

UNIT – V NUCLEAR CHEMISTRY

Nuclear Reactions:

- **Definition:** Nuclear reactions involve changes in the composition of atomic nuclei, leading to the formation of new nuclides.
- **Types of Nuclear Reactions:**
 - Fusion: Combination of lighter nuclei to form a heavier nucleus.
 - Fission: Splitting of heavy nuclei into lighter nuclei.
 - Radioactive decay: Spontaneous transformation of unstable nuclei into more stable forms, emitting particles or radiation.

2. Nuclear Cross Section:

- **Definition:** Nuclear cross section represents the probability of a nuclear reaction occurring when a particle interacts with a target nucleus.
- **Measurement:** Expressed in barns ($1 \text{ barn} = 10^{-28} \text{ m}^2$).
- **Factors Affecting Cross Section:** Depends on factors like the energy of the incident particle, the target nucleus, and the reaction mechanism.

3. Q-Values:

- **Definition:** Q-value (reaction energy) is the energy released or absorbed during a nuclear reaction, calculated as the difference in mass-energy before and after the reaction.
- **Expression:** $Q = (\Delta m)c^2$, where Δm is the mass defect and c is the speed of light.
- **Significance:** Determines the feasibility and energetics of nuclear reactions.

4. Coulombic Barrier:

- **Definition:** Coulombic barrier represents the electrostatic repulsion between positively charged nuclei in a nuclear reaction.

- **Effect:** Determines the minimum energy required for the reactants to overcome repulsion and undergo a nuclear reaction.
- **Dependence:** Increases with the charge of the interacting nuclei and decreases with increasing distance between them.

5. Threshold Energy:

- **Definition:** Threshold energy is the minimum kinetic energy required for a particle to initiate a nuclear reaction.
- **Significance:** Below the threshold energy, the reaction does not occur due to insufficient energy to overcome the Coulombic barrier.
- **Application:** Important parameter in nuclear fusion and fission reactions, influencing reactor design and operation.

6. Excitation Function:

- **Definition:** Excitation function represents the variation of the reaction cross section with incident particle energy.
- **Purpose:** Provides insights into the energy dependence of nuclear reactions, identifying resonance peaks and threshold energies.
- **Experimental Determination:** Measured through experiments involving varying incident particle energies and detecting reaction products.

Applications:

1. **Nuclear Energy:** Understanding nuclear reactions and associated parameters is essential for the design and operation of nuclear reactors for power generation.
2. **Nuclear Medicine:** Nuclear reactions play a vital role in medical imaging (e.g., positron emission tomography) and cancer treatment (e.g., radiotherapy).
3. **Nuclear Weapons:** Knowledge of nuclear reactions is crucial for the development and maintenance of nuclear weapons.
4. **Isotope Production:** Nuclear reactions are used to produce radioisotopes for various applications, including medical diagnostics and industrial processes.

Nuclear Chemistry: Different Types of Nuclear Reactions and Isotope Distribution Analysis

Introduction to Nuclear Chemistry: Nuclear chemistry deals with the study of reactions involving atomic nuclei, including nuclear reactions and processes such as radioactive decay. These reactions involve changes in the composition of atomic nuclei and often result in the emission of radiation.

Different Types of Nuclear Reactions:

Introduction to Transmutation:

- Transmutation refers to the process of changing one chemical element into another through nuclear reactions.
- It involves altering the number of protons and/or neutrons in the nucleus of an atom, leading to the formation of a different element.
- Transmutation can occur naturally through radioactive decay or can be induced artificially in nuclear reactors or particle accelerators.

Mechanisms of Transmutation:

1. **Alpha Decay:**

- In alpha decay, an unstable nucleus emits an alpha particle, consisting of two protons and two neutrons.
- Example: Uranium-238 decays into thorium-234 by emitting an alpha particle.
- Application: Used in radioisotope dating and nuclear medicine.

