry
DSF	Defatted Soy Flour
DTG	Derivative Thermogravimetric
EDX	Energy Dispersive X-ray Spectroscopy
EM	Electromagnetic
Fe ₂ O ₃	Hematite/Iron (III) Oxide
FTIR	Fourier Transform Infrared Spectroscopy
HVL	Half Value Layer
IA-PAE	Itaconic Acid Polyamidoamine-Epichlorohydrin
ICRP	International Commission on Radiological Protection
JIS	Japanese Industrial Standard
keV	Kilo-electron Volt
kV _p	Kilo-voltage Peak
MCA	Multichannel Analyser
MCNP	Monte Carlo N-particle Transport
MeV	Mega-electron Volt
MFP	Mean Free Path
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MPa	Mega-Pascal
NaOH	Sodium Hydroxide
NR	Natural Rubber
Pb _{eq}	Lead Equivalent Thickness

PVC	Polyvinyl Chloride
ROI	Region of Interest
RPE	Radiation Protection Efficiency
SEM	Scanning Electron Microscopy
SPC	Soy Protein Concentrate
SPECT	Single Photon Emission Computed Tomography
SPI	Soy Protein Isolate
TG	Thermogravimetric
TGA	Thermogravimetric Analyzer
TiO ₂	Titanium Dioxide
TS	Thickness Swelling
TVL	Tenth Value Layer
WA	Water Absorption
WO ₃	Tungsten (VI) Oxide
XCOM	X-ray Computed
ZnO	Zinc Oxide

**PARAMETER PERLINDUNGAN SINARAN BAGI PAPAN PARTIKEL
KOMPOSIT YANG DITAMBAH BaSO_4 DAN Bi_2O_3 PADA JULAT TENAGA
ORTHOVOLTAGE**

ABSTRAK

Komposit berasaskan kayu semakin mendapat perhatian sebagai bahan perlindungan sinaran disebabkan sifatnya yang ringan, potensi untuk penambahbaikan ciri-cirinya, serta kesesuaiannya untuk pelbagai aplikasi. Kajian ini dihasilkan untuk mengkaji papan partikel komposit baharu yang ditambah dengan logam sebagai bahan yang setara dengan plumbum untuk perlindungan sinaran. Kayu bakau dari spesies *Rhizophora Apiculata* dipilih sebagai bahan asas untuk pembuatan komposit kayu-logam kerana ketumpatannya yang tinggi, yang menggalakkan sifat pengecilan yang berkesan. Barium sulfat (BaSO_4) dan bismut (III) oksida (Bi_2O_3) digunakan sebagai komponen tambahan logam dalam bahan komposit papan partikel. Partikel kayu diikat dengan resin epoksi untuk menghasilkan sampel papan partikel yang mengandungi komposisi logam yang berbeza. Sifat fizikal, mekanikal, dan kestabilan dimensi telah dinilai, termasuk prestasi penyerapan radiasi dan ketebalan setara plumbum (Pb_{eq}), menggunakan alat ukur Pb_{eq} dengan pemancar gama pada tenaga 59 keV, 122 keV dan 356 keV. Hasil kajian menunjukkan penambahan unsur logam telah meningkatkan ketumpatan dari 1.08 hingga 1.33 g/cm³ dan kestabilan haba papan partikel komposit. Ujian pembengkakan ketebalan berjaya memenuhi syarat di bawah 12% yang disyorkan oleh Standard Industri Jepun (JIS) untuk semua sampel papan partikel. Penambahan resin epoksi meningkatkan sifat hidrofobik permukaan komposit dengan ketara. Komposisi unsur yang diperolehi digunakan untuk mengira nombor atom berkesan (Z_{eff}) dan nombor elektron berkesan (N_e) yang memberikan nilai antara 43 hingga 76, dan

$6.1 \times 10^{23} \text{ e/cm}^3$ hingga $8.1 \times 10^{23} \text{ e/cm}^3$, masing-masing, bagi sampel yang ditambah logam. Selain itu, pekali penyerapan linear (μ) papan partikel komposit yang ditambah logam meningkat daripada 0.848 hingga 1.297 cm^{-1} apabila kandungan $\text{BaSO}_4/\text{Bi}_2\text{O}_3$ meningkat manakala pekali penyerapan jisim (μ/ρ) meningkat dari 0.664 hingga $0.970 \text{ cm}^2/\text{g}$. Nilai μ dan μ/ρ bagi sampel papan partikel komposit yang ditambah dengan 40% Bi_2O_3 lebih tinggi daripada konkrit barit pada semua tenaga foton yang diuji. Nilai separuh lapisan nilai (HVL) dan laluan bebas purata (MFP) berkurang apabila kandungan $\text{BaSO}_4/\text{Bi}_2\text{O}_3$ ditingkatkan. Kecekapan perlindungan sinaran untuk semua papan partikel komposit berkurang dengan peningkatan tenaga foton gama. Kesan ketebalan papan partikel terhadap transmisi foton menunjukkan bahawa papan yang lebih tebal dan mengandungi lebih banyak logam menyerap lebih banyak sinaran. Hasil analisis Pb_{eq} bagi 2.0 dan 1.0 mm Pb, papan partikel dengan 40% Bi_2O_3 memerlukan ketebalan masing-masing 4 cm dan 2 cm pada tenaga 59 keV. Kesimpulannya, papan partikel dengan 40% Bi_2O_3 menunjukkan keupayaan perlindungan terbaik, diikuti oleh komposit dengan 30% Bi_2O_3 , dan berpotensi menggantikan plumbum dalam aplikasi perlindungan sinaran bagi julat tenaga radiologi diagnostik.

