Applications of Nuclear Materials

Applications of Nuclear Materials:

An Industrial Prospective

Edited by

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PREFACE

In the era of unprecedented technological advancements and environmental challenges, it becomes imperative to explore the diverse applications of nuclear materials through a comprehensive lens. The ever-evolving landscape of industrial technology, the significance of nuclear materials cannot be overstated. Nuclear materials play a pivotal role in numerous sectors, shaping our modern world profoundly and subtle. This book, "Applications of Nuclear Materials: An Industrial Perspective," is a culmination of collective insights and expertise from various fields, offering a holistic exploration of the multifaceted roles played by nuclear materials in industry. Through meticulous research, analysis, and practical examples, this volume endeavours to illuminate the intricate interplay between nuclear science, engineering, and industrial applications.

From energy generation and propulsion systems to healthcare, agriculture, and beyond, the chapters within this book delve into the myriad ways in which nuclear materials contribute to enhancing efficiency, sustainability, and innovation across industries. This book consists of eight chapters. The first chapter is aimed to the real-life applications of one of the radioisotopes, Terbium. The radioisotopes of Terbium ($^{155,156,157,158,159m,160,161,162,163\&164}Tb$), possess vivid applications in the medical domain, industry, and environmental sustainability. Targeted radiotherapy using radioisotopes of terbium help in curing life threatening diseases. Theranostic applications of terbium is a hot topic of research and application and MEDICIS-ProMED venture of CERN is striving to produce mass scale radioisotopes of terbium, which otherwise are rare in nature. The enhanced magnetic property of doped radioactive terbium has widespread application in manufacturing magnetic products and in mobile industry. Production and decay of radioisotopes of terbium are also discussed along with its radioactive waste management in the present chapter. The second chapter is aimed to the applications of radio-isotopes for smart agriculture. The knowledge of radioisotopes like ^{2}H, ^{13}C ^{15}N, ^{32}P, ^{35}S, ^{59}Fe, ^{54}Mn and ^{65}Zn is providing an avenue to study many plant nutrients. Some gamma-emitting radioactive isotopes are used in the measurements of water content in soil samples e.g., ^{60}Co, ^{133}Ba, ^{137}Cs, ^{241}Am etc, using attenuation of gamma rays through soil and water utilised to detect the water content in the soil. Third and fourth chapters introduce an emerging technology “Thin Layer Activation Technique” to study surface phenomenon using ion beam interaction with materials. TLA is nuclear measurement technique which can be employed to determine surface degradation in various materials by choosing appropriate ion beam in industries of strategic importance due to its high sensitivity, precision & reliable results. In the third chapter, an attempt has been made to find correlation and systematic between projectile mass and linear activity using different beams viz; proton, deuteron, ^{3}He and Alpha and linear activity induced in materials like Aluminium, Iron & Nickel have been reported in almost same energy region. Fourth chapter gives the detailed information on tribological investigations for measurement and monitoring of wear induced within the thin layer of the surface of material which have significant importance with its widespread applications across various industries. A number of experimental & theoretical studies have been explored, influencing tribological wear under different operating conditions, reflecting the importance of various mechanisms involved. Further, in this chapter, an attempt has been made to review the recent tribological mechanism with the inclusion of a new emerging wear measurement nuclear technique known as Thin Layer Activation technique, which is a multidisciplinary approach applicable across diverse fields such as materials, process industries, automobiles, biomedical, defence, thermal & nuclear plants and aerospace industries operating and influenced by altogether different set of parameters. Fifth chapter is dedicated to Molecular Dynamics simulations which are an indispensable tool in computational material science. It enables researchers to explore and understand nuclear materials at the atomic level, offering insights that contribute to the development of safer, more efficient, and more reliable nuclear technologies. This chapter gives an insight to the synergy between Molecular Dynamics simulations, experimental work, and theoretical models, which is essential for pushing the boundaries of nuclear materials science. The sixth chapter is a detailed explanation of the applications of various nuclear materials. The application of nuclear materials is immense. It extends from defence, health care, electricity production to space exploration. The potential of nuclear materials is not yet explored completely due to the risk of radiation involved. A deeper understanding into the world of nuclear materials can lead to a better world altogether. But this opportunity comes with a word of caution, as their power can also lead to immeasurable destruction if not used responsibly. Holmium, a rare earth element, has garnered significant attention in recent years due to its versatile applications across various fields. Seventh chapter explores the environmental, medical, and industrial uses of holmium radioisotopes. In the environmental sector, holmium isotopes find application in environmental tracing studies, particularly in groundwater and soil analysis. The unique properties of holmium isotopes make them ideal tracers for studying hydrological systems, pollutant transport, and soil erosion processes. In the medical field, holmium isotopes play a crucial role in brachytherapy, a form of radiotherapy used in the treatment of various cancers. Holmium-166 exhibits promising characteristics for targeted cancer therapy due to its suitable half-life and emission properties. Additionally, holmium-based contrast agents are utilized in magnetic resonance imaging procedures, aiding in the visualization of organs and tissues. Moreover, holmium finds applications in industrial settings, primarily in the production of specialized glass and ceramics. Holmium oxide is incorporated into glass to create optical filters for specific wavelengths, making them valuable in laser technology, telecommunications, and spectroscopy. Additionally, holmium-doped materials are utilized in fiber optics for signal amplification and laser systems for precise material processing. The multifaceted applications of holmium radioisotopes underscore their significance in advancing environmental monitoring, medical treatments, and industrial processes, highlighting the pivotal role they play in various scientific endeavors. The next chapter is based on the various applications of radioactive sources in logging tools and Oil & Gas industry. In case of oil & gas exploration and production, a particular method used logging operations as well to evaluate and predict the capacity of an oil or gas well to produce the type and amount of specific hydrocarbon (oil or gas) has been explored. This evaluation and prediction are based on the subsurface geological formation and the formation parameters such as density, texture, radioactivity, porosity, permeability, and the available fluid types either formation of water or hydrocarbon. Well logging, a process for continuous monitoring and gathering the subsurface information with respect to depth has been pointed out. Some of the electro-mechanical devices are also discussed which generally used to record the petro-physical characteristics, and they are well known as eye of the exploration and production industry. Their working principal and applications are very specific and depend on the borehole environment. These tools are classified based on acquisition parameters and tools specifications. Some of them are measuring lithology, porosity, bulk density, resistivity, and fluid types individually and also work in a combined manner. For subsurface lithology and density measurement tools have specific sources, receivers are used, and they are known as Gamma ray, Gamma-Gamma ray (Density log), Gamma spectrometry tool and neutron tool. Gamma ray tool works on natural radioactivity of subsurface rock and minerals. Whereas Density tool and neutron too have radioactive materials as source, which emits with certain energy of neutrons or gamma photons from the source. Two basic sources are utilized for evaluation of hidden information; these sources may be 4, 8, or 19 Curie Am-241 sources or a 1.5 or 2 Curies Cs-137 source depending on the specific tool function and design. These tools are used in sets and computer algorithms to determine the conditions of the specific well and geological formation, compared to the collected data. The density tool utilizes a 1.5 or 2 Curie Cs-137 source depending on the design of the specific tool to measure the formation density as well as a related evaluation of the formation porosity. The neutron tool may utilize either a 4, 8, or 19 Curie Am-241 source depending on the specific tool design to identify porous formations and for an estimate of the actual porosity of the formation. It is also possible to use the data from these tools to distinguish between oil, gas, or water zones within the formation by comparison to other log data. Further, in the present chapter, the working principle and applications of all nuclear family tools are explained.