2. **Beta Decay:**

- In beta decay, a neutron in the nucleus is converted into a proton, emitting a beta particle (electron) or a positron (positively charged electron).
- Example: Carbon-14 undergoes beta decay to form nitrogen-14.
- Application: Used in medical imaging and radiocarbon dating.

3. **Gamma Decay:**

- Gamma decay involves the emission of high-energy gamma rays from an excited nucleus following alpha or beta decay.
- Example: Cobalt-60 decays by emitting gamma rays to form nickel-60.
- Application: Used in cancer treatment (radiotherapy) and sterilization processes.

4. Neutron Capture:

- Neutron capture occurs when a nucleus absorbs a neutron, leading to the formation of a heavier nucleus.
- Example: Uranium-235 captures a neutron to form uranium-236.
- Application: Used in nuclear reactors to produce plutonium-239 for nuclear weapons and power generation.

5. Fusion Reactions:

- Fusion reactions involve the combination of two light nuclei to form a heavier nucleus, releasing large amounts of energy.
- Example: Deuterium and tritium undergo fusion to form helium-4 and a neutron.
- Application: Potential source of clean and abundant energy in controlled fusion reactors.

Applications of Transmutation:

1. Nuclear Energy Production:

- Transmutation processes are used in nuclear power plants to generate electricity through controlled fission reactions.
- Uranium and plutonium isotopes undergo transmutation in reactors to produce energy.

2. Nuclear Medicine:

- Radioisotopes produced by transmutation are used in diagnostic imaging (e.g., technetium-99m) and cancer therapy (e.g., iodine-131 for thyroid cancer treatment).

3. Isotope Production:

- Transmutation processes are used to produce radioisotopes for various applications, including radiotracer studies, radiopharmaceuticals, and industrial processes.

Nuclear Chemistry: Stripping and Pick-Up

Reactions - Isotope Distribution Analysis

Introduction to Stripping and Pick-Up Reactions:

- **Stripping Reactions:** Involves the removal of one or more nucleons from a projectile nucleus during a collision with a target nucleus.
- **Pick-Up Reactions:** Occurs when a target nucleus captures one or more nucleons from a projectile nucleus during a collision.

Mechanism of Stripping and Pick-Up Reactions:

1. Stripping Reactions:

- The incident projectile interacts with the target nucleus, leading to the transfer of energy and momentum.
- If the collision energy is sufficient, nucleons from the projectile nucleus can be transferred to the target nucleus.
- The resulting product nucleus has fewer nucleons than the original projectile nucleus.

2. Pick-Up Reactions:

- In pick-up reactions, the target nucleus captures one or more nucleons from the projectile nucleus.
- The collision energy determines the probability of nucleon capture, with higher energies favoring pick-up reactions.

Isotope Distribution Analysis:

- Isotope distribution analysis involves the measurement of the relative abundances of different isotopes of a particular element.
- Stripping and pick-up reactions play a crucial role in isotope distribution analysis by facilitating the production of specific isotopes.
- Isotope distribution analysis provides valuable information about nuclear processes, reaction mechanisms, and elemental composition.

Applications:

1. Nuclear Forensics:

- Isotope distribution analysis is used to determine the origin and history of nuclear materials.
- By analyzing the isotopic composition of nuclear samples, experts can identify sources of nuclear materials and track illicit nuclear activities.

2. Radiopharmaceutical Production:

- Stripping and pick-up reactions are utilized in the production of radioisotopes used in nuclear medicine.
- Isotope distribution analysis ensures the purity and isotopic composition of radiopharmaceuticals, critical for safe and effective medical imaging and therapy.

3. Environmental Monitoring:

- Isotope distribution analysis is employed to study the movement and behavior of radioactive contaminants in the environment.
- By measuring isotopic ratios in environmental samples, scientists can assess the impact of nuclear activities on ecosystems and human health.

