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1 Introduction

Radiation is used in various fields, including medical treatment, industry, and research. Radiation is a form of energy that can have both beneficial and harmful effects on living organisms. Therefore, it is important to accurately measure and monitor the levels of radiation to which individuals are exposed. Radiation exposure is a major concern in various fields, including medical treatment, industry, and research. Accurate measurement and monitoring of radiation levels are crucial to prevent the harmful effects of radiation exposure. It is crucial to accurately measure and monitor radiation doses to ensure the safety of individuals working with radiation sources and to evaluate the potential risks associated with radiation exposure. **Thermoluminescence dosimetry (TLD)** is a well-established technique that provides reliable and precise measurements of ionizing radiation doses. TLDs use a variety of materials that emit light when exposed to ionizing radiation. Among these materials, nanophosphors show promising properties that make them a potential candidate for use in TLDs. The aim of this research is to investigate the thermoluminescent properties of synthesized nanophosphors for use in radiation dosimetry.

1.1 Radiation

Radiation is an integral part of our natural environment and encompasses various forms of energy emitted by atoms and subatomic particles. It is both a natural phenomenon and a byproduct of human activities, playing significant roles in numerous scientific, medical, and technological fields. While radiation has beneficial applications in areas such as medicine, energy production, and communication, it can also pose risks to human health and the environment. Understanding the nature, types, sources, and effects of radiation is essential for ensuring its safe and responsible use. Radiation is the transfer of energy through electromagnetic waves or subatomic particles. It occurs in various forms, including electromagnetic radiation (such as gamma rays, X-rays, ultraviolet, visible light, and radio waves) and particulate radiation (such as alpha particles, beta particles, and neutrons). Each type of radiation possesses unique properties and interacts differently with matter. Radiation can therefore be classified based on the way it interacts with matter as shown in Figure 1

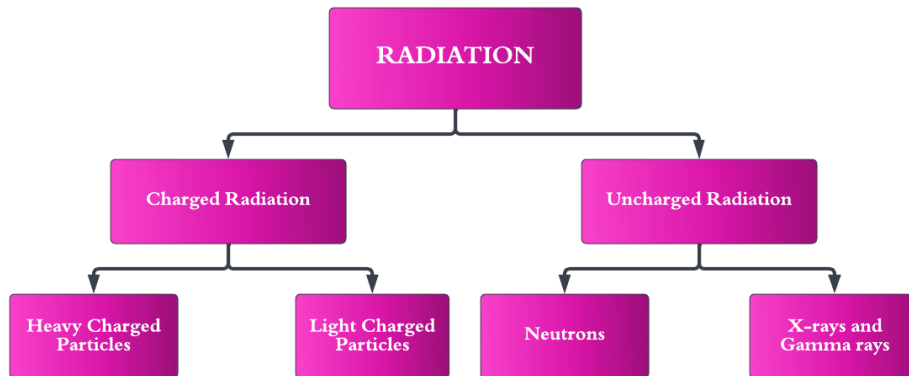


Figure 1: Classification of radiation

• Uncharged Radiation

A.) **X-Ray and Gamma Rays:** Gamma Rays and X-rays interact with matter through 3 main processes :-

- (a) **Photoelectric Effect:** In this process, a photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place, an energetic *photo-electron* is ejected by the atom from one of its bound shells. The energy of the photo-electron is given by:

$$E_{e^-} = h\nu - E_b$$

where E_b is the binding energy of photo-electron in its original shell.

- (b) **Compton Scattering:** In this process, the incoming γ -ray photon strikes an electron in the absorber medium and the γ -ray is deflected through an angle θ with respect to its original position. The photon transfers a portion of its kinetic energy to the electron, which is known as recoil electron. The amount of energy transferred depends on the angle of scattering θ . The energy of the scattered photon is given by:

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1 - \cos \theta)}$$

where m_0c^2 is the rest mass energy of electron.

- (c) **Pair Production:** If the γ -ray energy exceeds twice the rest-mass energy of electron (1.02 MeV), the process of pair production is energetically possible. In this interaction, the γ -ray photon disappears and is replaced by an electron-positron pair.

B.) **Neutrons:** Neutrons are generally difficult to detect as their interaction with matter is very less and can travel large distances without causing any interactions and hence can be detected only through indirect methods depending on its speed. **Slow Neutrons** do not directly interact with detector atoms, however they have a high probability of causing neutron induced nuclear reactions which in turn produce secondary particles/radiation which can be detected. While **Fast Neutrons** with high Kinetic Energies are mainly detected through scattering. For example, for reactions with moderators like hydrogen, the recoil neutrons become secondary radiation. If Kinetic Energy of neutrons is sufficiently high, inelastic collisions occur with detector atoms causing nucleus to excite to higher states, the excited nucleus quickly de-excite to release radiation, which can then be detected.

- **Charged Radiation** Charged particles interact with matter through *Coulomb Forces* between the radiation and the detector. These particles interact simultaneously with many electrons and in one such encounter, the electron receives sufficient impulse from Coulomb force of the passing particle to excite the electron to higher state (*excitation*) or completely remove the electron from the atom (*ionization*). The average energy loss is given by the **Bethe-Bloch**[16] formula:

$$\frac{dE}{dx} = -K \frac{Z}{A} \frac{\rho}{\beta^2} \left\{ \ln \frac{2mc^2\beta^2 E_M}{I^2(1 - \beta^2)} \right\}$$

where β is the velocity (in units of c) of particle, $K = \frac{2\pi N z^2 e^4}{mc^2}$ and $E_M = \frac{2mc^2\beta^2}{1 - \beta^2}$ is the maximum energy transfer allowed.