**RADIATION SHIELDING PARAMETERS FOR COMPOSITE
PARTICLEBOARD ADDED BaSO₄ AND Bi₂O₃ AT ORTHOVOLTAGE
ENERGY RANGE**

ABSTRACT

Wood-based composites have gained attention as potential radiation shielding materials due to their lightweight nature, adaptability for property enhancement, and versatility across various applications. This research studies a new metal added composite particleboard as a lead equivalent material for radiation shielding. Mangrove wood from the *Rhizophora Apiculata* species was chosen as the base material for the composite manufacturing due to its high density, which promotes effective attenuation properties. Barium sulphate (BaSO₄) and bismuth (III) oxide (Bi₂O₃) were utilised as the metal additives in the particleboard. Wood particles were bonded with epoxy resin to fabricate particleboard samples with varying compositions of metal elements. The physical, mechanical, and dimensional stability were evaluated, including radiation shielding performance and lead equivalent thickness (Pb_{eq}), using a Pb_{eq} gauge with gamma emitters at 59, 122, and 356 keV. Following characterisation, adding metal elements has increased the density from 1.08 to 1.33 g/cm³ and the thermal stability of the composite particleboards. The thickness swelling test successfully falls under the 12% recommendation by the Japanese Industrial Standard (JIS) for all particleboard samples. The addition of epoxy resin significantly enhanced the surface hydrophobicity of the composites. The elemental compositions obtained were used to calculate the effective atomic number (Z_{eff}) and effective electron number (N_e), given the values ranging from 43 to 76, and 6.1×10²³ e/cm³ to 8.1×10²³ e/cm³, respectively, for metal added composite particleboards. The linear attenuation coefficients (μ) of the metal

added composite particleboards increased from 0.848 to 1.297 cm⁻¹ as BaSO₄/Bi₂O₃ contents increased, while the μ/ρ increased from 0.664 to 0.970 cm²/g. The μ and μ/ρ values for 40% of Bi₂O₃-added particleboards were higher than those of barite concrete at all investigated photon energies. Half value layer (HVL) and mean free path (MFP) values were reduced when the BaSO₄/Bi₂O₃ contents were raised. It was observed that the radiation shielding efficiency for all composite particleboards decreased with increasing gamma photon energy. The effect of particleboard thickness on photon transmission showed that thicker boards and those with higher metal content absorbed more gamma photons. The results of Pb_{eq} analysis showed that for 2.0 and 1.0 mm Pb, the required thickness for the 40% Bi₂O₃-added particleboard sample were 4 and 2 cm, respectively, at 59 keV. In conclusion, the composite particleboards incorporated with 40% Bi₂O₃ demonstrated the optimum shielding ability, followed by those with 30% Bi₂O₃, which potentially replace lead in radiation shielding applications for the diagnostic radiology energy range.

CHAPTER 1

INTRODUCTION

1.1 Background

The advancement of technology has resulted in a rise in ionising radiation usage in various fields. Despite their benefits, gamma and X-rays are known to have adverse biological effects on people and the environment due to how they naturally interact with matter. Increasing evidence has been documented on non-cancer illnesses, such as cardiovascular ailments, cataracts, and neurological issues in response to low and moderate radiation doses, in addition to the conventional carcinogenic effect associated with extended or high-dose exposures (Ainsbury et al., 2021; Lumniczky et al., 2021; Tapio et al., 2021; Ghosh, 2022; Lowe et al., 2022). Therefore, radiation shielding is essential in areas with radioactive sources and radiation-emitting machinery like X-ray tubes and accelerators. The International Commission on Radiological Protection (ICRP) recommends the As Low As Reasonably Achievable (ALARA) approach, which can be implemented to control radiation dose by decreasing exposure time, increasing distance, and employing shielding (ICRP, 2007).

The primary purpose of structural shielding material is to limit radiation exposures for employees and the public to acceptable levels, thereby minimising unnecessary exposures. Lead is commonly chosen for shielding in building structures, mainly because it has a high atomic number (Z), which provides high attenuation of X-rays and gamma rays, and its cost-effectiveness. However, occupational exposure in facilities utilising lead, such as radiation shields, has been identified as a significant source of lead poisoning in adults (AbuAlRoos et al., 2019; Debnath et al., 2019; Kumar et al., 2020; Mahuta, 2020). Thus, ongoing research explores the development of

various non-lead shielding materials, with numerous studies investigating alternatives. Concrete is more economical and offers several advantages, including high structural strength and simplicity in forming required geometries while effectively absorbing X-rays. Nonetheless, the non-uniformity of its thickness, composition and loss of moisture when heated due to radiation energy absorption are the drawbacks of concrete (Gökçe & Andiç-Çakır, 2019; Khalaf et al., 2019; Tamayo et al., 2022; Tekin et al., 2022). Similarly, steel exhibits excellent fire resistance and absorption capabilities of X-rays and gamma rays but is notably more expensive than other shielding materials.

Hardwood has been recognised as a cheaper and renewable building material capable of providing sufficient gamma ray and neutron shielding at high density (Barman et al., 2022). Wood, in the form of particleboards embedded with heavy metal chemicals, has been explored as an effective material for gamma ray shielding as well (Özkan, 2020; Poltabtim et al., 2021; Kamarudin et al., 2022; Chang et al., 2023). The evaluation of *Rhizophora* spp. particleboard, on its physical, mechanical, and dimensional stability, has found applications in radiation dosimetry. The gamma ray's attenuation of the hardwood has shown a comparable value to that of water. (Hamid et al., 2019; Anugrah et al., 2020; Zuber et al., 2020; Azlan et al., 2024). Extensive studies have indicated that incorporating high atomic number substances and suitable adhesives enhances the physical-mechanical and radiation shielding properties of *R. apiculata* (Samson et al., 2021).

Researchers working on structural shielding materials commonly use high-density oxides: barium oxide (BaO), tungsten (VI) oxide (WO₃), boron trioxide (B₂O₃), zinc oxide (ZnO) in the composites to enhance the radiation shielding efficiency. Bi₂O₃ and BaSO₄ have shown excellent potential to effectively attenuate high energy (<1 MeV) photon beams when mixed with polymers (Noor Azman et al., 2016; Ambika et

al., 2017; Cao et al., 2020; Thumwong et al., 2022), glasses (Tekin et al., 2019; Boukhris et al., 2020; Al-Buriahi, 2023), mortar (Shalbi et al., 2021; Sousa et al., 2021) and textiles (Verma et al., 2021). Researchers have proven that both metals have key potential properties such as less toxicity, high effective atomic number and high density when mixed in various shielding materials. Furthermore, adding such metal powder enhanced the attenuation ability of the material, shown in increased linear and mass attenuation coefficient values and the decrease in HVL of the investigated material.