4. Nuclear Fuel Cycle Analysis:

- Isotope distribution analysis is used to monitor nuclear fuel cycles and assess the performance of nuclear reactors.
- By analyzing isotopic compositions in spent nuclear fuel, researchers can optimize fuel management strategies and enhance reactor safety.

Nuclear Chemistry: Neutron Activation Analysis

Introduction to Neutron Activation Analysis (NAA):

- Neutron activation analysis is a nuclear analytical technique used for the qualitative and quantitative determination of elements in a sample.
- It involves irradiating the sample with neutrons to induce nuclear reactions, resulting in the formation of radioactive isotopes, which can then be detected and quantified.

Principle of Neutron Activation Analysis:

1. Neutron Irradiation:

- The sample is exposed to a neutron flux in a nuclear reactor or a neutron generator.
- Neutrons are absorbed by stable nuclei in the sample, leading to the formation of radioactive isotopes through neutron capture reactions.

2. Radioactive Decay:

- The radioactive isotopes produced during neutron activation decay over time, emitting characteristic gamma rays.
- The intensity of gamma ray emissions is directly proportional to the concentration of the corresponding element in the sample.

3. Gamma Ray Spectroscopy:

- The emitted gamma rays are detected using a gamma ray spectrometer.
- By measuring the energies and intensities of the gamma rays, the elemental composition of the sample can be determined.

Procedure of Neutron Activation Analysis:

1. Sample Preparation:

- The sample is prepared by homogenizing and, if necessary, digesting it to ensure uniform composition and accessibility of elements.

2. Neutron Irradiation:

- The prepared sample is irradiated with neutrons for a specific period in a neutron flux.
- Neutron activation reactions occur, leading to the formation of radioactive isotopes in the sample.

3. Cooling Period:

- After irradiation, the sample is allowed to cool to allow short-lived isotopes to decay, reducing interference during analysis.

4. Gamma Ray Spectrometry:

- The sample is placed in a gamma ray spectrometer, and the emitted gamma rays are detected and analyzed.
- The energies and intensities of gamma rays are recorded, allowing for the identification and quantification of elements in the sample.

Applications of Neutron Activation Analysis:

1. Forensic Analysis:

- NAA is used in forensic science for the analysis of trace elements in evidence such as hair, soil, and gunshot residues.
- It can provide valuable information for criminal investigations and court proceedings.

2. Environmental Monitoring:

- NAA is employed to monitor environmental pollution by analyzing samples such as air, water, sediment, and biological tissues.
- It helps in identifying sources of pollution and assessing the impact of human activities on the environment.

3. Archaeological Studies:

- NAA is used in archaeology to determine the elemental composition of artifacts, pottery, and ancient remains.
- It aids in tracing the origin of materials, understanding ancient technologies, and reconstructing past human activities.

4. Quality Control in Industry:

- NAA is utilized in various industries for quality control and assurance purposes.
- It is employed in the analysis of metals, alloys, ceramics, and electronic components to ensure compliance with specifications and standards.

Nuclear Chemistry: Projectile Capture and Particle Emission

Introduction to Projectile Capture and Particle Emission:

Projectile capture and particle emission are fundamental processes in nuclear chemistry involving the interaction of a projectile with a target nucleus, resulting in the capture of the projectile by the target nucleus and subsequent emission of particles. These processes are essential for understanding nuclear reactions, nuclear decay, and the synthesis of new isotopes.

Mechanisms of Projectile Capture and Particle Emission:

1. Projectile Capture:

- In projectile capture, a fast-moving particle (projectile) interacts with a target nucleus and becomes bound to it through nuclear forces.
- This process typically occurs in nuclear reactions induced by particle accelerators or in natural processes such as cosmic ray interactions.
- Example: Neutron capture by a target nucleus to form a new isotope.