Sources of Radiation

Sources of radiation can be categorized into two main groups [2]: natural sources and artificial (or man-made) sources. The average annual radiation dose is shown in figure 2

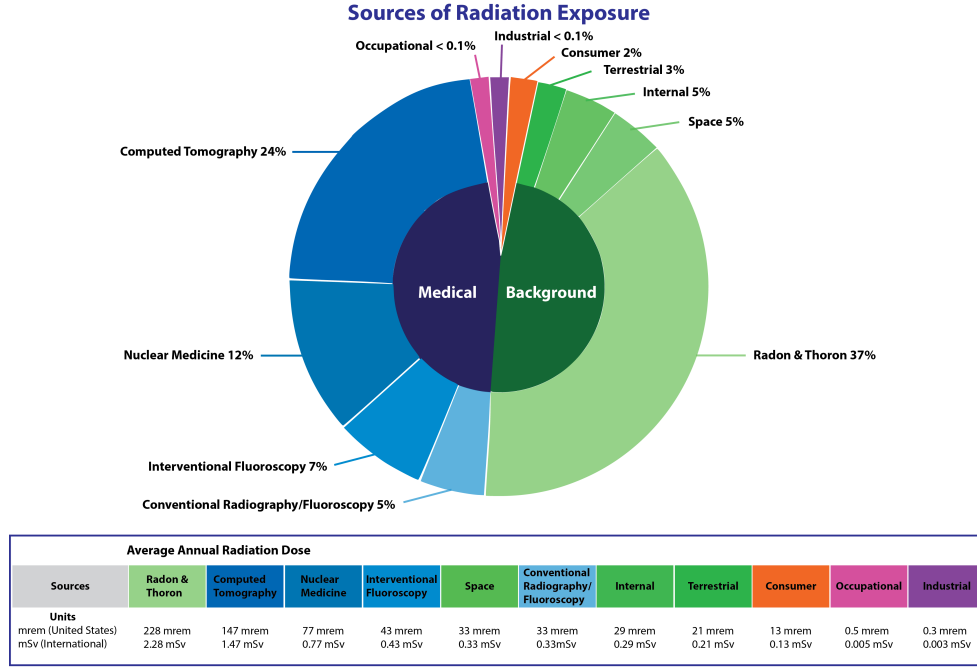


Figure 2: Average Annual Radiation Dose[17]

A.) Natural Sources of Radiation:

- **Cosmic Radiation:** High-energy particles, such as protons and atomic nuclei, that originate from outer space and reach the Earth's atmosphere.
- **Terrestrial Radiation:** Naturally occurring radioactive elements present in the Earth's crust, such as uranium, thorium, and radon gas.
- **Radon Gas:** A radioactive gas that is released from the decay of uranium and thorium in rocks, soil, and water. It can accumulate in buildings, particularly in basements and poorly ventilated areas.
- **Radioactive Isotopes in the Environment:** Small amounts of radioactive isotopes, such as potassium-40 and carbon-14, are naturally present in the environment and contribute to background radiation.

B.) Artificial (Man-Made) Sources of Radiation:

- **Medical and Dental Procedures:** Diagnostic imaging techniques like X-rays, computed tomography (CT) scans, and nuclear medicine procedures involve the use of ionizing radiation.
- **Radiation Therapy:** High-energy radiation, such as X-rays or gamma rays, used to treat cancer and other medical conditions.
- **Nuclear Power Plants:** Nuclear fission in reactors generates heat and electricity but also produces low-level radiation during normal operation and potential radioactive releases during accidents.
- **Industrial Applications:** Industrial radiography, gauging, and research activities that involve the use of radiation for inspection, measurement, and scientific experiments.

A chart depicting the levels of ionizing radiation is given below figure 3

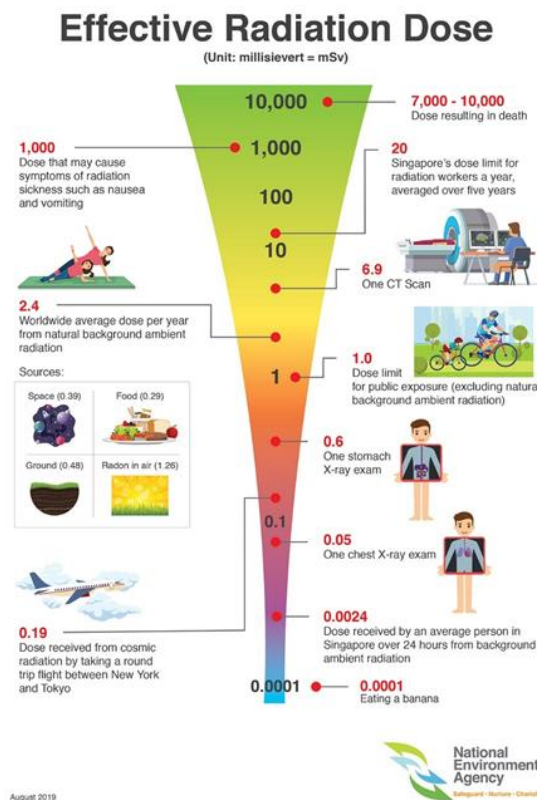


Figure 3: Effective Radiation Dose [1]

Effects of Radiation

The effects of radiation on living organisms can be divided into two main categories: deterministic effects and stochastic effects. These effects depend on various factors, including the type of radiation, the dose received, and the duration of exposure. Here is an overview of the different effects of radiation:

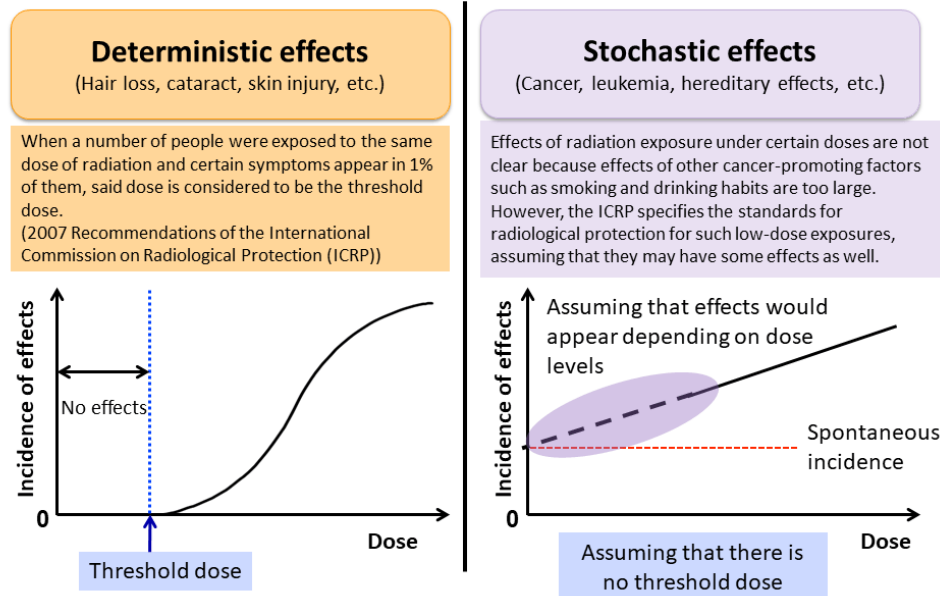


Figure 4: Deterministic and Stochastic Effects of Radiation [14]