This volume serves as a valuable resource for students, researchers and professionals for their understanding of nuclear materials and their applications in industrial contexts. It is designed to foster interdisciplinary dialogue, encourage critical thinking, and inspire future generations to harness the potential of nuclear materials for the betterment of society.

As editors, we extend our heartfelt gratitude to the contributors who have generously shared their knowledge and expertise, making this book possible. We hope that "Applications of Nuclear Materials: An Industrial Perspective" will serve as a catalyst for further exploration and innovation, ultimately contributing to a more sustainable and technologically advanced future.

D. P. Singh
Vivek Kumar Anand

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Warm regards
D. P. Singh

CHAPTER 1

PROPERTIES AND REAL-LIFE APPLICATIONS; TERBIUM RADIOISOTOPES

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Abstract

In this manuscript, effort has been made to gauge real life applications of radioisotopes of terbium. Terbium radioisotopes possess vivid applications in medical domain, industry, and environmental sustainability. Targeted radiotherapy using radioisotopes of terbium help in curing life threatening diseases. Theranostic applications of terbium is a hot topic of research and application and MEDICIS-PROMED venture of CERN is striving to produce mass scale radioisotopes of terbium, which otherwise are rare in nature. The enhanced magnetic property of doped radioactive terbium has widespread application in manufacturing magnetic products and in mobile industry. Production and decay of radioisotopes of terbium are also discussed along with its radioactive waste management.

Keywords: Terbium radioisotopes; Radiotherapy; Theranostic applications; MEDICIS-PROMED; Radioactive waste management.

1. Introduction

Terbium, denoted by the symbol Tb and atomic number 65, is categorized as a rare earth metal. It occurs naturally and does not possess radioactivity in its unaltered form. This soft and malleable silvery-white metal has an atomic weight of 158.925 and a density of 8.23 g/cm^3. Its melting point is recorded at 1356^{0}C, while its boiling point reaches 3230^{0}C. Various isotopes of terbium exist, some of which can be generated through either nuclear decay or artificial means [1]. Terbium is naturally found in minerals like bastnasite and monazite, located in different countries including China, the United States, and Australia. However, it is relatively uncommon compared to other elements, often obtained as a byproduct during the refinement of heavy mineral sand [2].

