ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct347

# Recent Advance in Radiation Decay Radioisotopes for Targeted Nuclear Medicine and Cancer Treatment

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Publication Date: 2026/10/27

**Abstract: Radioactive decay is one of those processes that seems narrow until you see how many fields depend on it. This review looks at how decaying radioisotopes are used across science and medicine, with a focus on targeted nuclear medicine and cancer treatment. We start with the basics, the different types of decay and how half- life governs the way radioactivity fades, and then trace its uses in energy, industry, space science, and materials testing. The care of the paper is medical. PET and SPECT scans rely on isotopes like Tc-99m and F-18 to show how organs are actually functioning, not just how they look. On the treatment side, targeted radionuclide therapy uses Lu-177, Y-90, and the alpha emitter Ac-225 to deliver radiation straight to tumour cells while sparing much of the healthy tissue around them. We also cover why safety practices like ALARA and patient- specific dosimetry matter so much in getting that balance right. Finally, we look ahead to 2030.AI-assisted imaging, cyclotron-based isotope production closer to patients, and nanoparticle-based alpha therapies all look promising, though each still needs broader clinical validation and better manufacturing before it becomes routine. If they get there, nuclear medicine could move beyond diagnostics and become a central part of personalized cancer care.**

***Keywords:*** *Radioactive Decay, Nuclear Medicine, Radiopharmaceuticals PET-SPECT Imaging, Targeted Radionuclide Therapy (TRT), Dosimetry Half-Life, Alpha-Beta-Gamma Decay, Theranostics, Actinium-225, Lutetium-117, Technetium-99M, Radiation Safety (ALARA), Nuclear Medicine Imaging.*

**How to Cite:** Sarvar Jahan; Payal Patle; Surbhi Dhurve; Savan Kanade; Anjali Kushwha (2026) Recent Advance in Radiation Decay Radioisotopes for Targeted Nuclear Medicine and Cancer Treatment. *International Journal of Innovative Science and Research Technology*, 11(10), 1806-1812. https://doi.org/10.38124/ijisrt/26oct347

## I. INTRODUCTION

Radioactivity is the process where an unstable atomic nucleus spontaneously changes inti a different from . It is fundamentally different from an ordinary chemical reaction because the principal change occurs inside the nucleus rather than in the arrangement of electrons. When an unstable nucleus move toward a more stable state, it may release alpha particles, beta particles, gamma photons, or other forms of nuclear radiation. The emitted radiation may ionize matter and therefore has important chemical, biological, and medical consequences.

The nucleus contains protons and neutrons. The number of protons determines the element, while a different number of neutrons gives a different isotope. Some isotopes are stable, whereas other are radioactive. Nuclear stability is influenced by the neutron-to-proton ratio, nuclear binding energy, and the balance between the attractive nuclear force and the electrostatic repulsion between protons.

According to the world health organization, ionizing radiation includes electromagnetic radiation such as x-rays and gamma rays, and particles, such as alpha particles, beta particles, and neutrons. Ionizing radiation has enough energy to remove electrons from atoms or molecules. This property explains both its usefulness and its potential biological hazards.

While the decay of a single nucleus is completely random. The collective behavior of a large number of nuclei can be predicted with high accuracy. This statistical predictability is the basis for measuring detector, and planning nuclear medicine procedures.

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➢ *Types of Radioactive Decay*

- *Alpha Decay*

Alpha decay occurs mainly in heavy nuclei. An alpha particle which is identical to a helium-4 nucleus made of two protons and two neutrons is released by the nucleus. The daughter nucleus therefore has an Alpha atomic number two units lower and a mass number four units lower.

General form : $^{A}ZX \rightarrow {}^{A-4}Z_{-2}Y + {}^{4}_{2}He$

Alpha particles have relatively short ranges in matter but produce dense ionization along their path. This makes them biologically powerful emitted near a cellular target and has encouraged their use in targeted alpha therapy research.