2. Particle Emission:

- After projectile capture, the resulting compound nucleus may undergo various decay processes, emitting particles such as protons, neutrons, alpha particles, or gamma rays.
- The emitted particles carry away excess energy and stabilize the nucleus.
- Example: Beta decay of a neutron-rich nucleus, where a neutron is transformed into a proton, emitting a beta particle (electron) and an antineutrino.

Types of Particle Emission:

1. Alpha Decay:

- Emission of an alpha particle (a helium-4 nucleus) from the nucleus.
- Example: Uranium-238 decaying to Thorium-234 by alpha emission.

2. Beta Decay:

- Emission of a beta particle (electron or positron) from the nucleus.
- Example: Carbon-14 decaying to Nitrogen-14 by beta emission.

3. Gamma Decay:

- Emission of gamma rays (high-energy photons) from an excited nucleus.
- Example: Decay of an excited state of a nucleus following alpha or beta decay.

4. Neutron Emission:

- Emission of a neutron from the nucleus.
- Example: Spontaneous fission of heavy nuclei such as Uranium-235.

Applications of Projectile Capture and Particle Emission:

1. Nuclear Power Generation:

- Understanding projectile capture and particle emission processes is crucial for nuclear power generation, where controlled nuclear reactions produce heat to generate electricity.

2. Medical Imaging and Therapy:

- Radioisotopes produced through projectile capture and particle emission are used in medical imaging techniques such as positron emission tomography (PET) and in cancer therapy.

3. Nuclear Astrophysics:

- These processes play a vital role in understanding stellar nucleosynthesis, the production of elements in stars through nuclear reactions.

4. Nuclear Forensics:

- Studying the products of projectile capture and particle emission can help in forensic analysis of nuclear materials, including nuclear weapon proliferation detection and tracing the origin of nuclear materials.

5. Radiometric Dating:

- Isotopes produced by projectile capture and particle emission are used in radiometric dating techniques to determine the age of geological and archaeological samples.

Nuclear Chemistry: Spallation, Fragmentation, Nuclear Fission, Nuclear Fusion

1. Spallation:

- Spallation is a nuclear reaction in which a heavy nucleus is bombarded with high-energy particles, typically protons, neutrons, or other nuclei.
- The collision causes the heavy nucleus to break apart into smaller fragments, including nuclei, neutrons, and various nuclear particles.
- Spallation reactions are commonly used in particle physics research and in the production of certain radionuclides for medical and industrial applications.
- Applications include the production of isotopes for medical imaging, neutron sources for scientific research, and neutron activation analysis for elemental analysis.

2. Fragmentation:

- Fragmentation refers to the process by which a heavy nucleus breaks apart into smaller fragments due to the repulsive forces between nucleons.
- This process occurs spontaneously in some radioactive isotopes and can also be induced by external factors such as high-energy collisions.
- Fragmentation plays a significant role in nuclear reactions in particle accelerators and cosmic ray interactions with matter.
- Applications include the study of nuclear structure, the production of exotic nuclei for research purposes, and understanding the mechanisms of nuclear decay.

3. Nuclear Fission:

- Nuclear fission is a nuclear reaction in which the nucleus of a heavy atom, such as uranium-235 or plutonium-239, splits into two or more lighter nuclei, along with the release of a large amount of energy.
- This process can occur spontaneously in certain isotopes or can be induced by bombarding the nucleus with neutrons.
- Nuclear fission is the basis of nuclear power generation in nuclear reactors, where the heat produced by fission reactions is used to generate electricity.
- It is also used in nuclear weapons, where controlled or uncontrolled fission reactions release enormous amounts of energy.
- Research into nuclear fission continues for applications such as transmutation of nuclear waste and production of medical isotopes.