Typically, the naturally occurring isotopes of terbium are non-radioactive and not extensively employed in medical or industrial applications. Conversely, radioactive terbium isotopes are commonly produced artificially to cater to specific needs that rely on their distinctive properties, such as half-life and energy emission. Although some terbium isotopes like Tb-160 are radioactive, they occur naturally in negligible quantities and are primarily generated artificially for specific applications. The most prevalent and stable isotope of terbium is Tb-159, which lacks radioactivity [3]. Determining the most abundant naturally occurring radioactive isotope of terbium is challenging due to the substantial variation in isotope abundance based on geographical location and specific sample conditions. Moreover, the artificial production of specific terbium isotopes for medicinal or other purposes can influence the relative abundance of different isotopes [4].

It's important to note that the handling and use of radioactive isotopes, including terbium isotopes, require strict safety precautions and regulations to protect workers and the public from the potential health hazards associated with exposure to radiation.

2. Radioactive Isotopes of Terbium

There are several radioactive isotopes of terbium, including:

1. Tb-155
2. Tb-156
3. Tb-157
4. Tb-158
5. Tb-159^{m}
6. Tb-160
7. Tb-161
8. Tb-162
9. Tb-163
10. Tb-164

It's worth noting that Tb-159m is a metastable isotope, meaning that it decays to a more stable isotope through emission of gamma rays or internal conversion electrons. The other isotopes listed are also radioactive and decay to more stable isotopes through various decay mechanisms. The specific half-life, decay mode, and radioactivity of each isotope depends on its atomic number and other factors.

3. Applications of Terbium

Radioactive isotopes of terbium have enormous potential for an extensive range of applications across numerous domains. In the medical field, these isotopes can modernize targeted radiotherapy treatments. Through selectively delivering radiation to cancer cells, they can minimize damage to healthy neighboring tissues around the tumor site. This precise methodology holds pronounced aptitude for augmenting the effectiveness of cancer treatments along with reducing side effects. Also, terbium isotopes can play a vital role as tracers in medical imaging techniques. By cataloging specific compounds or molecules with radioactive terbium isotopes, medical professionals can track their circulation within the body. This simplifies the procedure of diagnosis of diseases, monitoring of treatment progress, and the assessment of drug efficacy.

Other than healthcare, terbium isotopes find applications in industrial settings as well. They can be employed in quality control processes which ensure the reliability and integrity of manufactured goods. Detection of defects and structural flaws in materials, these isotopes interject in preventing product failures and maintaining high standards. Furthermore, terbium isotopes have importance in non-destructive testing methods. By using these isotopes, engineers can measure the integrity of critical components without damaging them. This allows for cost-effective and efficient inspections. Furthermore, radioactive terbium isotopes hold prospectives in environmental research. They can be utilized to trace the behavior and movement of pollutants. This provides valuable understandings into their diffusion patterns and impact on ecosystems. This knowledge can help in progressing strategies for environmental conservation and pollution mitigation. The applications of radioisotopes of terbium are varied and constantly expanding, propelling advancements in science and technology, and on various aspects of human well-being. Their exclusive properties and resourcefulness open up a wide range of opportunities for progress in multiple fields and widespread innovation.

3.1 Applications of Terbium Isotopes in Medical Field

Radioactive terbium isotopes have some medicinal applications, mostly in the field of nuclear medicine [5]. Terbium-based compounds can be used as tracers in diagnostic imaging procedures, such as liver scans and bone scans, to envisage the function and distribution of various tissues and organs in the body [6]. Radiopharmaceuticals with terbium composition can be used to treat and image several medical conditions, including cardiovascular disease and cancer. Radioisotopes of terbium can also be used in medical research to study the metabolic processes and functions of tissues and various organs in the body. Tb-153 is one of the most used radioactive isotopes of terbium in medical applications, specifically in nuclear medicine. This is since it has a relatively long half-life of nearly 2.2 years and it being a high energy gamma emitter, which makes it apt as a tracer for diagnostic imaging procedures. Tb-149 is another radioisotope of terbium that is used in certain medical applications. It has a relatively short half-life of nearly 33 days and is also a high energy gamma emitter making it useful for some medical procedures, such as bone scans. Terbium-169 is also used in medical imaging, where gamma rays are emitted and thereafter can be detected by specialized cameras to produce images of tissues and internal organs. Furthermore, the use of radioisotopes of terbium in medicine is mostly limited to specific research projects and medical procedures, and the use of alternative imaging methods is favored whenever possible.

3.1.1 Theranostic Applications of Terbium

Terbium (Tb) holds great potential as a valued element in the field of nuclear medicine, predominantly in the theranostic approach where a single substance is used for both treatment and diagnosis [5]. Terbium has a range of beneficial properties that make it very attractive for theranostic applications. Its striking luminescence makes it compatible for purposes of imaging and thus, enabling accurate diagnostic techniques. Terbium's unambiguous nuclear properties, including its capacity to generate alpha and gamma rays, makes it suitable for therapeutic interventions such as radiation therapy. Furthermore, terbium displays outstanding biocompatibility, guaranteeing its safe use in medical applications without rendering prominent adverse effects on the human body. Terbium's prolonged half-life supplies several prolonged benefits, permitting for therapeutic outcomes and sustained imaging.