- *Beta-Minus Decay*

Beta minus decay occurs when a neutron turns into a proton resulting in the emission of an electron and an antineutrino. Consequently, the elements atomic numbers go up by one, but its total mass number does not change.

$n \rightarrow p + e^{-} + \bar{\nu}_e$

Beta-minus emitters are useful in therapy because their electron can travel farther in tissue than alpha particles and deposit radiation around the site where the radionuclide accumulates.

- *Beta-Plus Decay*

A proton changes into a neuteon during beta- plus decay emitting both a positron and a neutrino. The positron eventually encounters an electron, producing annihilation photons. Detection of these photons is the physical basis of positron emission tomography (PET).

$p \rightarrow n + e^{+} + \nu_e$

- *Electron Capture*

Electron capture occurs when a nucleus pulls in an inner orbital electron. This process transforms proton into a neutron while emitting a neutrino. The resulting vacancy in the electron shell may produce characteristic vacancy in the electron shell may produce characteristic X-rays or Auger electron as the atomic structure relaxes.

- *Gamma Emission*

Gamma emission shifts the nucleus to a lower energy level without altering its identity or mass. Gamma photons can travel out of the body and be detected externally, making gamma-emitting radionuclides important for SPECT and other imaging procedures.

- *Spontaneous Fission*

Some very heavy nuclei can split spontaneously into smaller nuclei while releasing neutrons and energy. Spontaneous fission is particularly important in nuclear science and reactor physics rather than routine diagnostic medicine.

➢ *Global Importance of Nuclear Science*

Nuclear science connects physics, chemistry, biology, engineering, environmental science, and medicine. Its application includes energy production, industrial testing, agriculture, food technology, environmental tracing, scientific research, and health care.

- *Energy*

Nuclear fission can release very large amounts of energy from transformations involving heavy nuclei. Nuclear power can provide continuous electricity with low direct carbon dioxide emissions during operation. At the same time, nuclear safety, radioactive waste, fuel-cycle management, and long-term stewardship require strong technical and regulatory systems.

- *Industry*

✓ Radiography and non-destructive testing can reveal defects in welds and industrial components.
✓ Radioisotope gauges can measure thickness, density, level, and moisture.
✓ Radiation can be used for sterilization of selected medical products and materials.
✓ Tracer methods can investigate flow, leakage, and industrial processes.

- *Agriculture and Food*

Isotopic techniques can study plant nutrition, soil processes, water use , and nutrient movement. Radiation technologies also have applications in food preservation and insect- control programmes under controlled conditions.

- *Environment*

Radioisotopes can act as tracers for groundwater movement , sediment transport, and pollutant pathways, Natural radionuclides can also provide information about geological and hydrological processes.

- *Scientific Research*

Radiolabelled compounds allow researchers to follow biochemical pathways, receptor binding, metabolism , and molecular transport. Because radioactive labels can be detected at very low concentrations, isotope tracing is a powerful method in chemistry, biotechnology , and life-science research.

➢ *Role of Radioactive Decay in Nuclear Reactors and Power Generation*

Radioactive decay plays a fundamental role in nuclear reactors and the generation of nuclear power. In a nuclear reactor, energy is primarily produced through nuclear fission , in which heavy nuclei such as uranium -235 or plutonium-239 split into smaller nuclei after absorbing a neutron. This process releases a large amount of energy, mainly as kinetic energy of the fission fragment , along with additional neutrons and gamma radiation. The released energy is converted into heat , which is ultimately used to generate electricity.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct347

Radioactive decay is particularly important after fission has occurred. The fission products produced inside the reactor are often radioactive and undergo successive radioactive decays. These decays release additional energy, known as decay heat or residual heat. Even after the reactors fission chain reaction is stopped, radioactive fission products continue to decay and produce heat. Therefore, continuous cooling is required to remove this residual heat and maintain reactor safety.