A.) **Deterministic Effects:** Deterministic effects, also known as non-stochastic effects, occur when an individual is exposed to high levels of radiation. These effects have a clear threshold dose below which no adverse effects are observed. As the dose increases above the threshold, the severity of the effects increases. Key deterministic effects include:

- **Radiation Sickness:** At high doses, radiation can cause radiation sickness, also known as acute radiation syndrome. Symptoms may include nausea, vomiting, fatigue, diarrhea, loss of appetite, and decreased blood cell counts. The severity and onset of symptoms depend on the radiation dose received.
- **Skin Burns:** High doses of radiation can cause severe burns on the skin, similar to thermal burns. These burns can be painful and may require medical attention.
- **Organ Damage:** Radiation exposure can result in damage to specific organs, such as the gastrointestinal system, cardiovascular system, and reproductive organs. The severity of organ damage depends on the dose received and the sensitivity of the organ to radiation.

B.) **Stochastic Effects:** Stochastic effects, also called probabilistic effects, are random in nature and occur without a clear dose threshold. They are associated with long-term exposure to low or moderate doses of radiation. The probability of these effects occurring increases with higher radiation doses, but their occurrence is not guaranteed. Key stochastic effects include:

- **Increased Risk of Cancer:** Prolonged exposure to radiation, even at low doses, can increase the risk of developing cancer. Ionizing radiation has the potential to damage DNA, leading to genetic mutations that can initiate cancerous growth. The types of cancer that may develop depend on the irradiated organs and tissues.
- **Hereditary Effects:** Radiation exposure can also affect future generations. High doses of radiation to reproductive cells (sperm or eggs) can increase the risk of genetic mutations and hereditary disorders in offspring.

It is important to note that the likelihood and severity of both deterministic and stochastic effects depend on factors such as the type of radiation (e.g., gamma rays, alpha particles), the duration of exposure, and the sensitivity of the exposed individual or organism. To protect individuals and mitigate the effects of radiation, radiation protection guidelines and regulations are implemented in various fields, including medicine, industry, and nuclear power. These measures aim to minimize radiation exposure, optimize radiation practices, and ensure the safety of workers and the general public.

Applications Of Radiation

Radiation has numerous applications across various fields, including medicine, industry, agriculture, research, and energy production. Here are some notable applications of radiation:

- **Medical Imaging:** Radiation is widely used in medical imaging techniques to diagnose and monitor diseases. X-rays and computed tomography (CT) scans utilize ionizing radiation to create detailed images of the body's internal structures, aiding in the detection of fractures, tumors, and other abnormalities.
- **Radiation Therapy:** Radiation therapy, also known as radiotherapy, is a common treatment modality for cancer. High-energy radiation, such as X-rays or gamma rays, is precisely targeted to destroy cancer cells and shrink tumors. Techniques like external beam radiation therapy and brachytherapy are used to deliver radiation to specific areas of the body.
- **Nuclear Medicine:** In nuclear medicine, small amounts of radioactive substances called radiopharmaceuticals are administered to patients for diagnostic and therapeutic purposes. These substances emit gamma rays that can be detected by imaging devices to create functional images of organs and tissues, aiding in the diagnosis and treatment of various conditions.
- **Industrial Applications:** Radiation is utilized in various industrial applications, including non-destructive testing (NDT) and quality control. Radiography techniques, such as X-ray and gamma-ray imaging, are employed to inspect welds, detect flaws in structures, and assess the integrity of materials without damaging them. Radiation is also used for sterilization of medical equipment, food preservation, and insect control in agriculture.
- **Research and Scientific Studies:** Radiation plays a crucial role in scientific research, enabling scientists to study the properties and behavior of materials, molecules, and subatomic particles. Techniques such as X-ray crystallography, neutron scattering, and positron emission tomography (PET) are employed to investigate the structure, composition, and dynamics of various substances.
- **Energy Production:** Nuclear power plants generate electricity by harnessing the energy released from nuclear reactions. Controlled fission of radioactive isotopes, such as uranium-235, produces heat, which is then converted into electrical energy. Nuclear energy provides a reliable and low-carbon source of power, contributing to the global energy mix.
- **Radiation Therapy for Food Preservation:** Ionizing radiation is used to preserve food by inhibiting the growth of bacteria, molds, and insects. This technique, known as food irradiation, can extend the shelf life of perishable foods, improve food safety, and prevent the spread of foodborne illnesses.

It is worth noting that the application of radiation is carefully regulated to ensure safety and minimize potential risks. Strict guidelines, protocols, and safety measures are in place to protect individuals, the environment, and public health in all areas where radiation is used.