3.1.2 Terbium Radio-Isotope Production at MEDICIS-PROMED

MEDICIS-PROMED is an acronym for MEDICIS-produced radioisotope beams for medicine, is a revered research organization located at the European Organization for Nuclear Research (CERN) in Switzerland [7]. This organization is the result of a cooperative attempt amongst CERN and various European partners, including the University of Liverpool and the University of Valencia. The major concentration of MEDICIS-PROMED is to produce unconventional and rare isotopes that are not easily available, with the purpose of progressing research in the fields of nuclear physics and medicine. This is attained by commissioning a proton beam from the CERN accelerator to target and thereby produce these rare isotopes. The isotopes produced at MEDICIS-PROMED finds applications in various medical realms, such as in treatment of Parkinson's, cancer diagnosis and in investigation of inventive remedial methodologies for Alzheimer's disease. Additionally, MEDICIS-PROMED impacts quite significantly the research in nuclear physics, with inferences in areas of nuclear forensics, environmental monitoring, and materials science. In quintessence, MEDICIS-PROMED aids as an important reserve for researchers in the nuclear physics communities and researchers, providing access to very rare isotopes that nurture a deeper understanding of various scientific investigations.

MEDICIS-PROMED also puts a prominent stress on the development of terbium radionuclides for theranostic treatments in nuclear medicine. This program intends to expediate collaboration between experts from various specialties to create innovative terbium-based radiopharmaceuticals for both therapeutic and imaging purposes. Terbium radionuclides possess appealing properties for theranostic applications. This includes high luminescence, gamma ray emission for radiation therapy, biocompatibility, and a prolonged half-life. The MEDICIS-PROMED program endeavors to formulate novel synthesis methods for terbium radionuclides, formulate innovative theranostic agents suitable for diverse medical conditions and optimize their production. Furthermore, the program targets improving imaging procedures and approaches to augment the meticulousness and dependability of terbium-based imaging, and also refining the delivery and directing of terbium radionuclides for medicinal use.

Terbium-155 is an example of a terbium isotope with potential theranostic applications and is produced at MEDICIS-PROMED. Terbium-155 can be paired with a molecule that particularly focuses on cancer cells. This enables its utilization in both targeted alpha therapy and diagnostic imaging. Diagnostic imaging includes commissioning PET (Positron Emission Tomography) scans to find the position and magnitude of cancer. In directed alpha therapy, Terbium-155 transports a focused radiation dose straightaway to cancer cells while minimizing any harm to adjoining healthy tissue. This is attained by attaching Terbium-155 to a molecule that targets the cancer cells selectively and administers the compound to the patient. Terbium-155 is an alpha emitter having a limited range, permitting for the dispensation of a potent radiation dose to cancer cells while moderating damage to adjacent healthy tissue. With a comparatively long half-life of 5.3 days, Terbium-155 residues in the body for an adequate duration to distribute a therapeutic radiation dose without professing any significant risks to the medical personnel patients or patient. Thus, the application of Terbium-155 in theranostics is very promising for refining the effectiveness of cancer treatment while reducing the harm to the adjacent healthy tissue. Research in this area is still ongoing, and MEDICIS-PROMED plays a vital role in the progress of new theranostic agents employing Terbium-155 and other isotopes.

3.2 Applications of Terbium in Industry

Terbium is mostly mixed or doped with other materials for use in various industrial applications [8]. The material that terbium is doped with depends on the desired properties of the final product or its detailed application. Doping terbium with other elements is used to produce a special type of optical fiber called a rare-earth-doped fiber [9]. This novel fiber is used in laser systems and optical amplifiers. Terbium is generally doped with metals such as nickel, cobalt, or iron to produce magnetic materials that possess enhanced magnetic properties, such as amended magnetic stability or superior magnetic strength. These materials have various applications which are used in hard disk drives, magnetic sensors, and electric motors. Terbium can also be doped with semiconducting materials such as silicon or gallium arsenide to fabricate semiconducting materials with upgraded electrical properties. This may include increased electron mobility and enhanced electrical conductivity. These materials are used in various electronic devices, such as transistors and solar cells. Terbium-159 has applications in the nuclear industry as a neutron absorber in nuclear reactors. It helps to control the neutron balance in the reactor core. Various radioactive terbium isotopes, including Terbium-149, Terbium-151, and Terbium-159, are used in research and development as tracer isotopes in various scientific experiments. Additionally, the specific isotope used in a particular industry may change over time as new isotopes become available or as the needs of the industry change. Additionally, the use of terbium doping is subject to ongoing research and development to find new and improved applications for terbium-doped materials.

3.2.1 Terbium and Smartphones

Terbium, because of its magnetic characteristics, is used in certain smartphones. Specially, terbium is employed in smartphone magnetic sensor components, and it serves the purpose of sleuthing the orientation of the phone and supporting the input for various functions such as screen rotation [10]. Moreover, terbium is used in the manufacturing of magnetic materials used in the components of hard disk drives. These drives are used for data storage in smartphones. It is found that terbium has a strong magnetic moment, and it also displays great sensitivity to magnetic fields, making it a valuable material for the use in magnetic sensors. Through the integration of terbium with other substances like cobalt, iron or nickel, magnetic materials with boosted magnetic properties can be produced. These materials play an important role in magnetic sensors which enables the detection of very slight changes in the magnetic field, consequently ascertaining the phone's orientation. It is worthy to comprehend that though terbium can be utilized in certain components of smartphones, yet it is not a dominant material in smartphones. Instead, rare earth metals are commonly used. Additionally, the specific deployment of terbium in smartphones may differ based on factors such as the manufacturer, phone's model, and compliance with district requirements and regulations inside the industry.