1.2 Problem statement

The use of lead as a shielding material in radiation protection poses significant health and environmental concerns (Ninyong et al., 2017; Rakkaew et al., 2022; Abualroos et al., 2024). Consequently, researchers and product developers have focused on developing lead-free and less hazardous materials with comparable or superior radiation attenuation properties. However, insufficient data remains on the comparative performance of lead-free composite particleboards and traditional lead-based materials. So, evaluating and comparing the radiation shielding efficacy of lead-free substitutes is crucial while aiming to shift away from lead-based shielding materials. Comprehensive studies comparing lead-free composite particleboards' performance with traditional lead-based materials are essential for selecting materials for radiation shielding applications.

The effectiveness of radiation shielding is a critical concern in various industries utilising ionising radiation. However, the inconsistency in the effectiveness of concrete and brick as radiation shields due to variations in materials and manufacturing processes poses significant challenges (Sopapan et al., 2020; Kilic et al., 2021). Despite the advanced development of lead-free, lighter, and more flexible materials as alternatives

to address these challenges, extensive work has not been done on composite particleboard in radiation protection.

Past studies that utilised alternative heavy metal additives such as Bi_2O_3 and BaSO_4 in composite particleboards introduce potential drawbacks that warrant thorough investigation (Nikbin et al., 2019; Cao et al., 2020; Intom et al., 2020; Sousa et al., 2021; Tasnim et al., 2021; Agrawal et al., 2022). While these alternative additives may offer radiation attenuation properties, their impact on structural integrity and long-term shielding effectiveness requires careful consideration.

One of the primary challenges in achieving optimal radiation shielding effectiveness is the homogenous dispersion of heavy metal additives within the particleboard (More et al., 2021; Tyagi et al., 2021). The distribution and concentration of these additives play a crucial role in determining the material's ability to attenuate radiation. Variations in dispersion can lead to uneven shielding properties, compromising the overall effectiveness of the particleboard as a radiation shield. Therefore, there is a pressing need to develop advanced manufacturing techniques and quality control processes to ensure consistent and uniform dispersion of heavy metal additives throughout the particleboard.

The potential of wood and wood-derived materials as radiation shielding remains underexplored and needs a comprehensive investigation into their physical, mechanical, and chemical properties. Particleboard composites have demonstrated comparable shielding efficacy to gypsum wallboard and brick in low-energy X-ray applications, such as dental radiography and mammography (Aggrey-Smith et al., 2016; Poltabtim et al., 2021; Muhammad et al., 2022), highlighting their suitability as radiation shielding materials. Additionally, *Rhizophora*-based composites have shown

promise as radiation attenuators due to their high density and excellent physical and mechanical stability. While their characteristics have been extensively studied following the Japanese Industrial Standard (JIS) (Al-Shipli et al., 2019; Samson et al., 2021; Zuber et al., 2022; Azlan et al., 2024), there is a lack of research on the application of *Rhizophora*-based composites as radiation shielding materials in orthovoltage radiation settings, underscoring the need for further studies in this area.

The impact of water resistance and durability on the long-term shielding performance of composite particleboards remains inadequately understood. Exposure to moisture and environmental factors can degrade the structural integrity of the particleboard, potentially compromising its radiation shielding capabilities over time (Azreen et al., 2020; Wu et al., 2023; Kaky et al., 2024). It is essential to evaluate the effects of water resistance and durability on the long-term performance of composite particleboards to develop materials that can withstand harsh environmental conditions or natural disasters without compromising their radiation shielding effectiveness.

The influence of epoxy resin's structural and functional properties on radiation shielding effectiveness requires deeper exploration. Epoxy resin is commonly used as a binder in composite particleboards, and its characteristics can significantly impact the material's overall performance as a radiation shield (Muthamma et al., 2021; Avila et al., 2022; Vishnu et al., 2023). Understanding how epoxy resin's structural and functional properties interact with radiation and influence shielding effectiveness is crucial for optimising composite particleboard design and formulation.

The interaction between particleboard composition, thickness, and radiation shielding effectiveness remains inadequately understood. The complexity of material composition, thickness variations, and radiation attenuation properties requires

comprehensive research to study the underlying mechanisms of these relationships. Investigating how factors such as heavy metal concentration, resin content and particleboard thickness influence radiation shielding effectiveness will provide valuable insights for optimising composite particleboard design for specific radiation shielding requirements.

In conclusion, addressing the challenges associated with radiation shielding effectiveness in composite particleboards requires extensive studies encompassing material science, manufacturing processes, structural analysis, and radiation physics. By focusing on understanding the impact of water resistance and durability, evaluating structural stability, exploring epoxy resin properties, comparing lead-free alternatives, assessing alternative heavy metal additives, ensuring consistent radiation attenuation, understanding material composition interactions, and establishing standardised testing methods, significant advancements can be made in developing high-performance composite particleboards for effective radiation shielding applications. This study contributes to improved safety in various ionising radiation fields by providing advanced methods to develop metal added particleboard composites and rigorous radiation shielding assessments for possibilities in shielding applications.

1.3 Research objective

The objectives of the present study are as follows:

- i. To fabricate JIS-grade particleboards incorporating BaSO_4 and Bi_2O_3 compounds to enhance their radiation shielding capabilities.
- ii. To examine the physical and mechanical characteristics of the newly developed metal added composite particleboards, with particular attention to their thermal stability and resistance to thickness swelling.

- iii. To investigate the effect of the particleboards' metal composition and physical attributes on their ability to attenuate ionising radiation, focusing on half value layer and the mean free path parameters.
- iv. To study the lead equivalent thickness for the particleboard composites when subjected to gamma photon energies of 59, 122, and 356 keV to evaluate their effectiveness as radiation shielding in these specific diagnostic energy ranges.