Radiation Protection and Safety

Radiation protection and safety encompass a range of measures and practices aimed at minimizing radiation exposure and ensuring the safety of individuals, the public, and the environment [18]. The principles of radiation protection are based on the **ALARA** principle, which stands for "*As Low As Reasonably Achievable*," as shown in figure 5



Figure 5: Principle of ALARA [13]

Here are some key aspects of radiation protection and safety:

- **Dose Limits:** Regulatory authorities and international organizations establish dose limits that specify the maximum allowable radiation doses for individuals in different contexts. These limits vary depending on factors such as occupation, public exposure, and medical procedures. Compliance with dose limits is essential to prevent excessive radiation exposure.
- **Risk Assessment and Management:** Radiation risks are assessed and managed by conducting thorough risk assessments. This involves evaluating the potential hazards associated with radiation sources, estimating the likelihood and magnitude of exposures, and implementing appropriate control measures to mitigate risks.
- **Shielding and Containment:** Shielding materials, such as lead, concrete, and steel, are used to attenuate radiation and protect individuals from exposure. Proper shielding design and construction are crucial in areas where radiation sources are used, such as medical facilities and nuclear power plants. Additionally, containment measures ensure that radioactive materials are safely stored and handled to prevent their release into the environment.
- **Personal Protective Equipment (PPE):** Personal protective equipment, such as lead aprons, gloves, and goggles, is utilized to protect individuals who work with or around radiation sources. PPE helps to reduce radiation exposure to specific body parts and ensures that workers adhere to safety protocols.
- **Training and Education:** Comprehensive training and education programs are essential for individuals who work with radiation sources. This includes radiation safety training, radiation protection protocols, proper handling and storage of radioactive materials, and emergency response procedures. Continuous education and awareness campaigns help maintain a strong safety culture.
- **Monitoring and Dosimetry:** Regular monitoring of radiation levels and individual doses is conducted to ensure compliance with safety standards and detect any potential overexposures. Dosimeters, such as **Thermoluminescent dosimeters (TLDs)** and electronic personal dosimeters (EPDs), are used to measure and record radiation doses received by individuals.
- **Regulatory Compliance and Inspections:** Regulatory bodies oversee and enforce radiation safety regulations. They conduct inspections, audits, and assessments to ensure that radiation practices comply with safety guidelines. Non-compliance can result in penalties, fines, or the suspension of operations.
- **Emergency Preparedness and Response:** Preparedness for radiation emergencies, such as accidents or incidents involving radiation sources, is crucial. Emergency response plans, evacuation procedures, and communication protocols are established to protect the public and mitigate the consequences of such incidents.

It is important to note that radiation protection and safety require a multidisciplinary approach involving collaboration among regulatory bodies, radiation safety officers, medical professionals, researchers, and workers handling radiation sources. Continuous improvement, adherence to best practices, and staying up-to-date with advancements in radiation protection are vital to ensuring the safe and responsible use of radiation.

1.2 Radiation Dosimetry

Radiation Dosimetry^[7] is the science and practice of measuring and assessing the dose of ionizing radiation received by an object or an individual. It plays a crucial role in radiation protection, medical diagnostics, and therapeutic applications. By accurately quantifying radiation doses, dosimetry enables the evaluation of potential health risks, optimization of radiation procedures, and adherence to safety standards.

Measurement Techniques

Dosimetry measurement techniques^[3] are used to directly or indirectly quantify the dose of ionizing radiation received by an object or an individual. These techniques vary depending on the type of radiation, the purpose of measurement, and the specific application. Here are some commonly used dosimetry measurement techniques:

- **Ionization Chambers:** Ionization chambers are widely employed in radiation dosimetry. They consist of a gas-filled chamber where ionization occurs when radiation interacts with the gas molecules. The resulting ion pairs are collected, and the electrical current generated is proportional to the radiation dose. Ionization chambers are versatile and can measure both high and low radiation doses accurately.

- **Thermoluminescent Dosimeters (TLDs):** TLDs are solid-state dosimeters that utilize the phenomenon of thermoluminescence. When exposed to ionizing radiation, certain crystals or materials trap energy within their lattice structure. Heating the TLD causes the trapped energy to be released as light, which is measured and correlated to the radiation dose. TLDs offer high sensitivity and can be used for personal and environmental dosimetry.
- **Film Dosimeters:** Film dosimeters use radiation-sensitive films, such as radiographic films or photographic emulsions, to measure radiation doses. The films darken when exposed to radiation, and the degree of darkening is related to the absorbed dose. Film dosimeters are commonly used in medical imaging, industrial radiography, and radiation therapy verification.
- **Solid-State Detectors:** Solid-state detectors employ semiconductor materials, such as silicon or germanium, to measure radiation doses. These detectors produce an electrical signal in response to ionizing radiation. Examples of solid-state detectors include diode detectors, silicon detectors, and metal oxide semiconductor field-effect transistors (MOSFETs). Solid-state detectors offer high precision, small size, and real-time dose measurement capabilities.
- **Scintillation Detectors:** Scintillation detectors utilize scintillating materials that emit light when exposed to radiation. The scintillation light is converted into electrical signals using photomultiplier tubes or photodiodes. Scintillation detectors are commonly used in nuclear medicine, environmental monitoring, and high-energy physics research.
- **Optically Stimulated Luminescence (OSL) Dosimeters:** OSL dosimeters use similar principles to TLDs but employ different materials. OSL dosimeters contain optically sensitive materials that store radiation energy. When exposed to light, the stored energy is released as luminescence, which is proportional to the radiation dose. OSL dosimeters are widely used in personal and environmental dosimetry.
- **Biological Dosimeters:** Biological dosimeters measure the biological effects of radiation on living cells or tissues. These dosimeters include techniques such as chromosomal aberration analysis, cytogenetic biodosimetry, and biological marker assays. Biological dosimeters are particularly useful in radiation accidents or emergencies to assess radiation exposure and estimate potential health risks.
- **Environmental Monitoring Instruments:** Environmental monitoring instruments, such as Geiger-Muller counters and scintillation detectors, are used to measure ambient radiation levels in the environment. These instruments provide real-time or continuous monitoring of radiation doses in occupational settings, nuclear facilities, or areas with potential radioactive contamination.

It is worth noting that dosimetry measurement techniques are often complemented by data analysis, calibration, and quality assurance procedures to ensure accurate and reliable results. The choice of dosimetry technique depends on factors such as the radiation type, dose range, required sensitivity, portability, and specific dosimetry application.