3.3 Environmental Applications of Terbium

Terbium, categorized as a rare earth metal, exhibits numerous environmental applications encompassing water purification, soil decontamination, air purification, and waste treatment [11]. Terbium, in conjunction with other rare earth elements, demonstrates efficacy in eliminating impurities and purifying water. Studies have indicated the effectiveness of terbium in extracting heavy metals from polluted soil, contributing to soil decontamination efforts. Terbium oxide can serve as an agent for filtering air pollutants within gas masks and air purifiers, thus facilitating air purification. Also, terbium finds utility in the treatment of nuclear waste and other hazardous waste, aiding in the removal of detrimental contaminants. Altogether, terbium has noteworthy prospective in environmental protection and thereby remediation of contaminated areas.

4. Production and Decay of Radioactive Terbium Isotopes

There are some specialized companies in the nuclear industry and research institutions furnished with the essential proficiency and amenities are characteristically accountable to produce radioactive terbium isotopes [12]. It is imperative to state that the handling and production of these isotopes, including terbium isotopes, are austerely regulated to ensure safety because exposure to such isotopes can cause potential health risks. Some prominent companies are involved in the production of radioactive terbium isotopes. They also provide provision for development of radiopharmaceuticals containing terbium isotopes for the use in medical applications. These companies are Nordion (a subsidiary of Sterigenics International), GE Healthcare, Lantheus Medical Imaging, Institute of Radioelements (IRE) and NTP Radioisotopes (Pty) Lt [13]. Though, this list is not comprehensive and can vary over time, with new companies entering the market and some even exiting. It is critical to observe that requirements and regulations specific to a particular jurisdiction and region, as they may vary and control the utilization and availability of radioactive terbium isotopes. Radioactive terbium can be produced through nuclear reactions, which involve bombardment of a target made of terbium with high energy particles such as deuterons and protons in an accelerator or nuclear reactor. Another method of production of isotopes of terbium is through separation of isotopes of terbium by using different physical and chemical processes which include gas centrifugation, gas diffusion and fractional distillation. Another method of production is trough neutron activation wherein terbium or its compounds are exposed to neutron flux. This leads to the absorption of neutrons by terbium and the resultant sample becomes radioactive. The choice of a specific technique for terbium radioisotope depends upon the intended application of the resultant product, desired purity, desired isotope, and the availability of the instrument. Strict regulations are subjected for the production of these radioisotopes in specialized facilities and handling by proficient and trained personnel.

During the decay process of a radioactive terbium isotope, it undergoes transformation by emitting radioactive particles and ultimately becomes a stable isotope of a different element. For instance, the decay of Tb-149 results in the formation of stable dysprosium (Dy-149), while the decay of Tb-153 leads to the creation of stable holmium (Ho-153). It is noteworthy that the specific decay products generated after the decay of a radioactive terbium isotope are contingent upon the particular isotope and decay mechanism involved. The atomic structure of the radioactive isotope and the available decay pathways determine the resulting end products of the decay process.

5. Radioactive Waste Management of Terbium

The proper management of radioactive waste, which may include waste containing radioactive terbium isotopes, adheres to stringent regulations and guidelines to guarantee the secure and safe disposal of such materials [14].

The specific approaches employed to manage radioactive waste containing terbium isotopes may differ based on the type and quantity of the waste, as well as the regulations established within the particular region or jurisdiction. Radioactive waste is often temporarily stored in secure facilities, allowing for radioactive decay and a subsequent reduction in radioactivity before the final disposal takes place. Another method involves encapsulating radioactive waste within materials like concrete or steel. This process serves to minimize the release of radioactive particles and enhances the safety of waste transportation and disposal. Radioactive waste can also be disposed of in deep geological repositories, where the waste is enclosed in secure containers and buried at considerable depths within stable geological formations. In certain cases, radioactive waste can undergo treatment or processing to recover valuable materials or reduce the volume of waste requiring disposal. It is important to acknowledge that the management of radioactive waste, including waste containing radioactive terbium isotopes, remains an active area of research and development. Continuous efforts are made to ensure the application of the safest and most effective methods. Furthermore, it should be noted that regulations and requirements governing the management of radioactive waste can vary between regions and may evolve over time.