In a nuclear power plant, the heat generated inside the reactor is transferred to a coolant such as water, gas, or liquid metal , depending on the reactor design. In common water-cooled reactors, this heat produces steam either directly or through a secondary heat-transfer system. The steam drives a turbine, which is connected to an electric generator. The generator converts the mechanical energy of the turbine into electrical energy.

Radioactive decay also contributes to the formation and transformation of different radioisotopes inside a reactor. Some radioactive isotopes have relatively short half-lives and decay rapidly, while others remain radioactive for much longer periods. The rate of decay follow the radioactive decay law:

$$N = N_0 e^{-\lambda t}$$

Where $N_0$ is the initial number of radioactive nuclei, N is the number remaining after t, and $\lambda$ is the decay constant.

The concept of half-life is important for estimating how long radioactive materials will remain active and how much decay heat they will produce. Knowledge of radioactive decay is therefore essential for reactor operation, fuel management, radiation protection, and the safe handling and storage of radioactive waste.

Radioactive decay also has an important role in nuclear fuel cycles. Uranium and plutonium isotopes undergo various nuclear transformations, producing daughter isotopes and Radioactive fission products. Understanding these processes helps scientists and engineers evaluate fuel performance and reactor safety.

➢ *Radioactive Decay in Space Science*

Radioactive decay is an important natural process in space science, astrophysics, planetary science, and space exploration. Radioactive decay occurs when an unstable atomic nucleus transforms into a more stable nucleus by releasing radiation in the form of alpha particles, beta particles, gamma rays, or other forms of nuclear energy. Because radioactive isotopes are naturally present in stars, planets, asteroids, meteorites, and interstellar material, their decay provides valuable information about the origin, evolution, and age of celestial objects.

## II. MATERIALS AND METHODOLOGY

➢ *Use of Radioactive Decay in Materials Science*

Radioactive decay has important applications in materials science, particularly in the study, characterization, modification, and development of advanced materials. Radioactive isotopes and the radiation produced during nuclear decay can interact with matter and provide useful information about the structure, composition, and properties of materials.

One major application is material characterization radiation from radioactive isotopes, especially gamma radiation, can be used to investigate the composition and internal structure of materials. Techniques based on radioactive sources can help scientists identify elements, detect impurities, and study defects in metals, ceramics, polymers, and other materials.

Radioactive decay is also useful in non-destructive testing (NDT). Gamma radiography uses penetrating radiation to examine materials without cutting or damaging them. It can reveal internal cracks, voids, weld defects, and other structure irregularities. This application is particularly important in industries such as aerospace, construction , manufacturing, and nuclear engineering.

Another important use is the modification of material properties through radiation. Radiation can cause changes in the molecular and atomic structure of materials. Controlled irradiation can be used to modify polymers, improve their cross-linking , and alter properties such as strength, hardness, and resistance to heat or chemicals. Radiation processing is therefore useful in the development of specialized industrial materials.

In nuclear materials science, radiation effects are studied to understand how materials behave under prolonged exposure to radiation. Materials used in nuclear reactors may experience atomic displacement and structural changes. Studying these effects helps researches develop materials with improved radiation resistance and longer service life.

Radioactive isotopes can also serve as tracers for studying diffusion, corrosion, and chemical processes in materials. By monitoring the movement of a radioactive isotope, scientists can determine how atoms move through a material. Together, these techniques- characterization, non-destructive testing, radiation processing, and tracer studies - support the design of safer, stronger, and more durable materials for modern technological and industrial applications.

➢ *Fundamentals of Nuclear Medicine*

Nuclear medicine is a specialized field of medicine that uses radioactive substances (radioisotopes) for the diagnosis, monitoring, and treatment of diseases. Its fundamental principle is based on the use of small amounts of radioactive materials, known as radiopharmaceuticals, which are introduced into the body and selectively accumulate in particular organs or tissues.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct347

A radiopharmaceutical generally consists of two components : a radioactive isotope and a biological molecule that directs the isotope toward a specific tissue or biological process. Commonly used diagnostic radionuclides include technetium-99m (Tc-99m), fluorine-18 (F-18), iodine-123 (I-123), and gallium-68 (Ga-68). These radionuclides emit radiation that can be detected by specialized instruments.