4. Nuclear Fusion:

- Nuclear fusion is a nuclear reaction in which two light atomic nuclei combine to form a heavier nucleus, releasing a large amount of energy in the process.
- Fusion reactions occur naturally in stars, including our Sun, where hydrogen nuclei fuse to form helium and release energy.
- Achieving controlled nuclear fusion on Earth is a major goal of research, as it offers the potential for a nearly limitless and clean energy source.
- Fusion research projects, such as tokamaks and inertial confinement fusion, aim to replicate the conditions of stellar fusion and harness the energy released for practical applications.
- Fusion energy has the potential to revolutionize global energy production, providing a sustainable and environmentally friendly alternative to fossil fuels.

Applications:

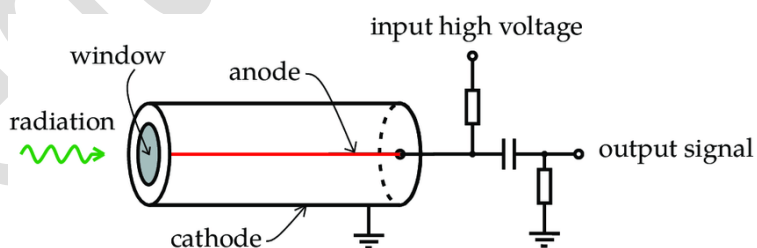
- **Energy Production:** Nuclear fission and fusion have the potential to provide significant amounts of clean energy, reducing dependence on fossil fuels and mitigating climate change.
- **Medical Isotope Production:** Nuclear reactions are used to produce radioactive isotopes for medical imaging, diagnosis, and treatment of various diseases, including cancer.
- **Materials Science:** Nuclear reactions are used to study materials at the atomic level and to produce novel materials with specific properties for various applications.
- **National Security:** Nuclear reactions play a crucial role in national security, including the development and maintenance of nuclear weapons and detection of nuclear materials for non-proliferation efforts.

Nuclear Chemistry: Proportional Counter, Geiger-Muller Counter, Scintillation Counter, and Cherenkov Counter

Introduction to Radiation Detection:

- Radiation detection plays a crucial role in various fields such as nuclear medicine, environmental monitoring, and nuclear power generation.
- Different types of radiation detectors are used to measure the intensity, energy, and type of radiation emitted by radioactive substances.

1. Proportional Counter:



Proportional Counter: Working Principle (Short Summary in Points):

1. Gas-filled Detector:

- A proportional counter is a type of gas-filled radiation detector used to detect and measure ionizing radiation.

2. **Gas Medium:**

- The detector contains a gas-filled chamber, typically filled with a noble gas such as argon, xenon, or helium, at low pressure.

3. **Electrodes:**

- The chamber has a central wire anode surrounded by a cathode or outer shell. High voltage is applied between the anode and cathode.

4. **Ionization of Gas:**

- When ionizing radiation interacts with the gas atoms, it ionizes them, producing positively charged ions and free electrons.

5. **Electron Avalanche:**

- The electric field between the anode and cathode accelerates the free electrons towards the anode, causing them to undergo multiplication through an electron avalanche process.

6. **Proportional Region:**

- In the proportional region, the number of electrons produced is proportional to the energy deposited by the incoming radiation.

7. **Signal Generation:**

- The avalanche of electrons generates a measurable electrical pulse at the anode, proportional to the energy of the incident radiation.