Conclusion

In the end it can be concluded that radioactive terbium has emerged as an instrumental tool with a wide range of applications in various domains. Within the medical field, it exhibits large potential for targeted therapy, non-invasive and precise diagnostic imaging and effectively detecting and treating diseases. Furthermore, its application in industries such as the production of luminous devices and lasers contributes to technological progressions and promotes innovation. Also, the use of radioactive terbium in environmental applications plays a vital role in economically monitoring and remediating contaminants, thereby conserving our ecosystems. Projects like MEDICIS-PROMED further augment its medical applications by enabling the production of original isotopes for both research and therapy purposes. Additionally, the projections of theranostic applications using radioactive terbium offer favorable prospects for tailored medicine, combining diagnostic competencies with therapeutic involvements. As continuing research endures to unravel new possibilities, the multipurpose nature of radioactive terbium guarantees its continued significance and momentous impact in addressing critical confronts across various domains, ultimately profiting both civilization and the environment.

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Dr. Navjot Hothi

Dr. Hothi is a Theoretical High Energy Physicist, specializing in the field of Quantum Chromodynamics and Regge Trajectories. Her research interests also extend to Physics Education Research, particularly focusing on Exotic Hadrons and Environmental Sciences. Dr. Hothi is passionate about promoting Physics education and has created approximately 25 audio and video lectures covering various topics in Physics to further this endeavour. Before joining UPES, Dr. Navjot Hothi held the position of Assistant Professor at Bahra University, Shimla Hills, and Chitkara University, Rajpura. Additionally, she contributed as a teacher at Kumaun University, Nainital while serving as an R. F. S. M. S. fellow. Dr. Navjot's remarkable academic journey includes receiving the Junior Research Fellowship (JRF) and Senior Research Fellowship (SRF) from UGC under the Research Fellowship in Science for Meritorious Students (RFSMS) scheme during her Ph.D. pursuit. She also received a prestigious cultural fellowship from the Ministry of Culture for "Sitarwaden," a recognition she held for three years. Several national and international research articles are in her credit. She has also contributed a number of chapters in books published by national and international publishers.

CHAPTER 2

RADIOISOTOPES FOR SMART AGRICULTURE; GREEN ROLE OF ATOM: THE GREEN ATOM

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Abstract

With over 800 million people suffering from Hunger around and globe the problem of food productions, supply chain related issues and preservation for longer times requires attention of all the stakeholders and end uses. The food wastage figures are alarming and hence require immediate attention. The sustainable development goals given by the United Nations also seeks for goals of zero hunger and clean, sustainable energy sources. Atoms are serving mankind since decades now and contributing towards the sustained availability of food products at an affordable price. Through this chapter the major application areas of radioisotopes in the food production and processing sector have been summarized. Globally acclaimed and time-tested techniques are being used to ensure to meet the SDGs and ensure the world moves a step towards hunger free land.

Keyword; Nuclear, Radiation, Isotope, Soil Health, Measure and Monitoring, Plant Nutrition and Fertilisers

Introduction

When the name of an atom comes into the mind of people a picture of a mushroom appears i.e., an atomic bomb explosion cloud. Only a few are aware and realise the other aspect of the atom also exists which is "the greener side". Since the last few decades, atoms have been serving mankind in various other ways apart from energy sustenance. The nucleus was discovered in 1911 whereas the idea existed much earlier since 1800. In the latter half of the 19th Century after the Second World War, the International Atomic Energy Agency (IAEA) came into the picture with the objective of spreading and promoting the wider uses of radioisotopes in research, agriculture, industry, and medicine. Only a few people have the awareness regarding these laid down objectives and their status achieved. One of the objectives of the deployment of radiation/radioisotopes is to improve food grains, crops and their sustenance. For the better lives of living beings' good food and water are essential requirements, good food leads to good health and a healthy mind. In the present context, radioisotopes play a vital role in providing for the basic needs of mankind specifically food security.

In 1964, the Food and Agriculture Organization (FAO) of the United Nations and the International Atomic Energy (IAEA) jointly set up a division of atomic energy for Food and Agriculture, and its headquarters were established in Vienna. The agency holds international activities to promote the (a) production of high-yield crops (b) protein-rich crops (c) the production of disease and weather-resisting varieties of crops (d) multiple variant crop or mutation (d) localization and effective utilisation of water resources (e) determining need of fertilizers (f) elimination and control of pests and insects (g) suggestions/solutions to cope for losses of crops during the storage or improvised storage. Other side, by utilising the decay energy of the radioisotopes nuclear scientists and engineers are unlocking the unravelled fact of agriculture, which could not have been possible with traditional methods and conventional techniques. One of the milestones is the study of the uptake of carbon dioxide to produce glucose and oxygen using ^{14}C and ^{18}O in addition to the study of the entire process of photosynthesis. Moreover, to increase crop yield detailed knowledge of soil health, fertiliser, seed quality and insects prevalent in the crop is needed [1-4]. Keeping in mind the above points, radioisotopes are used for determining the impact of fertilizers on different plants. In addition, the energies of radioisotopes are also utilised to kill insects to prevent crop damage [5-7]. Moreover, the storage of crops for a longer duration also needs the attention of nuclear scientists. Besides, a gentle use of radiation exposure can increase the shelf-life of the crop. The radioisotopes and radiations may help to address the growth-related issues, duration of growth can be shorter time. Following are the areas related to agriculture where radioisotopes are used extensively by developed countries.