Nuclear medicine imaging mainly uses gamma cameras, SPECT ( single photon emission computed tomography), and PET ( positron emission tomography). In SPECT, gamma – emitting radionuclides are detected to produce three-dimensional images of organs and their functions. PET uses positron-emitting radionuclides the emitted positrons ultimately produce detectable photons that allow detailed imaging of metabolic activity.

An important feature of nuclear medicine is that it can provide information about physiological and biochemical functions, rather than only showing the anatomical structure of an organ. It is therefore useful in detecting abnormalities at an early stage.

Nuclear medicine also has important therapeutic applications. Radioisotopes such as iodine-131 can deliver radiation to targeted tissues for treatment. More recent approaches use targeted radionuclide therapy to deliver radiation preferentially to specific cancer cells.

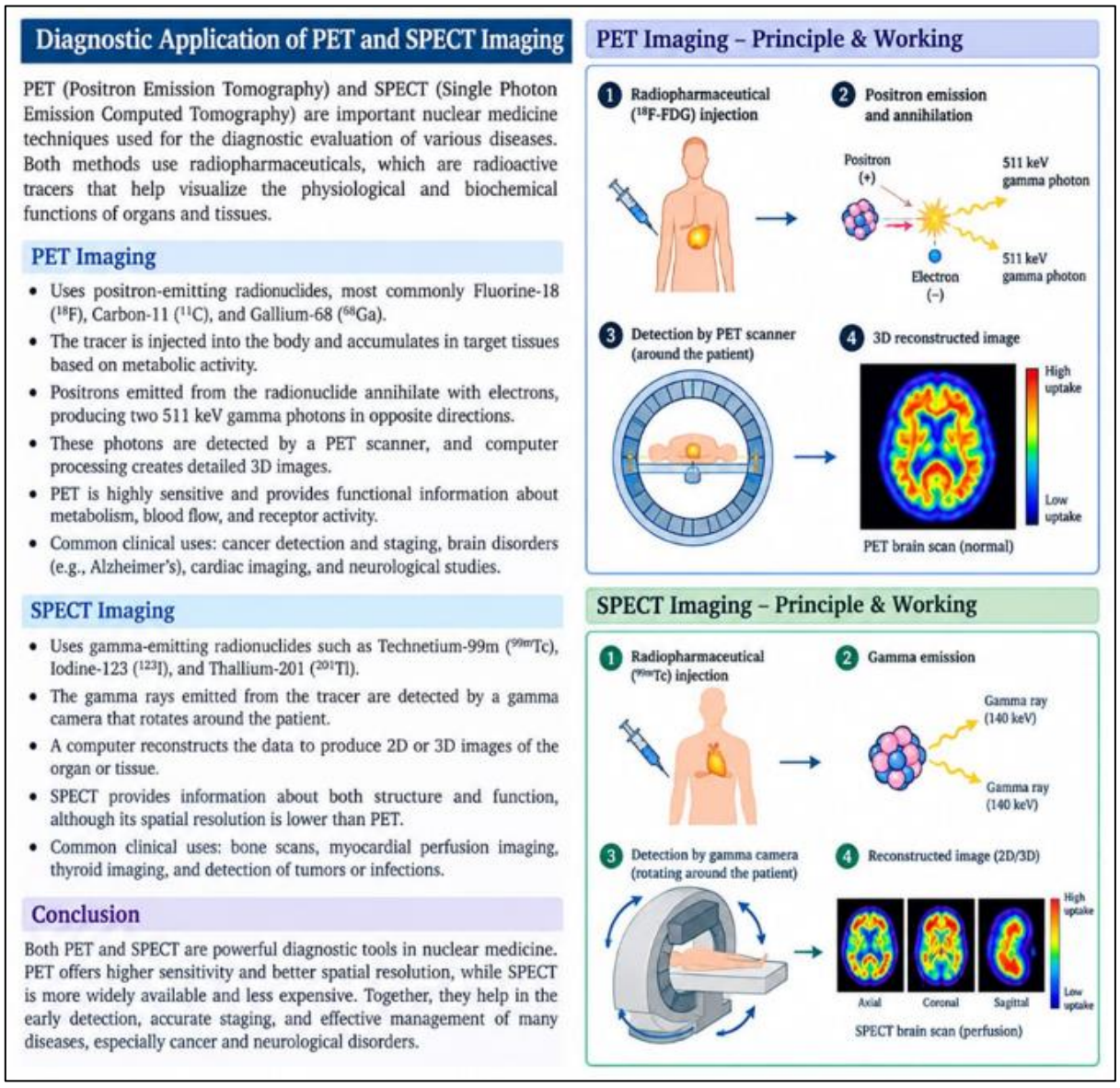

Fig 1 Diagnostic Application: PET and SPECT Imaging

➢ *Therapeutic Application: Targeted Cancer Treatment Using Radionuclides*

Targeted radionuclide therapy (TRT) is an important therapeutic application of nuclear medicine in which radioactive isotopes are selectively delivered to cancer cells. Unlike conventional radiation therapy, which generally delivers radiation from outside the body, targeted radionuclide therapy carries the radioactive material directly to tumour cells through a radiopharmaceutical. This allows radiation to be concentrated at the disease site while reducing exposure to surrounding healthy tissues.

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The basic principle involves two components: a targeting molecule and a therapeutic radionuclide. The targeting molecule recognizes specific receptors or proteins that are highly expressed on cancer cells. After administration, the radiopharmaceutical binds to these targets and accumulates in the tumor. The radionuclide then undergoes radioactive decay and releases therapeutic radiation, which damages the cancer cells DNA and can ultimately prevent its growth and survival.