8. **Amplification and Readout:**

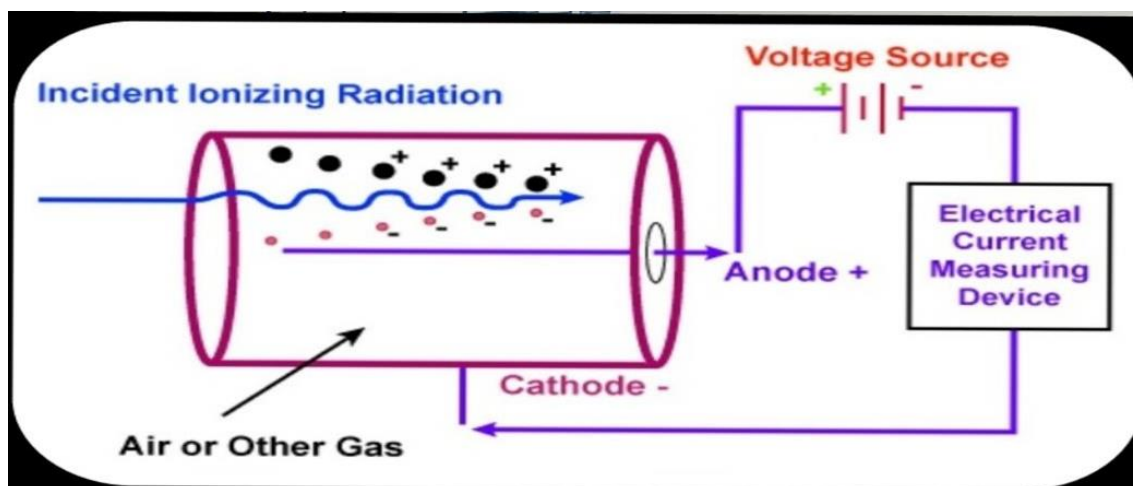
- The electrical pulse is amplified and processed by associated electronics to measure the energy and intensity of the radiation.

9. **Gas Composition:**

- The gas composition and pressure are carefully chosen to ensure that the detector operates in the proportional region.

- **Application:** Used in nuclear physics research, environmental monitoring, and radiation protection.

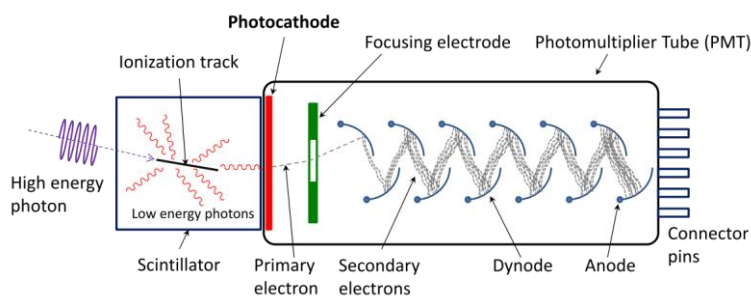
2. Geiger-Muller Counter:



Working Principle of Geiger-Muller Counter:

- **Gas-Filled Tube:** The Geiger-Muller (GM) counter consists of a gas-filled tube containing an inert gas such as helium, neon, or argon at low pressure.
- **Central Electrode:** A thin wire or rod acts as the central electrode running along the axis of the tube.
- **High Voltage:** A high voltage is applied between the central electrode and the outer cylindrical wall of the tube, creating a strong electric field within the gas.
- **Ionization by Radiation:** When ionizing radiation enters the tube, it interacts with the gas atoms, ionizing them and producing free electrons and positively charged ions.
- **Electron Avalanche:** The electric field accelerates the free electrons towards the central electrode, causing them to gain kinetic energy and ionize additional gas atoms through collisions.
- **Townsend Avalanche:** The process continues, resulting in a cascade of electron multiplication known as a Townsend avalanche.
- **Signal Generation:** The avalanche of electrons produces a detectable electrical pulse or discharge across the electrodes.
- **Counting and Detection:** The electrical pulse is detected and counted by the electronic circuitry connected to the GM counter, registering the presence of ionizing radiation.
- **Quenching:** A quenching gas, such as alcohol or halogen, is often added to the inert gas to prevent multiple avalanches from occurring simultaneously and ensure that each ionizing event produces only one measurable pulse.
- **Application:** Radiation safety instrumentation, radioactive contamination detection, and particle physics experiments.

3. Scintillation Counter:



Working Principle of Scintillation Counter:

1. Interaction with Ionizing Radiation:

- Ionizing radiation interacts with the scintillator material, depositing energy and exciting its atoms.