Plant Nutrition and Fertilizers

To increase the yield of crops, the repeated use of fertilisers is of great concern to the economy of the country as well as the environmental pollution which indirectly impacts living things. The unbalanced use of fertilizers may damage the soil health as well as the environment. It is therefore necessary to optimise the use of fertilisers [1]. The labelled fertilisers with radioactive isotopes such as Nitrogen-15/ Phosphorus-32 are the means of determining how much of the fertilizer is taken up by the plant and how much is lost to the environment. Nitrogen-15 provides a direct assessment of the amount of nitrogen being fixed from the atmosphere under field conditions. A Nitrogen Phosphorous Potassium (NPK) -labelled fertilizer has concentrations of phosphorus and potassium elements, P_2O_5 consists of 56.4% elemental oxygen and 43.6% elemental phosphorus by weight. Hence, the elemental phosphorus percentage of a fertilizer is 0.436 times its P value Further, the N value in NPK labels represents the actual percentage of nitrogen element by weight, so it does not need to be converted.

Example: An 18−51−20 fertilizer contains by weight.

(i)18% elemental nitrogen,
(ii) $0.436 \times 51 = 22\%$ elemental phosphorus,
(iii)$0.83 \times 20 = 17\%$ elemental potassium.

Hence, with the optimised use of fertilisers, a county will save millions of dollars. Countries like Sri Lanka took part in a research programme for fertilisers, which was organized by the Joint FAO/IAEA division, for coconut palms. It was found that the optimise use of fertilizer not only yielded direct savings in the cost of fertilizer but also an estimated potential saving in production cost. In a similar fashion, a group of experts recently estimated and reported that an amount 50% of the fertilizer used at present in all countries could be reduced by improved fertilizer management.

Soil Health Measure and Monitoring

Soil health [2] is the capacity of soil to function to sustain plants continuously throughout the plant life, hence the measure of essential micronutrients in the soil such as nitrogen, potassium and phosphorus is the key indicator of soil health. The motoring of micronutrients and remedial will help to achieve high-yield crops [3]. The knowledge of radioisotopes like ^{2}H, ^{13}C ^{15}N, ^{32}P, ^{35}S, ^{59}Fe, ^{54}Mn and ^{65}Zn is providing an avenue to study many plant nutrients. Using radioisotopes, one can easily estimate the presence of any element & locate, even a single atom and its moment, hence scientists/researchers can follow up step by step all kinds of processes related to plant nutrients from germination to maturity. In addition, plant radiography can be done using radiotracers, which helps to locate specific molecules. Hence, radiotracer enables us to trace elements taken by the plants accurately and precisely.

Soil Moisture

Another key factor in agriculture is the water content or moisture [5] in the soil, it is the amount of water present in the soil, which influences plant growth and helps to maintain the soil temperature and transportation of nutrients. The most widely used parameters for quantifying soil water content (SWC) are volumetric water content (VWC) and soil matric potential (SMP). VWC is the ratio of the amount of water [8-10] to the unit amount of soil in unit volume. It can be expressed as a percentage, or depth of water per depth of soil in unit surface area.

Example: In a soil sample, if the amount of water is 0.20 cc in a unit volume of soil. the VWC can be written as

$$VWC = \frac{amount\ of\ water\ in\ unit\ volume}{amout\ of\ soil\ in\ unit\ volume} \times 100$$

$VWC = \frac{0.2\ cc}{1.0\ cc} \times 100$; $VWC = 20\%$

The volumetric water contained in the soil sample was reported as 20 %.

Some gamma-emitting radioactive isotopes are used in the measurements of water content in soil samples e.g., ^{60}Co, ^{133}Ba, ^{137}Cs, ^{241} Am etc, in this method attenuation of gamma rays through soil and water utilised to detect the water content in the soil. Nuclear technology based on Neutron scattering can be used to measure water content in the soil, it is a non-destructive, fast, efficient, reproducible, and economical technique also high in accuracy. In this method, the interaction property of the neutron with the water molecules is utilised to determine the SWC. When neutrons interact with the water, neutrons slow down, since neutrons are very similar in size to the Hydrogen atom. The neutrons are elastically scattered, lose a large amount of energy, and have the highest interaction cross-section, as result, neutrons become thermalise, these thermal neutrons can be detected easily, we can calculate the number of thermal neutrons using the neutron detection device, which will give information on the number of the hydrogen atom. While the neutron capture cross-section of a thermal neutron with other soil elements is almost constant.

A typical sketch of a neutron probe to monitor WCS is shown in Figure 1. It is firmly used to monitor WCS.