Several radionuclides are used in targeted cancer treatment. Lutetium-177 ( $^{177}$Lu) is an important beta-emitting radionuclide used in targeted therapies, including treatments directed against certain neuroendocrine tumours and prostate cancer. Yttrium-90 ($^{90}$Y) is another beta emitter used in selected targeted treatments. Actinium-225 ($^{225}$Ac) is an alpha-emitting radionuclide that has attracted considerable research interest because alpha particles deposit very high energy over a short distance, making them potentially effective against small groups of cancer cells.

An important advantage of targeted radionuclide therapy is its ability to treat cancer cells that may be distributed throughout the body, including metastatic disease. The treatment can also be monitored using nuclear imaging in suitable theranostic approaches, where diagnostic and therapeutic radionuclides are used together.

However, TRT may also cause side effects because some normal tissues can take up the radiopharmaceutical. Therefore, careful selection of patients, accurate targeting, radiation- dose calculation, and monitoring of organs such as the kidneys and bone marrow are important.

- *Radiation Safety and Dosimetry in Patients*

Radiation safety and patient dosimetry are essential components of modern nuclear medicine and cancer treatment. Radiation safety aims to obtain the required diagnostic or therapeutic benefit while minimizing unnecessary exposure to ionizing radiation. The basic principle is ALARA (as low as reasonably achievable), which means radiation exposure should be kept as low as reasonably possible without compromising the medical purpose. Patient exposure depends on the type of radionuclide, administered activity, radiation energy, and duration of exposure.

Dosimetry is the measurement or calculation of the radiation dose absorbed by a patient or a particular organ. In nuclear medicine, dosimetry helps determine the appropriate amount of radiopharmaceutical required for diagnosis or targeted therapy. For therapeutic applications, patient-specific dosimetry is particularly important because it estimates the radiation absorbed by the tumor and healthy organs. This helps maximize the therapeutic effect while reducing damage to normal tissues.