1.4 Scope and limitations of the research

This research aims to develop an advanced methodology for fabricating wood-metal composite particleboard, alongside establishing a comprehensive evaluation technique to determine its efficacy as a gamma radiation shielding, particularly within the energy spectrum typical of diagnostic radiology applications. *R. apiculata* mangrove wood particles and epoxy resin were used to construct the wood composites with BaSO₄ and Bi₂O₃ as metal additives. The physical, mechanical and dimensional stability properties of the selected shielding materials are evaluated following the JIS recommendations, specifically for density, thermal stability, functional group, flexural strength, thickness swelling, morphology, elemental composition, and Z_{eff} . Radiation attenuation properties are measured using a narrow beam geometry at specific energy levels of gamma photon emitters. The shielding performance of fabricated composite particleboard is evaluated and compared to existing literature. Several limitations applied to this study include the optimisation of the composite particleboard's thickness, pressed using the hot-pressing machine, which is only at 0.5 cm. Higher thickness targeted more than 0.5 cm resulted in uneven compression by the metal plates during the hot-pressing method. The maximum target density for the particleboard's

fabrication calculation is 1.2 g/cm^3 . This is due to the compression strength of the hot-pressing machine. Higher material proportions have higher moisture content, which, during compression, will expand and result in an explosion of wood dust. The gamma energies used in this study are fixed at 59, 122 and 356 keV.

1.5 Thesis structure

This thesis is structured into five comprehensive chapters. Chapter 1 introduces the entire study, with an overview of radiation safety and the principles of radiation protection. It also concisely reviews the current materials used for structural shielding. The chapter lays out the specific problems that the research aims to address and clearly states the aims, objectives, scope and limitations of the study.

Chapter 2 provides a theoretical background on the fundamental principles of X-ray and gamma rays, lead as a conventional shielding material, and previous literature reviews on structural shielding materials. Their research into radiation shielding parameters is also discussed.

Chapter 3 meticulously describes the materials and methodology used in the study. The chapter explains the process of fabricating wood composites with different compositions of BaSO_4 and Bi_2O_3 , as well as the subsequent assessments of their physical and attenuation properties. The instruments utilised throughout the study are described in detail, including an in-depth explanation of how each experiment was conducted on the metal added composite particleboards.

Chapter 4 discusses the results of all the experiments conducted in this study, including the physical, mechanical, and attenuation properties of the fabricated metal added composite particleboards. The effect of particleboard's density, composition and

thickness on the radiation shielding parameters are discussed. The shielding performance of the particleboards related to gamma photon energy is presented. Moreover, the chapter also discusses the lead equivalent thickness for the BaSO₄/Bi₂O₃-added composite particleboard as a competent shielding material in diagnostic radiology energy.

Finally, Chapter 5 concludes the thesis by summarising the findings and contributions of the study. It reflects on the implications of the findings and suggests future research in the field of radiation shielding materials.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter aims to provide relevant concepts and theories about ionising radiation and radiation shielding. Furthermore, detailed reviews of current research in shielding materials and parameters are discussed. Concise overviews are presented on conventional radiation shielding, wood composite as shielding materials and the characterisation methods employed in assessing the radiation shielding properties.

2.2 Ionizing radiation and atomic structure

Radiation refers to the process by which energy travels through space or a medium. It encompasses a broad spectrum of energy forms as waves or particles. There are two types of radiation: electromagnetic radiation (e.g., light and radio waves) and particle radiation (e.g., alpha and beta particles, along with neutrons).

Electromagnetic radiation (Figure 2.1) refers to a wide range of energy that travels through space in a waveform. This broad category, divided into ionising and non-ionising radiation, includes visible light, radio waves, microwaves, X-rays and gamma rays, all of which have distinct energy levels and properties. This understanding is crucial in fields such as medical imaging, where the unique properties of each type of radiation are utilised for distinct purposes.

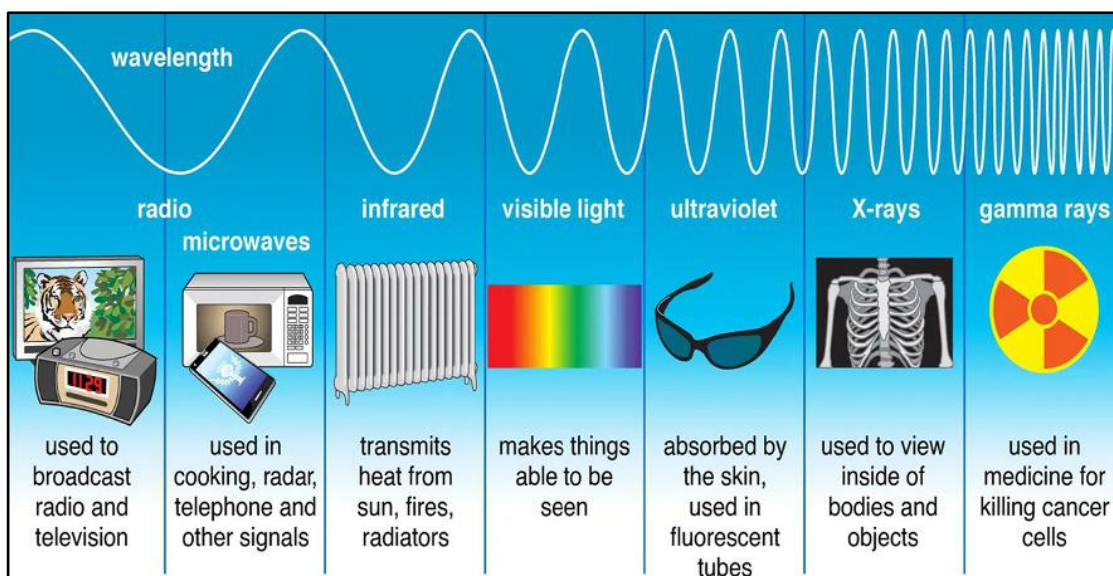


Figure 2.1 The electromagnetic spectrum (Verma & Srivastava, 2024).

Particle radiation refers to the release of subatomic particles during radioactive decay processes. Alpha and beta particles stand out among these particles, each with unique characteristics. These unique properties have important implications for various applications, particularly radiation protection and medical uses.

2.2.1 Ionising radiation

Ionising radiation, characterised by its ability to remove electrons from atoms and induce ionisation, plays a crucial role in various fields, including medicine, industry, and research. Ionising radiation encompasses two primary types: X-rays and gamma rays. X-rays, discovered by Wilhelm Roentgen in 1895, are electromagnetic radiation with wavelengths shorter than ultraviolet light and have found extensive applications in medical diagnostics. X-ray radiography is a widely used diagnostic tool that visualises internal structures such as bones and organs. Furthermore, X-ray crystallography emerges as a cornerstone in understanding the structures of crystalline materials, significantly contributing to the field of chemistry.