Insect Control and Pests Management

Globally, a widespread estimation of crop damages due to insects is ~ 10 % while appreciably higher in developing countries. One of the ways of controlling the impact of insects/pests on crops is the use of genetically modified crops, which can reduce the use of insecticides. Another method is to disable the insects, while some of the insects are important for nature to maintain the natural ecological balance. On the other hand, the pesticide has adverse effects on public health. Save the crop from insects and pests via alternative methods i.e., radiation-based sterile insect technique (SIT) [6-7], it is an ecofriendly and cost-effective technique, in sterile insects remain sexually competitive but cannot produce offspring, in this way the

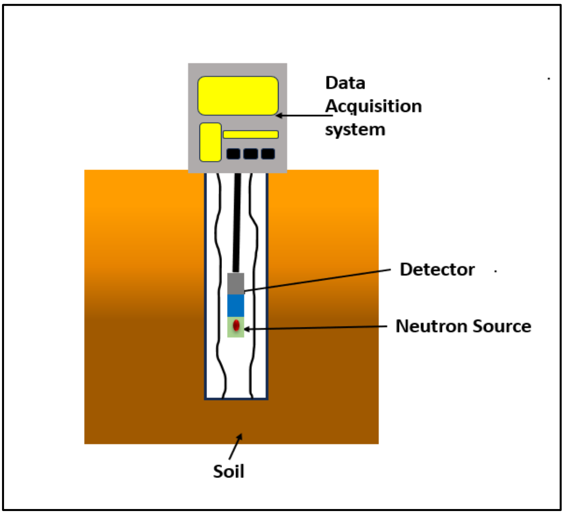

Figure 1. A typical sketch of a neutron probe for the detection of moisture contained in soil.

management of the insect can be done in mass where the pesticide failed. By using ionising radiation, the insects are being sterilised, in general, gamma irradiators, where the gamma rays of ^{60}Co radioactive source are used for irradiation. Nowadays researchers also exploring X-rays as sterilisers for insects which is a blood irradiator and has a wide application in medicine. Moreover, in 1960 the United States of America (USA) first developed SIT for pest management. Presently, SIT is applied globally across six continents and successfully controls the populations of several high-profile insects, including mosquitoes, moths, screwworms, tsetse flies, and various fruit flies. Three United Nations (UN) organizations, IAEA [12], FAO, and World Health Organisation (WHO) are promoting new SIT programs in many countries along with their government support. The most recent advanced application of SIT has been in the fight against the deadly Zika virus in Brazil and the broader Latin America and the Caribbean.

Plant Mutation Breeding

One of the ways to increase crop yield is the mutation of the plants. The technique has several important advantages, like quick growth of crops, cost-effective, environmentally friendly, and non-hazardous. The use of radiation for mutations in plant breeding has been used for several years along with different techniques. In general, gamma-ray or neutron irradiation along with other techniques are used to produce new genetics of plants of root crops, cereals, and oil seed crops. Up to now, around 3200 new crop varieties have been developed, and several new kinds of sorghum, garlic, wheat, bananas, beans, and peppers have been developed. These are more resistant to pests and more adaptable to harsh climatic conditions [11-12]. The IAEA jointly with the FAO, assists its member states in the development and implementation of plant mutation breeding.

Food Irradiation

After getting an increased yield of the crop, it is important to store it safely in storage, around 30% of food harvested spoiled, particularly in hot and humid climate countries before consumption. In food irradiation, the foodstuffs are irradiated by gamma rays to kill bacteria that can cause food-borne disease, subsequently increasing the shelf-life of foodstuff. It is like the conventional food preservation technique and has the same benefits as when food is heated, refrigerated, frozen, or treated with chemicals, but does not change the temperature or leave residues. The radiation dose used for application along with spices is given in Table 1. Globally, the use of irradiation technology to preserve food increasing rapidly, more than sixty countries have introduced regulations allowing the use of irradiation for food products including spices, grains, fruit, vegetables & meat. Exposure to radiation can replace potentially harmful chemical fumigants that are used to eliminate insects from legumes, spices, dried fruit and grain.

In the year 2015, numerous sustainable goals were suggested by the UN, and 17 goals were adopted for sustainable development, one of the important goals was the achieve "zero hunger" [13]. Further, in 2019 the UN & AFO estimated about 690 million people were suffering from chronic undernourishment. Subsequently, the UN reports that 828 million people were affected by hunger in 2021 globally. On the other hand, in 2022, a survey done by UNICEF, WHO and the World Bank jointly estimated child malnutrition under the age of 5, to be approx. 243.8 Hence, globally, countries are facing a triple burden of malnutrition- stunting, wasting and overweight. To cater for the issue of hunger and promote the use of nuclear techniques to enhance climate-smart agriculture, dedicated technology packages have been developed.

Table 1: Dose rate along with the Food irradiation applications.

S. No.	Dose	Application	Species	Radiation level
1	< 1 kGy	-Sprout Inhibition -Disinfestation -Delay ripening -Trichinosis -Insect sterilisation	Vegetables, Fruits Cereals, Pulses and Dried food	**Low**
2	1-10 kGy	-Kill pathogens -Extend shelf-life -Elimination of spoilage, -Kill parasites and insects	Meat, Fish, Strawberries, Mushrooms Fresh and Frozen Seafood, Poultry Grapes Patient diet/Medical food	**Medium**
3	10-50 kGy	-Sterilisation (Kill bacteria and Viruses) -Microbial Decontamination	Meat, Poultry, Seafood, Prepared foods Spices, Natural gum *etc.*	**High**