Types of Radiation Dosimetry

Radiation dosimetry encompasses different types of radiation and corresponding dosimetry techniques:

- **External Beam Dosimetry:** This type of dosimetry is employed in external beam radiation therapy, diagnostic imaging (e.g., X-rays, CT scans), and radiation protection. It focuses on measuring radiation doses delivered from an external radiation source to a specific target or region of interest.
- **Internal Dosimetry:** Internal dosimetry involves the assessment of radiation doses from internal radiation sources, such as radioactive materials ingested, inhaled, or injected into the body. It requires the estimation of radionuclide uptake, distribution, and elimination to calculate the radiation dose received by specific organs or tissues.
- **Environmental Dosimetry:** Environmental dosimetry aims to evaluate radiation doses in the environment, particularly in occupational settings or areas with potential radioactive contamination. It includes monitoring radiation levels in air, water, soil, and other environmental media to assess potential exposure risks.

Properties of Ideal dosimeter

An ideal dosimeter is a device or material that possesses certain key properties to accurately and reliably measure radiation doses. Here are some properties of an ideal dosimeter[15]:

- **Accuracy:** An ideal dosimeter should provide accurate measurements of radiation doses. It should have a linear response, meaning the measured dose should be directly proportional to the actual radiation dose received. The dosimeter should minimize uncertainties and errors in dose measurements.
- **Sensitivity:** The dosimeter should be highly sensitive to radiation, capable of detecting even low levels of radiation exposure. It should be able to measure doses accurately within the desired range, allowing for precise dose quantification.
- **Stability:** An ideal dosimeter should exhibit stability over time, meaning its response to radiation doses remains consistent throughout its operational lifespan. It should not show significant changes in sensitivity or response due to environmental factors or aging.
- **Energy Dependence:** The dosimeter should have minimal energy dependence, meaning it should provide consistent dose measurements across a broad range of radiation energies and types. This property ensures that the dosimeter can accurately measure doses from various radiation sources.
- **Linearity:** The dosimeter's response should be linear across a wide range of dose levels. This linearity ensures that the measured dose is directly proportional to the actual dose received, simplifying dose calculations and interpretations.
- **Tissue-Equivalent:** An ideal dosimeter should mimic the radiation absorption characteristics of human tissue. It should have similar energy deposition properties to accurately represent the dose received by biological tissues. Tissue-equivalent dosimeters provide more accurate measurements of the dose absorbed by human tissues in medical applications.
- **Readout Convenience:** The dosimeter should allow for easy and convenient readout of the accumulated dose. This could involve simple readout techniques, such as visual or electronic methods, allowing for efficient dose retrieval and interpretation.
- **Durability:** The dosimeter should be robust and durable, capable of withstanding environmental conditions and handling during usage. It should maintain its properties and performance even under challenging operational conditions.
- **Cost-effectiveness:** An ideal dosimeter should be cost-effective, considering factors such as the manufacturing cost, ease of use, and maintenance requirements. It should provide accurate dose measurements at a reasonable cost, making it accessible for various applications and users.
- **Radiation Type Independence:** The dosimeter should exhibit consistent response across different types of ionizing radiation, such as gamma rays, X-rays, and beta particles. This property ensures that the dosimeter can be used in diverse radiation environments without significant variations in its performance.

While it is challenging to achieve a dosimeter that meets all these ideal properties, ongoing research and development aim to improve dosimetry technologies and materials to enhance accuracy, sensitivity, and reliability in radiation dose measurements.

Applications of Radiation Dosimetry:

Radiation dosimetry has numerous practical applications:

- **Radiation Therapy:** In cancer treatment, radiation dosimetry is crucial for accurately delivering therapeutic radiation doses to tumor sites while minimizing radiation exposure to healthy tissues. Precise dosimetry measurements ensure effective treatment planning and monitoring of radiation therapy procedures.
- **Radiation Protection:** Dosimetry is essential for ensuring the safety of workers in radiation-related occupations. Occupational dosimetry involves monitoring radiation doses received by individuals to ensure compliance with safety regulations and implement necessary protective measures.
- **Radiological Accidents and Emergency Response:** Dosimetry plays a vital role in assessing radiation doses received by individuals involved in radiological accidents or emergencies. It aids in triaging patients, determining appropriate medical treatments, and evaluating potential long-term health effects.
- **Radiological Research:** Dosimetry is instrumental in research involving radiation, such as studying the effects of radiation on biological systems, evaluating radiation shielding materials, and optimizing radiation therapy techniques.

In summary, radiation dosimetry is an indispensable field that enables the measurement and assessment of radiation doses. By employing various measurement techniques, dosimetry contributes to radiation protection, medical treatments, emergency response, and scientific research. Accurate dosimetry practices are vital in ensuring the safe and effective use of ionizing radiation in various applications while minimizing potential health risks.

1.3 Thermoluminescence Dosimetry

Thermoluminescence Dosimetry (TLD) is a technique used to measure and assess radiation doses by exploiting the thermoluminescent properties of certain materials. It is widely employed in various fields, including medical radiation therapy, industrial radiation safety, environmental monitoring, and personal dosimetry.

The basic principle of thermoluminescence dosimetry involves the use of thermoluminescent materials, which are crystalline or amorphous substances capable of storing energy when exposed to ionizing radiation. These materials can be in the form of powders, pellets, or chips. Common thermoluminescent materials include lithium fluoride (LiF), calcium fluoride (CaF_2), and aluminum oxide ($Al_2O_3 : C$). A Thermoluminescence Dosimeter is shown in figure 6

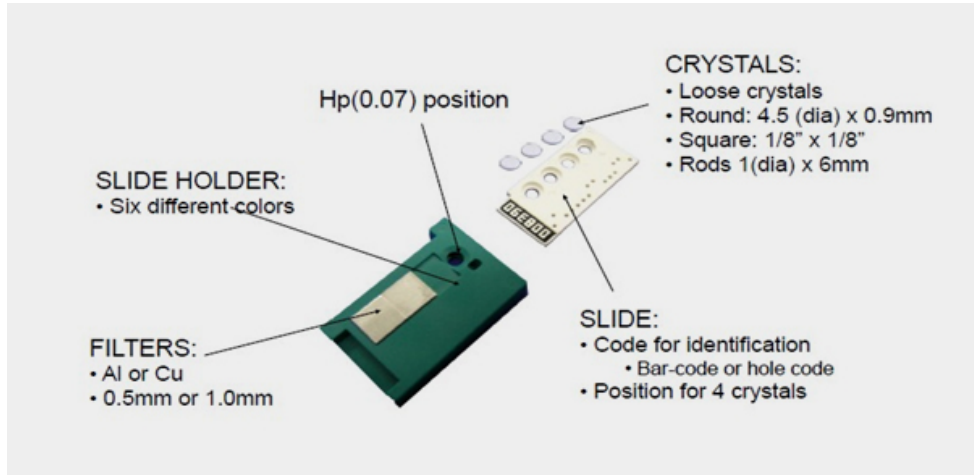


Figure 6: A thermoluminescent dosimeter [11]