Gamma rays are a form of electromagnetic radiation of higher energy and shorter wavelengths, often originating from nuclear processes. They play a crucial role in nuclear medicine and industrial non-destructive testing (NDT) (Knoll, 2000; Singh et al., 2019; Deepak et al., 2021; Gupta et al., 2022). Two of the most famous nuclear medicine procedures in diagnostic radiology are Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT), which visualise tissue and organ function. In nuclear medicine facilities, shielding is incorporated into the design of the facilities. Several types of shielding materials are used in nuclear medicine, including lead, tungsten, and concrete. Walls, doors, and windows may contain lead lining. Additionally, mobile shields are positioned around patients during procedures to protect healthcare workers. Gamma rays are also used in industrial NDT to examine material integrity, detect flaws, and ensure weld quality (Wardhani, 2019; Yenumula et al., 2019; Wang et al., 2020;). Despite having similar ionisation effects to X-rays, gamma rays require specialised shielding and safety precautions due to their higher energy. While their applications remain widespread and indispensable, ongoing research efforts aim to refine techniques to ensure maximum benefits while minimising associated risks. Radiation shielding is integral to nuclear medicine to reduce these risks.

2.2.2 Structure of an atom

An atom is the smallest unit of an element in which the element's chemical identity is preserved. The atom comprises an extremely dense positively charged nucleus with protons and neutrons and a cloud of light negatively charged electrons (Bushberg, 2012). Niels Bohr's 1913 model introduced the concept of quantised electron orbits, combining Newtonian laws of motion and Coulomb's law of electrostatic attraction with quantum theory. In Bohr's atomic model, each electron has

a discrete energy state within specific electron shells, denoted by letters such as K, L, M, N, etc., with K representing the innermost shell in which the electrons have the lowest energies. These shells are also labelled with quantum numbers (1, 2, 3, etc.), with quantum number 1 assigned to the K shell, as shown in Figure 2.2. The outermost electron shell of an atom, known as the valence shell, determines the element's chemical properties. The energy required to remove an electron from its orbit completely is known as orbital binding energy. For radiation to be ionising, the energy transferred to the electron must equal or exceed its binding energy. Because electrons are so close to the positively charged nucleus, the binding energy of the K-shell is greater than that of outer shells. Notably, the binding energy increases with the number of protons in the nucleus, or atomic number. For example, a K-shell electron of bismuth with 83 protons is much more tightly bound (~ 90.5 keV) than barium with 56 protons (~ 37.4 keV).

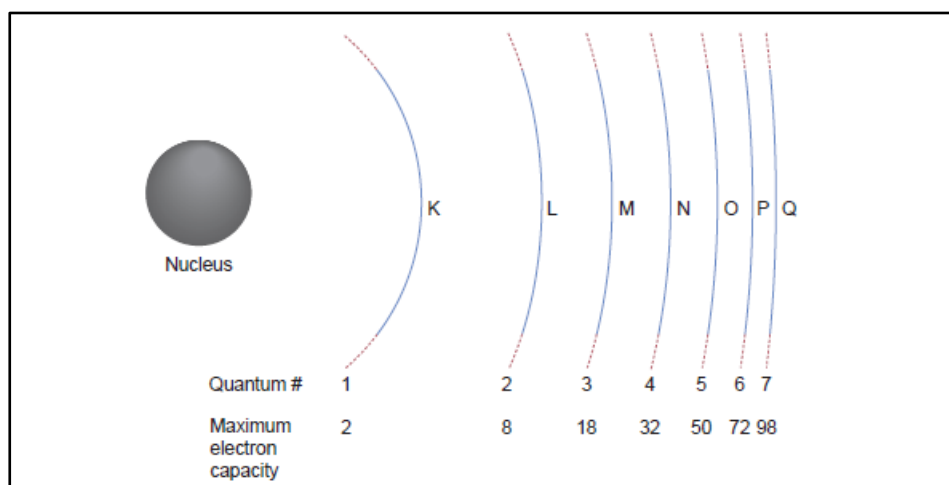


Figure 2.2 Electron shell designation of an atom (Retrieved from Bushberg, 2012).

When an electron undergoes removal from its shell due to an interaction with a photon (X-ray or gamma ray) or a charged particle, it creates a vacancy. Typically, this vacancy is filled by an electron from an outer shell, leading to a subsequent vacancy in the outer shell. This outer shell vacancy can then be filled by an electron transitioning

from a more distant shell. This sequence of transitions is referred to as an electron cascade. Throughout this cascade, energy is released in the form of an X-ray photon. The energy carried by an X-ray photon corresponds to the disparity in binding energy between the electron's initial and final shells. This energy release can manifest as characteristic X-rays or Auger electrons. Notably, the radiation's energy is distinctive for each atom, as the electron binding energy depends on the atomic number (Z). The arrangement of electron energy levels, unique to every element, produces characteristic X-rays with precisely defined energies. Figure 2.3 illustrates the example of the M to K shell electron transition of a tungsten atom, resulting in a characteristic X-ray with an energy of 67 keV.

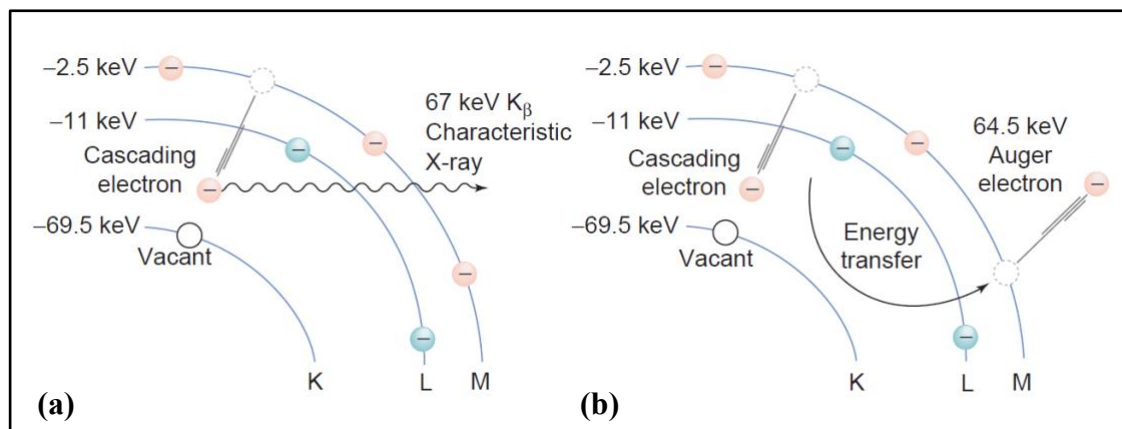


Figure 2.3 An electron transition in a tungsten atom resulting in (a) emission of 67 keV characteristic X-ray and (b) Auger electron (Retrieved from Bushberg, 2012).