Radiation protection also includes proper handling and administration of radiopharmaceuticals, minimizing unnecessary radiation exposure to patients and healthcare workers, and appropriate management of radioactive materials and waste. Modern imaging systems such as PET and SPECT, along with dose-monitoring and quantitative software, can improve dose assessment.

For radiopharmaceutical therapy, internal dosimetry considers the distribution, uptake , biological clearance, and physical decay of the radionuclide inside the body. Accurate dosimetry therefore supports personalized treatment planning, improves safety, and contributes to better clinical outcomes.

## III. FUTURE SCOPE

- *Artificial Intelligence in Nuclear Medicine Imaging*

A clear next step is genuinely personalized dosimetry, in which an algorithm calculates the radiation dose appropriate for a specific patient rather than relying on population averages. The main obstacle is not the underlying technology but trust and validation: the most promising results so far come single hospitals using their own retrospective data, and regulators such as the FDA and EMA will likely require broader multi-centre evidence before these tools become routine. There is also an equity dimension – for AI- based diagnosis to be genuinely useful, it needs to reach hospitals in low-resource regions rather than remaining confined to well-funded academic centres.

- *Cyclotron Versus Reactor Production of Medical Isotopes*

The clear direction in isotope production is decentralization. Because Tc-99m has a half-life of only about six hours, transport time from a distant reactor represents wasted activity, so locating smaller cyclotrons closer to patients is practically advantageous. Momentum is also building around electron-accelerator methods that could produce molybdenum-99 at industrial scale without a reactor, and market projections suggest accelerator-based production will grow faster than reactor-based methods through 2040. If this trend continues, it could reduce global reliance on highly enriched uranium, which carries security benefits beyond medicine.

- *Personalized Nuclear Medicine and Nano-Radiopharmaceuticals*

Future work is likely to focus on nanoparticles engineered to release their radioactive payload only upon reaching the tumor, rather than circulating and potentially affecting healthy organs. There is also growing interest in alpha-emitting isotopes such as actinium-225 , which deliver a concentrated dose of radiation over a very short range-a direction significant enough that AstraZeneca paid $2.4 billion to acquire fusion pharmaceuticals largely for its alpha-therapy pipeline. The main remaining challenges are practical: manufacturing these nanoparticles at consistent, large-scale volumes under GMP conditions, and establishing the long-term safety record regulators will require.

Taken together, nuclear medicine by 2030 is likely to look meaningfully different from today. Isotope production should spread across cyclotrons and accelerators rather than remaining concentrated in reactors. Image analysis will likely lean more heavily on AI- not to replace physicians, but to make their judgments faster and more consistent. Treatment

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct347

itself is moving toward nanoparticle-based, alpha-emitting theranostic agents built around a patient's individual tumor biology rather than a one-size-fits -all radioactive drug.

None of this happens automatically. It depends on regulators establishing multi-centre validation standards for AI tools, on manufacturers solving scale-up challenges for nano-radiopharmaceuticals, and on continues investment in non-reactor isotope production. If these pieces fall into place, nuclear medicine will shift from being primarily a diagnostic specialty to a fully personalized branch of precision oncology.

- *Decision*

The convention level represents the earliest and most established approaches to cancer treatment. Its main aim is to remove or destroy cancer cells and control tumor growth.

Surgery is one of the oldest methods and involve physically removing tumors from the body. It is mainly used when cancer is localized.

Cytotoxic chemotherapy uses anticancer drugs that interfere with the growth and division of rapidly dividing cells. However, these drugs can also affect some healthy cells.

Radiation therapy uses high-energy radiation to damage the DNA of cancer cells, preventing them from growing and dividing.

Thus, surgery, chemotherapy, and radiation therapy from the basic foundation of convention cancer treatment.