Thermoluminescence

Thermoluminescence (TL) is a luminescence phenomenon[4] of an insulator or semiconductor which can be observed when the solid is thermally stimulated. In order for a material to be thermoluminous, it must first be an insulator or a semiconductor because metals do not show thermoluminescence. Secondly, energy must have been absorbed by the substance at some point while it was exposed to ionising radiation. Thirdly, heating the material causes the luminescence emission to occur. Thus, a thermoluminescent material is one that, when subjected to ionising radiation, absorbs some energy that is then stored. When the substance is later heated, the accumulated energy is released in the form of luminescence.[5]

There are many models that explain the phenomenon of thermoluminescence[8], one such model is the one trapping—one recombination centre model[12] that uses the energy band theory of solids. The majority of the electrons in an ideal crystalline semiconductor or insulator are found in the valence band. The conduction band, which is above the valence band and is separated from it by the so-called forbidden band gap (separated by energy E_g), is the highest band that electrons can inhabit. However, when a crystal has structural flaws or the lattice contains impurities, it is possible for electrons to have energies that are not permitted in a perfect crystal. In a simple TL model two levels are assumed, one situated below the bottom of the conduction band and the other situated above the top of the valence band as shown in figure 7.

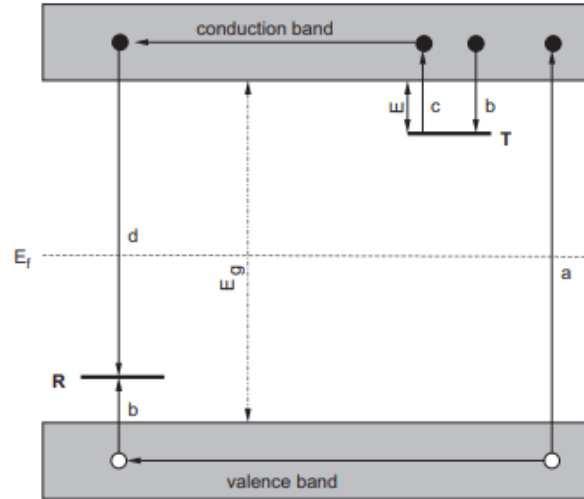


Figure 7: Energy band model showing the electronic transitions in a TL material according to a simple two-level model.[4]

The highest level is situated above the equilibrium Fermi level (E_f) and thus empty in the equilibrium state, i.e. before the exposure to radiation and the creation of electrons and holes. It is therefore a potential electron trap. The other level is a potential hole trap and can function as a recombination centre. The absorption of radiant energy with hE_g results in ionisation of valence electrons, producing energetic electrons and holes which will, after thermalisation, produce free electrons in the conduction band and free holes in the valence band. The free charge carriers recombine with each other or become trapped.

An amount of energy will be generated in the case of direct recombination, which may stimulate a luminescent centre (which might coincide with the recombination centre). Under the influence of light emission, the luminescent centre relaxes (returns to the ground state). However, in semiconductors and insulators a certain percentage of the charge carriers is trapped. As the free electrons and holes are created and annihilated in pairs, there must be an equal population of trapped holes. Because the normal equilibrium Fermi level E_f is situated below level T and above level R (as shown in figure 7), these populations of trapped electrons and holes represent a non-equilibrium state.

By increasing the temperature of the TL material above T_0 , the return to equilibrium can be accelerated. The likelihood of detrapping will rise as a result, and the electrons will then be liberated from the trap and enter the conduction band. Until it undergoes recombination at the recombination centre R, the charge carrier migrates through the crystal's conduction band. In the simple model this recombination centre is a luminescent centre where the recombination of the electron and hole leaves the centre in one of the higher excited states. Return to the ground state is coupled with the emission of light quanta, which give rise to the phenomena of **Thermoluminescence**.

Process of Thermoluminescence Dosimetry

The TLD typically involves the following steps:

1. **Pre-Irradiation:** The thermoluminescent material is first subjected to a controlled pre-irradiation process. This step ensures that any residual luminescence from previous radiation exposures is removed, allowing the material to return to its baseline state.
2. **Irradiation:** The pre-irradiated thermoluminescent material is then exposed to ionizing radiation. The type of radiation and its energy will depend on the specific application and purpose of the dosimetry measurement.
3. **Post-Irradiation:** After irradiation, the thermoluminescent material retains energy in the form of trapped electrons within defects or lattice imperfections. The sample is carefully protected from any light exposure to prevent the release of the stored energy prematurely.
4. **Heating Process:** When the thermoluminescent material is heated, the trapped electrons are released from their energy states and recombine with the trapped holes, resulting in the emission of light in the form of thermoluminescence. The emitted light is proportional to the radiation dose received by the material.

5. **Light Detection:** The emitted thermoluminescent light is detected using specialized photomultiplier tubes, photodiodes, or other light-detecting devices. The detected light signal is then converted into an electrical signal for further analysis.
6. **Analysis and Dose Calculation:** The electrical signal is analyzed to determine the intensity or luminescent response of the thermoluminescent material. This response is correlated with a calibration curve or conversion factors established through calibration with known radiation doses. By comparing the luminescent response to the calibration curve, the radiation dose received by the material can be determined.