2.3 X-ray and gamma ray interactions

Photons can travel through matter without interaction, scattering, or absorption (Sauerheber, 2021). X-ray and gamma ray are considered the same in that they are both photons. The primary interactions of X-ray and gamma ray photons with matter illustrated in Figure 2.4 include Compton scattering, photoelectric absorption, and pair

production, which each has essential implications, especially in diagnostic radiology and nuclear medicine.

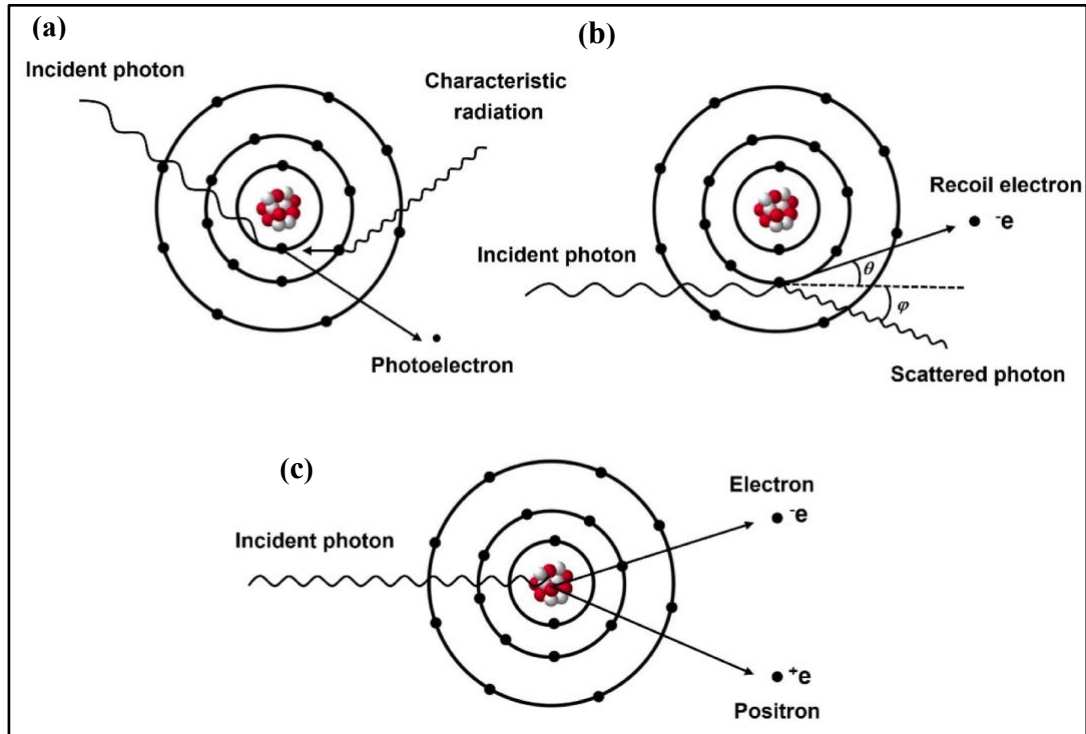


Figure 2.4 Schematic diagrams of (a) photoelectric effect, (b) Compton scattering, (c) pair production (Chang et al., 2023).

2.3.1 Mechanism of Compton scattering in radiation interaction

Compton scattering, or inelastic or nonclassical scattering, is the most common interaction of X-ray and gamma ray photons with soft tissue at diagnostic energies. Compton scattering dominates in the diagnostic energy range above 26 keV in soft tissue and continues to dominate well beyond diagnostic energies, reaching approximately 30 MeV. This interaction will likely occur between photons and outer (valence) shell electrons. The electron is ejected from the atom, and the photon is scattered with less energy than the incident photon. As with all interactions, energy and momentum must be conserved. Thus, the energy of the incident photon (E_i) is

equivalent to the sum of the energy of the scattered photon (E_{sc}) and the kinetic energy of the ejected electron (E_{e-}) expressed in Equation 2.1:

$$E_i = E_{sc} + E_{e-} \quad 2.1$$

The binding energy of the ejected electron is relatively low and can be ignored. Compton scattering ionises the atom and divides the incident photon's energy between the scattered photon and the recoiled electron illustrated in Figure 2.4b (Qiao et al., 2021).

The ejected electron will lose kinetic energy as atoms in the surrounding material are excited and ionised. The Compton scattered photon may pass through the medium without interaction or may be subjected to further interactions such as Compton scattering, photoelectric absorption, or Rayleigh scattering. As the incident photon energy increases, scattered photons and electrons scatter more in the forward direction. For a given scattering angle, the fraction of energy transferred to the scattered photon decreases as incident photon energy increases. Thus, most of the energy is transferred to the scattered electron for higher-energy incident photons. A Compton interaction will likely occur if the incident photon energy is significantly greater than the electrons' binding energy. As incident photon energy increases, so does the relative probability of a Compton interaction compared to Rayleigh scattering of photoelectric absorption. Electron density (number of electrons/g $\times$ density) also affects the probability of Compton interaction.

2.3.2 Photoelectric absorption in matter

The photoelectric effect, first observed by Albert Einstein in 1905, occurs when an incident photon collides with an atom, expelling an electron from its inner shell. This interaction is significant at lower energies and proportional to the material's atomic

number (Z). The expelled electron is known as a photoelectron, and its kinetic energy reveals essential information about the incident radiation. The kinetic energy of the ejected photoelectron (E_{pe}) is calculated by subtracting the orbital electron's binding energy (E_b) from incident photon energy (E_i) expressed by Equation 2.2:

$$E_{pe} = E_i - E_b \quad 2.2$$

For photoelectric absorption to occur, the incident photon energy must exceed or equal the binding energy of the ejected electron. The probability of characteristic X-ray emission diminishes with the decreasing atomic number of the absorber. As shown in Figure 2.5, the likelihood of the photoelectric effect for each element varies with energy and displays distinct and abrupt discontinuities referred to as absorption edges. These absorption edges arise when the photon energy slightly exceeds the binding energy of inner shell electrons, increasing the probability of photoelectric absorption. As a result, this process significantly increases the number of electrons available for interaction. This phenomenon is significant in high- Z elements such as barium and bismuth when dealing with X-rays in the diagnostic energy range.