2. Emission of Photons:

- Excited atoms within the scintillator emit photons (light) as they return to their ground state.

3. Detection by Photomultiplier Tube (PMT):

- Photomultiplier tubes detect the emitted photons and convert them into electrical signals.

4. Signal Processing:

- Signal processing electronics amplify, shape, and analyze the electrical signals generated by the photomultiplier tube.

5. Data Analysis:

- The processed signals are analyzed to determine the energy, intensity, and type of ionizing radiation detected.

6. Output:

- The results of the analysis, such as radiation dose or particle energy, are then displayed or recorded for further interpretation.

- Application: Gamma-ray spectrometry, positron emission tomography (PET), and high-energy physics experiments.

4. Cherenkov Counter:

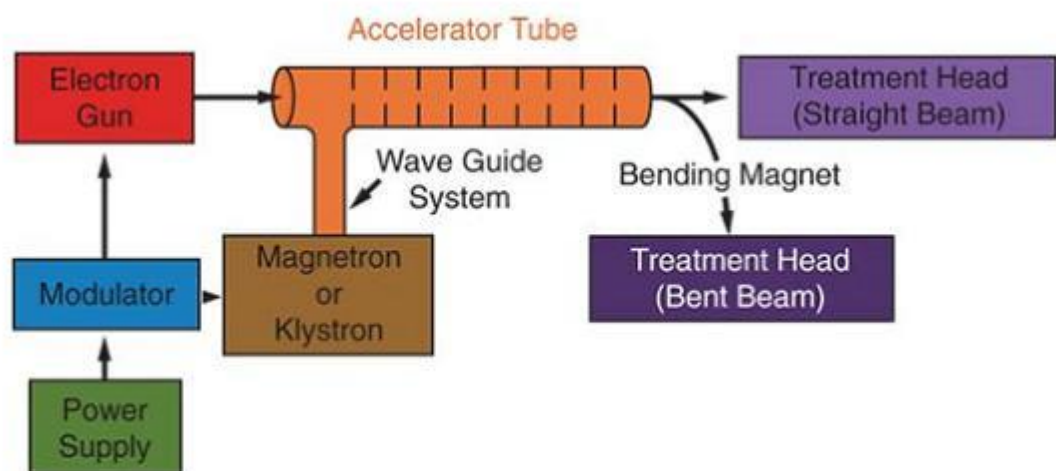
- Detects charged particles moving faster than the speed of light in a particular medium, emitting Cherenkov radiation.

- Cherenkov radiation appears as a faint blue glow and can be detected using photomultiplier tubes or other light detectors.
- The intensity of Cherenkov radiation is proportional to the particle's velocity.
- Used to detect high-energy particles in particle physics experiments and cosmic-ray studies.
- Application: Detection of neutrinos, measurement of particle velocities, and nuclear reactor monitoring.

Nuclear Chemistry: Linear Accelerator, Cyclotron, and Synchrotron

Introduction to Particle Accelerators: Particle accelerators are powerful tools used in nuclear physics and chemistry to accelerate charged particles to high energies. They play a crucial role in various fields, including nuclear research, medical diagnostics and treatment, and material science.

1. Linear Accelerator (LINAC): A linear accelerator accelerates charged particles along a straight path using a series of electric fields. It consists of the following components:

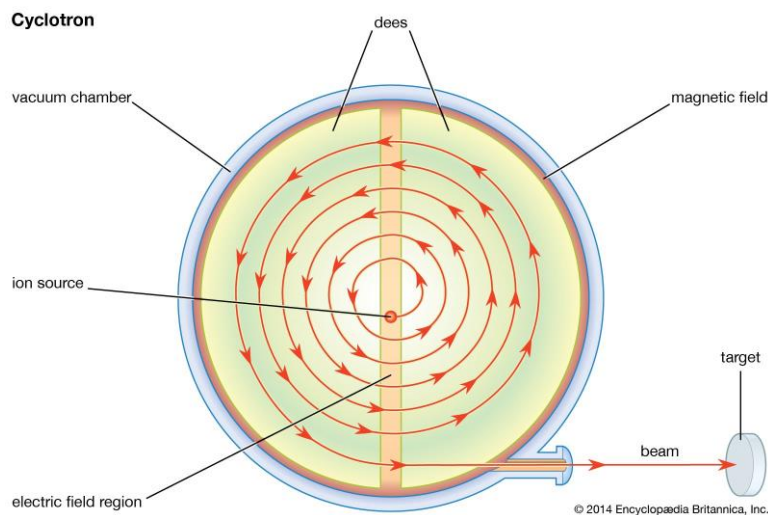


- **Electron Gun:** Emits electrons at the beginning of the accelerator.
- **Waveguide:** A series of alternating electric fields is generated along the accelerator tube, accelerating the particles.
- **Radiofrequency (RF) Cavities:** Provide the electric fields necessary for particle acceleration.
- **Beamline:** Guides the accelerated particles to the desired target.

Applications:

- **Radiation Therapy:** Linear accelerators are widely used in cancer treatment, delivering high-energy X-rays or electron beams to target and destroy tumors while minimizing damage to surrounding healthy tissue.
- **Industrial Applications:** Used for materials testing, sterilization, and non-destructive testing techniques like X-ray radiography and computed tomography (CT).

2. Cyclotron: A cyclotron accelerates charged particles in a circular path using a combination of electric and magnetic fields. It consists of the following components:

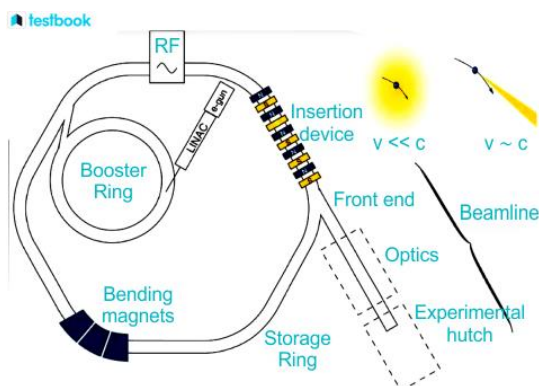


- **Dees (D-shaped chambers):** Charged particles are injected into the gap between the dees.
- **Magnetic Field:** Bends the path of the particles in a circular trajectory.
- **Radiofrequency (RF) Source:** Provides alternating electric fields to accelerate the particles as they cross the gap between the dees.

Applications:

- **Isotope Production:** Cyclotrons are used to produce radioisotopes for medical imaging (PET imaging) and therapy (radioimmunotherapy).
- **Nuclear Physics Research:** Used to study nuclear reactions and nuclear structure by bombarding target nuclei with accelerated particles.

2. Synchrotron: A synchrotron is a type of particle accelerator that uses magnetic fields to bend and focus beams of charged particles in a circular path. Unlike cyclotrons, synchrotrons can continuously accelerate particles to higher energies. Components include:



- **Ring Magnet:** Creates a magnetic field to bend the path of the particles.
- **RF Cavities:** Provide electromagnetic fields to accelerate particles.
- **Insertion Devices (Undulators and Wigglers):** Generate intense beams of X-rays or other electromagnetic radiation by causing the accelerated particles to oscillate.

Applications:

- **X-ray Crystallography:** Synchrotron radiation is used to determine the atomic and molecular structure of crystals, essential for understanding the properties and behavior of materials in chemistry, biology, and materials science.
- **Materials Science:** Synchrotron radiation is employed in spectroscopy techniques like X-ray absorption spectroscopy (XAS) and X-ray fluorescence (XRF) for studying the composition and properties of materials.
- **Biomedical Research:** Used in structural biology techniques like protein crystallography and small-angle X-ray scattering (SAXS) for studying biological molecules and complexes.