Applications of TLD

Thermoluminescence dosimetry (TLD) has numerous applications in various fields where accurate measurement of radiation doses is essential. Some of the key applications of thermoluminescence dosimetry are:

- **Radiation Therapy:** In medical radiation therapy, TLD is used to measure the radiation dose delivered to patients during treatments such as external beam radiation therapy or brachytherapy. TLD allows for precise and reliable dose verification, ensuring that the prescribed radiation dose is accurately delivered to the target area while minimizing exposure to healthy tissues.
- **Occupational Radiation Monitoring:** TLD is extensively used in industries involving radiation sources, such as nuclear power plants, radiography facilities, and research laboratories. Workers who are potentially exposed to ionizing radiation wear TLD badges or rings, which contain TLD materials. These dosimeters are then analyzed to assess the radiation dose received by the workers, ensuring compliance with safety regulations and maintaining a safe working environment.
- **Environmental Radiation Monitoring:** TLD is employed in environmental radiation monitoring to assess radiation levels in the environment, including soil, air, and water. It helps identify potential sources of radiation and monitor any changes or increases in radiation levels that could pose risks to human health or the environment. TLD is particularly valuable in assessing long-term exposure and cumulative dose assessments in environmental studies.
- **Personal Dosimetry:** TLD is used in personal dosimetry to measure individual radiation exposure in various settings. This includes personnel working with radiation sources in nuclear facilities, research laboratories, and industrial settings. TLD badges or rings worn by individuals capture their radiation exposure, which can be analyzed to assess dose levels and ensure compliance with safety regulations.
- **Radiation Protection:** TLD is employed in the design and evaluation of radiation shielding materials and techniques. It allows for the measurement of radiation doses behind shielding materials to ensure their effectiveness in reducing exposure. TLD is also used in quality assurance tests for radiation protection equipment, such as lead aprons and protective barriers, to verify their performance and ensure proper shielding.
- **Radiation Emergency Response:** In the event of a radiological incident or accident, TLD can be used to assess the radiation doses received by affected individuals. TLD badges or rings can be distributed to emergency responders and workers involved in recovery operations, providing valuable data on their radiation exposure and guiding appropriate medical interventions.
- **Archaeological Dating:** TLD is utilized in archaeological dating to determine the age of ancient artifacts and geological samples. By measuring the thermoluminescence emitted from the material, the accumulated radiation dose can be estimated, providing insights into the time since the material was last heated or exposed to sunlight.

Thermoluminescence dosimetry offers several advantages, including high sensitivity, wide dynamic range, and excellent tissue-equivalent properties. It is capable of measuring both high and low radiation doses, making it suitable for various applications. Additionally, TLD materials have good reproducibility and stability, allowing for reliable and accurate dose measurements over time.

1.4 Nanophosphors in Dosimetry

Nanophosphors, also known as nanocrystalline phosphors or nanoparticles, have emerged as promising materials for various applications, including lighting, displays, and imaging. These nanoscale phosphors possess unique properties that make them highly desirable in these fields. Here are some key aspects of nanophosphors[6]:

- **Size and Composition:** Nanophosphors are typically composed of crystalline materials, such as oxides, sulfides, or silicates, that emit light when excited by external energy sources. They are synthesized as nanoparticles with controlled sizes ranging from a few nanometers to several tens of nanometers. The composition of nanophosphors can be tailored to achieve specific desired properties, including emission wavelength and intensity.
- **Luminescent Properties:** Nanophosphors exhibit excellent luminescent properties, including high quantum efficiency and emission stability. When stimulated by an appropriate energy source, such as ultraviolet (UV) light or X-rays, they absorb energy and subsequently emit light in a process called luminescence. This emitted light can be tuned to different wavelengths depending on the composition and size of the nanophosphor.
- **Energy Transfer:** Nanophosphors can undergo energy transfer processes, where absorbed energy is efficiently transferred from one nanophosphor to another. This property is particularly useful in applications where multiple nanophosphors are combined to achieve desired emission colors or to enhance the overall emission efficiency.
- **Narrow Emission Bandwidth:** Nanophosphors typically exhibit a narrow emission bandwidth, which allows for sharper and more precise color generation. This property is beneficial for applications requiring high color purity, such as display technologies.
- **Stability and Longevity:** Nanophosphors are known for their stability and resistance to degradation over time. They have a long lifespan and can maintain their luminescent properties even under harsh environmental conditions, making them suitable for long-term applications.
- **Compatibility and Integration:** Nanophosphors can be integrated into various host matrices, including polymers, glasses, or ceramics, to create functional materials with tailored properties. This compatibility allows for their incorporation into a wide range of devices and systems, such as light-emitting diodes (LEDs), scintillators, and optical sensors.
- **Bioimaging and Biomedical Applications:** Nanophosphors have gained attention in the field of bioimaging and biomedical applications. Their small size, stability, and tunable emission properties make them attractive for fluorescent labeling, molecular imaging, and targeted drug delivery systems.

Nanophosphors hold significant potential in advancing various technological and biomedical applications due to their unique properties, including size control, luminescent efficiency, stability, and tunability. Nanophosphors have found significant uses in the field of radiation dosimetry due to their unique properties which make it extremely suitable for use in dosimeters.

Nanophosphors in Dosimetry

Nanophosphors, also known as nanocrystalline phosphors or nanoparticles, have emerged as promising materials for dosimetry applications. These nanoscale phosphors exhibit unique properties that make them highly suitable for radiation dosimetry. Here are some key aspects of nanophosphors in dosimetry:

- **Enhanced Sensitivity:** Nanophosphors possess a high surface-to-volume ratio due to their small size, resulting in increased sensitivity to radiation. This enhanced sensitivity allows for precise and accurate measurements of radiation doses, even at low levels.
- **Stability and Retention:** Nanophosphors are known for their long-term stability and low fading rates, which ensures the reliability of dose measurements over time. They can retain the stored energy and exhibit thermoluminescence or optically stimulated luminescence properties, allowing for subsequent readout and analysis.
- **Size-Tunable Properties:** The size of nanophosphors can be precisely controlled during synthesis, allowing tailoring of their optical and luminescent properties. By manipulating the nanoparticle size, the emission wavelength and intensity can be tuned to match specific dosimetry requirements.
- **Tissue-Equivalent Properties:** Some nanophosphors have tissue-equivalent characteristics, meaning they exhibit similar radiation response to human tissues. This property is crucial in medical dosimetry, where accurate measurement of radiation doses delivered to different tissues is essential.
- **Multifunctionality:** Nanophosphors can be functionalized with various coatings or surface modifications, enabling additional functionalities. For example, they can be embedded in polymeric matrices to form composite dosimeters with enhanced mechanical properties. Nanophosphors can also be conjugated with targeting molecules for specific applications, such as targeted radiation therapy.