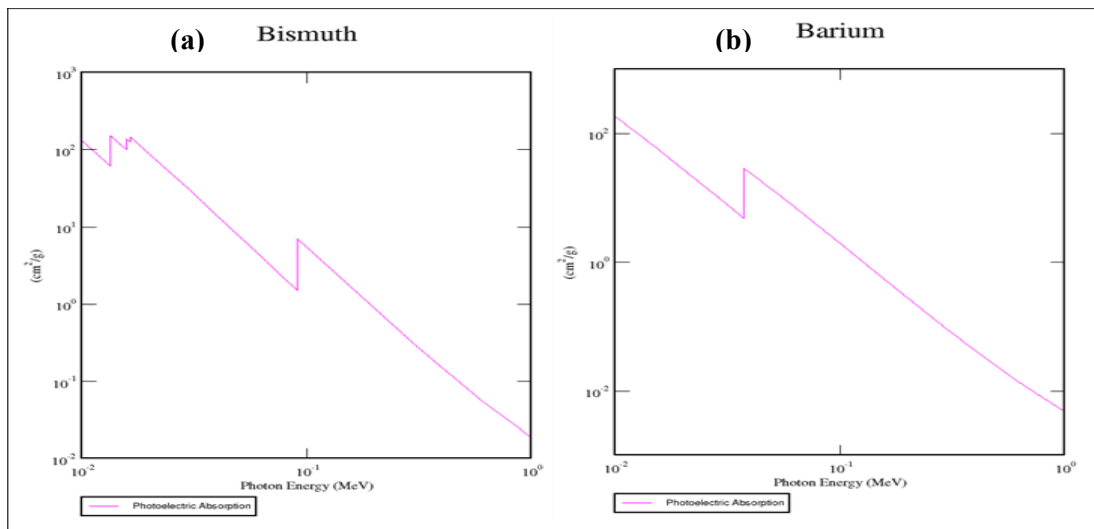


Figure 2.5 Photoelectric absorption for (a) bismuth and (b) barium obtained from XCOM (simulated using XCOM, 2024).

2.3.3 Pair production phenomenon in high-energy radiation

Pair production occurs only when the energies of X-rays and gamma rays exceed 1.02 MeV. During pair production, an X-ray or gamma ray interacts with the electric field of an atom's nucleus. The following energy is converted into an electron-positron pair. The rest mass energy equivalent of each electron is 0.511 MeV, which explains why the energy threshold for this reaction is 1.02 MeV. Diagnostic X-ray imaging produces no pair production interaction because the threshold photon energy is significantly higher than that used in medical imaging. Pair production becomes insignificant until the photon energy exceeds the 1.02 MeV energy threshold significantly.

The photoelectric effect is more prevalent at lower energies, with a significant increase in high atomic number materials. As energy levels rise, pair production becomes the dominant mechanism, and its efficacy is frequently increased in materials with higher atomic numbers. Understanding these interactions aids in the design of shields that reduce radiation penetration, limit human exposure, and minimise the impact on radiation-sensitive equipment. Shielding strategies must be tailored to the characteristics of the radiation sources and the specific needs of the environment or application.

2.4 Attenuation of X-rays and gamma rays in matter

Attenuation is the process of removing photons from an X-ray or gamma ray beam as it travels through matter. It is caused by the absorption and scattering of primary photons that interact with a specific thickness absorber material. The attenuation coefficient is the sum of the coefficients of various interaction modes, including the

photoelectric effect and Compton scatter. The proportion of each effect is determined by radiation energy and absorber properties.

2.4.1 Linear attenuation coefficients (μ) in material characterisation

The μ is an essential parameter for understanding how X-rays and gamma rays are attenuated when passing through matter and is a crucial parameter for estimating photon interaction probability. The μ indicates the likelihood of photon interaction per unit distance travelled through a material. The Beer-Lambert law, expressed as Equation 2.3, uses μ to measure monoenergetic photon intensity attenuation as it passes through a material.

$$I_t = I_0 e^{-\mu x} \quad 2.3$$

where I_t and I_0 represent the transmitted and attenuated photon intensity at the reference point, while x represents the thickness of the material. The relationship between μ and the shielding materials is critical for designing effective radiation shielding since it is directly related to a material's ability to attenuate radiation. Higher μ values indicate excellent absorption and attenuation, making materials more effective for radiation shielding (Chang et al., 2023). The μ also influences the choice of shielding materials. Materials with higher atomic numbers, densities and compositions have higher μ , making them good candidates for effective radiation shielding (Kaur et al., 2019). The energy dependence of the μ is a critical consideration. Understanding how μ varies with radiation energy levels is crucial for selecting materials that offer effective shielding across different energies.

Overall, the relationship between the μ and shielding materials is multifaceted. It influences material selection, thickness optimisation, energy-dependent considerations, and the development of effective multilayer shielding strategies.

2.4.2 Principles of mass attenuation coefficient (μ/ρ)

The probability of interaction for any given material and thickness is proportional to the number of atoms per volume. This dependency can be overcome by normalising the μ for the material density expressed as μ/ρ . The attenuation of compounds, Equation 2.3, can be rewritten as Equation 2.4:

$$N_t = N_0 e^{-\left(\frac{\mu}{\rho}\right)t} \quad 2.4$$

where N_t and N_0 represent the transmitted and attenuated photon intensity at the reference point, while t represents the thickness or areal thickness. For heterogeneous media, the mixture rule expresses the μ/ρ of a mixture of elements as follows (Singh et al., 2004):

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad 2.5$$

where ρ is the density of the material, w_i is the weight fraction of constituent element given by Equation 2.6:

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad 2.6$$

where n_i and A_i are the number of atoms and atomic weights of i^{th} element, respectively. The maximum error of the experimental μ/ρ ($\Delta(\mu/\rho)$) can be calculated from errors in the number of the net counts, thickness, and areal density (ρ) of the material using the propagation of error relation denoted by Equation 2.7 (Kumar et al., 2020):

$$\Delta\left(\frac{\mu}{\rho}\right) = \frac{1}{\rho x} \sqrt{\left(\frac{\Delta N_t}{N_t}\right)^2 + \left(\frac{\Delta N_0}{N_0}\right)^2 + \ln\left(\frac{N_t}{N_0}\right)^2 \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta x}{x}\right)^2} \quad 2.7$$

where ΔN_0 , ΔN_t , Δx and $\Delta \rho$ are the uncertainty in the net count without and with a thickness of absorber material, material thickness and density, respectively.