- *Modern Cancer Treatment*

In the 21st century, scientist discovered that cancer is mainly a genetic disease. This led to the development of more precise treatments. Targeted therapy attacks specific genetic changes (mutations) that cause tumor growth while reducing damage to healthy cells. Immunotherapy activates the body's immune system to recognize and destroy cancer cells. For example, checkpoint inhibitor such as Keytruda target the PD-1/PD-L1 pathway . hormone therapy is used in cancer such as breast and prostate cancer. It blocks hormones that promote cancer growth and helps control the development of the tumor.

- *Advanced Cancer Treatment*

Ultramodern cancer treatment is mainly based on precision medicine, which provides targeted and personalized therapies. Antibody –Drug Conjugates (ADCs) are called "smart bomds " because they combine monoclonal antibodies with chemotherapy drugs. They deliver the toxic drug mainly to cancer cells, reducing damages to healthy cells. Cellular therapy , especially CART T – cell therapy, use the patients own T-cell. These cells are genetically modified in a laboratory and reprogrammed to recognize and destroy cancer cells. CAR T- cells can target specific antigens, such as CD19. These advanced technologies provide new and more precise approaches for treating certain cancers.

- *Next – Generation Cancer Technologies*

Next – generation sequencing (NGS) is an advanced technique used to study the complete genetic profile of a tumor. It maps tumor DNA and helps doctors select personalized treatments according to specific genetic changes. Latest FDA- approved therapies include targeted drugs designed for rare and complex cancers. Some treatments target specific mutations, to block cancer growth. These technologies support precision medicine by matching treatment with the genetic characteristics of each patient's tumor. Thus, NGS and targeted therapies are important modern approaches that can improve cancer diagnosis, treatment selection , and personalized patient care.

## IV. CONCLUSION

Radioactive decay is a basic nuclear process, and the review shows it is useful in nuclear science , waste management, and space science. The decay law and half-life help explain how radioactivity decreases over time, and they are essential for handling radioactive materials safely. In nuclear medicine, decay makes it possible to take diagnostic images with PET and SPECT scans and to treat cancer with targeted radionuclide therapy. Radionuclides such as Tc-99m, F-18, Lu-177, Y-90 and Ac-225 show how important radioactive emissions are for both diagnosis and treatment. Dosimetry tailored to each patient is also important , since it helps maximize the treatments effect while limiting radiation exposure to healthy organs. The study also points out uses in materials science, including non-destructive testing, material characterization, radiation processing, tracer studies, and the development of radiation-resistant materials.

Radioactive decay looks like a narrow topic, but a surprising amount of science depends on it. Because the decay law, $N = N_0e^{(-\lambda t)}$, and half-life tell us how fast radioactivity fades, we can run reactors, store waste, protect workers, and even work out how old celestial objects are. In materials science, the same radiation lets us examine materials without damaging them, change their properties, and follow how atoms move inside them.

Medicine is where this matters most. PET and SPECT scans use isotopes like $^{99m}$Tc, $^{18}$F, $^{123}$I, and $^{68}$Ga to show how organs are working, not just what they look like. In treatment, $^{177}$Lu, $^{90}$Y, and the alpha emitter $^{225}$Ac carry radiation directly to cancer cells and spare much of the healthy tissue nearby. Patient-specific dosimetry and the ALARA principle keep that balance safe.

Looking toward 2030, nuclear medicine will likely change a lot. Isotopes will be made in cyclotrons and accelerators near patients instead of a few distant reactors. AI will help doctors read images faster and more consistently, without replacing their judgment. Treatment is moving toward nanoparticle-based, alpha-emitting theranostic agents built around each patient's tumor, not one drug for everyone.

None of this will happen automatically. Regulators must set multi-centre validation standards for AI tools, manufacturers must learn to produce nano-

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radiopharmaceuticals at scale, and non-reactor isotope production needs steady investment. If these pieces fall into place, nuclear medicine could grow from mainly a diagnostic field into a central part of personalized cancer care.

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