- **Real-Time Monitoring:** The small size and compatibility of nanophosphors with different matrices facilitate their integration into real-time monitoring systems. They can be incorporated into sensors or wearable devices, providing continuous monitoring of radiation exposure in various environments.

2 Synthesis and Characterization of Nanophosphors

The synthesis and characterization of nanophosphors for thermoluminescence dosimetry involve several steps to prepare the nanocrystalline phosphor materials and evaluate their properties. Here is a general overview of the process:

2.1 Synthesis Of Nanophosphors

Synthesis techniques for nanophosphors involve the preparation of nanocrystalline materials with controlled size, composition, and luminescent properties. Various methods are used to achieve this, and here are some commonly employed synthesis techniques for nanophosphors:

2.1.1 Co-Precipitation

The co-precipitation method[9] is a commonly used technique for the synthesis of nanophosphors, including those intended for thermoluminescence dosimetry. This method involves the simultaneous precipitation of metal cations and anions from a solution, resulting in the formation of nanocrystalline particles. The co-precipitation method offers advantages such as simplicity, cost-effectiveness, and scalability for the synthesis of nanophosphors. However, careful control of reaction conditions and post-treatment steps is essential to achieve desired particle properties and optimize the dosimetric performance of the nanophosphors for thermoluminescence dosimetry applications. Here is an overview of the co-precipitation method shown in8:

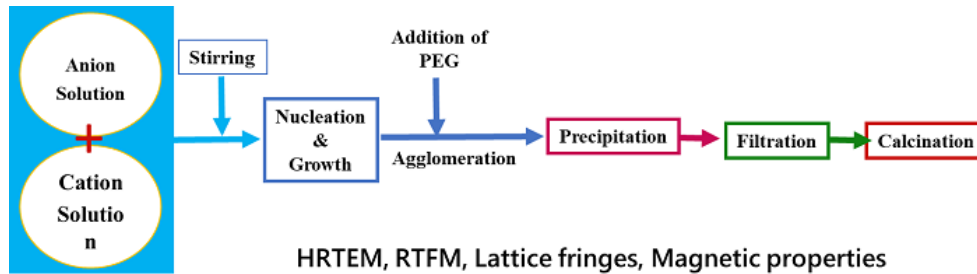


Figure 8: Synthesis using Co-Precipitation Method[19]

- **Selection of Precursor Salts:** Choose appropriate precursor salts that contain the desired metal cations and anions for the nanophosphor composition. The choice of precursors depends on the specific material being synthesized.
- **Preparation of Precursor Solution:** Dissolve the precursor salts in a suitable solvent to prepare a precursor solution. The solvent should facilitate the dissolution of the precursors and promote homogeneous mixing.
- **Control of Reaction Conditions:** Adjust the reaction conditions, including temperature, pH, and reaction time, to control the nucleation and growth of the nanophosphor particles. The reaction conditions play a crucial role in determining the size, composition, and crystallinity of the resulting nanophosphors.
- **Precipitating Agent Addition:** Add a precipitating agent to the precursor solution to induce the formation of the nanophosphor particles. The choice of precipitating agent depends on the specific reaction system and desired properties of the nanophosphors. Commonly used precipitating agents include ammonium hydroxide (NH_4OH), sodium hydroxide ($NaOH$), or carbonate solutions.
- **Precipitation and Aging:** Upon the addition of the precipitating agent, the metal cations and anions react to form insoluble salts, resulting in the precipitation of nanocrystalline particles. Allow the precipitates to age for a certain period, typically through continuous stirring or aging at a specific temperature, to promote particle growth and improve crystallinity.
- **Filtration and Washing:** Separate the formed nanophosphor precipitates from the solution by filtration. Wash the precipitates multiple times with a suitable solvent or deionized water to remove any residual impurities or unreacted ions.
- **Drying and Calcination:** Dry the filtered nanophosphor precipitates at a controlled temperature to remove the solvent and residual moisture. Depending on the specific material, the dried precipitates may undergo a subsequent calcination process to enhance crystallinity and remove any remaining organic species.

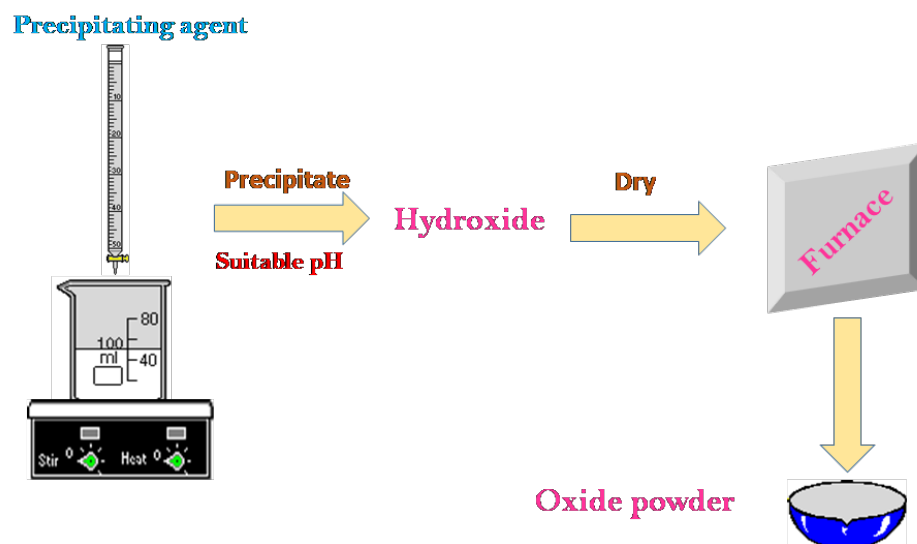


Figure 9: Schematic diagram for Co-Precipitation Method[10]

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