2.4.3 Half value layer (HVL) and tenth value layer (TVL)

In radiation physics and radiological protection, the half value layer (HVL) and tenth value layer (TVL) are crucial parameters that denote the material thickness required to reduce the intensity of a penetrating radiation beam by half and one-tenth of its original value. These parameters provide a practical measure of how well a shielding material can attenuate ionising radiation, particularly X-rays and gamma rays. HVL and TVL depend on several factors, including the photon energy, the atomic number (Z), and the density of the shielding material. Materials with higher atomic numbers and densities generally exhibit lower HVL and TVL values, indicating better attenuation performance. The choice of shielding material is critical in many applications, including medical and industrial radiography and radiation therapy. Understanding the material-specific behaviour of HVL/TVL helps to select and optimise shielding materials.

For a monoenergetic incident photon beam, the HVL and TVL can be easily calculated from the μ given by the following equation (Kaewjaeng et al., 2019):

$$HVL = \frac{\ln 2}{\mu} \quad 2.8$$

$$TVL = \frac{\ln 10}{\mu} \quad 2.9$$

Several researchers have studied the HVL of different materials used for radiation shielding. For instance, ALMisned et al. (2024) evaluated the HVL of concretes made with boron carbide (B₄C), iron (Fe), and iron boride (FeB), and found that adding iron significantly improved the shielding performance. Among the tested samples, the 20% iron and 80% concrete mixture showed the best attenuation capability. Similarly, Barman et al. (2022) investigated the shielding effectiveness of various wood

types with different densities. Their results showed that denser wood species had lower HVL values, especially at lower photon energies, indicating better shielding performance. In the field of composite materials, Marzban et al. (2025) examined polyethylene composites containing different metal oxides. They found that increasing the amount of bismuth oxide significantly reduced HVL across a wide photon energy range (0.015–10 MeV), demonstrating enhanced attenuation efficiency.

In summary, HVL and TVL are vital indicators of radiation attenuation efficiency. Prior studies consistently show that materials with higher atomic numbers and densities, such as bismuth and barite-based composites, are effective for radiation shielding.

2.4.4 Mean free path (MFP) as a radiation shielding parameter

The mean free path (MFP) is the distance a particle travels through a substance before experiencing a substantial interaction. It is impossible to predict the precise location of an individual photon using any method. Nonetheless, the average distance travelled prior to interaction can be determined using the beam's μ expressed in Equation 2.10:

$$MFP = \frac{1}{\mu} \quad 2.10$$

Several studies have investigated MFP values in different shielding materials. For example, EL Azzaoui et al. (2025) simulated the MFP of hybrid concrete mixed with heavy metal oxides, such as barite, iron-limonite and luminite-colemanite-barite. Their results showed that iron-limonite concrete has strong photon attenuation with an MFP of 3.23 cm at 1.33 MeV. Additionally, Kamislioglu (2021) studied the MFP of bismuth borate glasses and reported that materials with the highest compositions at 25%

of Bi₂O₃ showed the lowest MFP values, making them superior shielding properties for gamma radiation in combination with charged particles.

These studies highlight that MFP is influenced by both the composition and types of metal additives and the energy of the incident radiation. Understanding and comparing MFP values helps select suitable materials for radiation protection across different energy levels.

2.5 Concepts and applications of radiation protection

Although X-rays have many practical uses, their ionising characteristics may present potential health hazards. X-rays can adversely affect biological tissues when exposed in excess, causing concern in medical settings. Ongoing efforts by researchers to enhance imaging techniques are focused on reducing radiation doses without compromising diagnostic effectiveness (Goodman et al., 2019; Schicchi et al., 2020; Schuemann et al., 2020; Lu et al., 2021; Najjar, 2023).

Radiation protection is a set of principles and practices designed to reduce the risks of ionising radiation exposure. These principles are the main pillars in radiation safety programs in any facility using radiation sources (Bawazeer et al., 2023), including:

Justification: According to the principle of justification, any radiation exposure must be justified by potential benefits that outweigh the associated risks. This principle is fundamental in medical radiation applications, where diagnostic or therapeutic procedures should only be performed when the expected benefits to the patient outweigh the potential risks of radiation exposure.

Optimisation: Optimisation emphasises the importance of reducing radiation exposure to individuals and the environment while achieving the objectives of the radiation application. This principle promotes the use of appropriate radiation doses, techniques, and protective measures to reduce unnecessary exposure while maintaining the quality of diagnostic or therapeutic outcomes.

Dose Limitation: The principle of dose limitation establishes dose limits for occupational exposure, public exposure, and individual exposure during medical procedures. These dose limits are based on scientific evidence and risk assessments to avoid deterministic effects while reducing the risk of stochastic effects like cancer induction and hereditary effects.

Dose Constraints: Dose constraints provide additional guidance for controlling radiation exposure in cases where dose limits are not applicable or feasible. These constraints are valuable tools for optimising radiation protection measures and ensuring that exposures are kept as low as reasonably possible while considering societal and economic factors.

Exposure control methods are critical for reducing radiation doses to people in a variety of settings, including medical imaging, nuclear industries, and research facilities. The methods include:

Reducing Exposure Time: Limiting people's exposure to ionising radiation helps reduce their total radiation dose.

Increasing Distance: The inverse square law states that radiation intensity decreases as the square of the distance from the source. In medical imaging, positioning patients and personnel further away from the radiation source, such as an X-ray tube or radioactive material, reduces radiation exposure.