Unit 7

Nuclear Physics

Nuclear Physics Overview

1. Introduction to Nuclear Physics

Nuclear physics focuses on studying atomic nuclei, including their structure and the interactions that bind them. Key interactions include:

- **Radioactive Decay**: The process by which unstable nuclei release energy.
- **Fission**: The splitting of a heavy nucleus into lighter nuclei.
- **Fusion**: The merging of light nuclei to form a heavier nucleus.

The strong nuclear force, which acts over very short distances (a few femtometers), is crucial for binding protons and neutrons in the nucleus. This force is responsible for the stability and the energy released during nuclear reactions.

2. Atomic Structure

Atoms consist of:

- **Nucleus**: Contains protons (positive charge) and neutrons (neutral).
- **Electrons**: Negatively charged particles orbiting the nucleus.

Subatomic Particles:

- **Protons**: Charge = $+1.602 \times 10^{-19}$ C, Mass = 1.6726×10^{-27} kg.
- **Neutrons**: Charge = 0, Mass = 1.6749×10^{-27} kg.
- **Electrons**: Charge = -1.602×10^{-19} C, Mass = 9.1094×10^{-31} kg.

The mass number (A) is the sum of protons and neutrons, while the atomic number (Z) is the number of protons. For example, Carbon-12 (^{12}C) has 6 protons and 6 neutrons.

3. Isotopes

Isotopes are variants of an element with the same number of protons but different numbers of neutrons. They have the same chemical properties but differ in mass.

Examples:

- **Carbon Isotopes**: ^{12}C, ^{13}C, ^{14}C.
- **Hydrogen Isotopes**: ^{1}H (Protium), ^{2}H (Deuterium), ^{3}H (Tritium).

4. Historical Discoveries

- **Rutherford's Experiment (1909)**: Led to the discovery of the nucleus. Alpha particles were deflected by a small, dense, positively charged nucleus within the atom.
- **Discovery of Protons (1920)**: Rutherford identified the proton as a fundamental particle.
- **Discovery of Neutrons (1932)**: James Chadwick discovered the neutron, which has no charge and is slightly heavier than the proton.

5. Nuclear Forces

- **Strong Nuclear Force**: A short-range force that binds protons and neutrons in the nucleus, overcoming electrostatic repulsion.
- **Weak Nuclear Force**: Acts within individual nucleons and is involved in radioactive decay processes.

6. Nuclear Binding Energy

Binding energy is the energy required to disassemble a nucleus into its constituent nucleons. It can be calculated using the mass defect (Δm), which is the difference between the mass of the nucleus and the sum of the masses of its constituent protons and neutrons.

Formula: $B_E=\Delta m \cdot c^2$ where c is the speed of light (3×10^8 m/s).

Example Calculation: For Oxygen-16:

- Mass defect $\Delta m = 0.1276$ u.
- Binding energy $B_E = 0.1276 \times 931.1$ MeV = 118.8 MeV.
- Binding energy per nucleon $B_{EN} = \frac{118.8\ MeV}{16} \approx 7.4$ MeV.

7. Nuclear Stability

The stability of a nucleus is determined by its binding energy per nucleon. Heavier nuclei beyond iron tend to have lower binding energy per nucleon, leading to increased instability.

Radioactivity

Introduction: In 1896, French physicist Antoine Henri Becquerel discovered that uranium-rich minerals emit invisible, penetrating radiation that can darken photographic plates. This phenomenon was later understood as radioactivity, where unstable isotopes emit particles to become stable.

Radioactivity Basics:

- **Unstable Isotopes**: Atoms with an imbalance in the number of protons and neutrons in their nucleus are unstable. They emit radiation to achieve stability.
- **Radioisotopes**: Unstable isotopes that undergo radioactive decay.
- **Radiation**: The energy released during decay.

Types of Nuclear Radiation:

1. **Alpha Particles (α):**
   - **Composition**: Two protons and two neutrons (He-4 nucleus).
   - **Process**: The nucleus emits an alpha particle to become more stable.
   - **Example**: Uranium-238 decays to Thorium-234:

     $^{238}U \rightarrow {}^{234}Th + {}^{4}He$

   - **Properties**: High ionizing power but low penetration (stopped by paper or skin).
2. **Beta Particles (β):**
   - **Types**: Beta-minus (β-) and Beta-plus (β+).
   - **Beta-minus (β-)**: An electron is emitted when a neutron converts into a proton. $^{A}X \rightarrow {}^{A}Y + e^{-} + \bar{v}$

     Example: Thorium-234 decays to Protactinium-234:
     $^{234}Th \rightarrow {}^{234}Pa + e^{-} + \bar{v}$

   - **Beta-plus (β+)**: A positron is emitted when a proton converts into a neutron. $^{A}X \rightarrow {}^{A}Y + e^{+}$

     Example: Potassium-38 decays to Argon-38.

3. **Gamma Rays (γ):**
   - **Composition**: High-energy electromagnetic radiation.
   - **Process**: Emitted alongside alpha or beta decay to release excess energy.

- **Properties**: Low ionizing power but high penetration (stopped by lead or thick concrete).

Ionization and Penetration:

- **Ionizing Power**: Alpha particles have high ionizing power; gamma rays have low ionizing power.
- **Penetration Power**: Gamma rays penetrate the most; alpha particles have the least penetration.

Dangers of Radiation:

- **Ionization**: Radiation can ionize cellular tissue, leading to potential DNA damage, cell death, or mutation.
- **Factors Affecting Damage**:
    - Type of radiation
    - Sensitivity of tissues
    - Duration and intensity of exposure
    - Radioactive isotopes involved
    - Characteristics of the exposed individual

Effective Dose and Safety:

- **Absorbed Dose**: Measured in gray (Gy) or rad; describes energy deposited per unit mass.
- **Sievert (Sv)**: Accounts for biological effects.
- **Safety Precautions**:
    - Handle radioactive materials with tongs.
    - Use shielding (e.g., lead for gamma rays).
    - Follow strict hygiene and distance protocols.

Radiation Detectors:

- **Scintillators**: Detect high-energy radiation by emitting light when struck by radiation.
- **Geiger Counters**: Measure ionization by detecting electrical currents generated in a gas-filled chamber.

Half-Life:

- **Definition**: Time taken for half of the radioactive nuclei in a sample to decay.
- **Calculation**: $N=N_0e^{-\lambda t}$ where N is the number of undecayed nuclei at time t, and λ is the decay constant.

- **Half-Life Formula**: $t_{1/2}=\frac{ln2}{\lambda}$

Sample Questions and Answers:

1. **Why is Tritium (H-3) a radioisotope?**
   - Tritium decays because it has an unstable nucleus despite having no electrostatic repulsive forces. It undergoes beta decay to become Helium-3.
2. **Why does Uranium-235 decay via alpha emission?**
   - Uranium-235 has a large nucleus with many protons and neutrons. To achieve stability, it emits an alpha particle (He-4 nucleus), reducing its size and neutron-to-proton ratio.
3. **Factors Affecting Radiation Damage:**
   - Type of radiation
   - Sensitivity of tissues and organs
   - Duration and intensity of exposure
   - Radioactive isotopes
   - Individual characteristics
4. **Can decay constants or half-lives be determined with a few nuclei?**
   - No, because radioactive decay is statistical. Large numbers of nuclei are needed for accurate measurements.
5. **Determine the decay equations:**
   - **Uranium-238**: $^{238}U \rightarrow ^{234}Th + ^{4}He$
   - **Thorium-234**: $^{234}Th \rightarrow ^{234}Pa + e^{-} + \bar{\nu}$
   -
6. **Does the decay probability per unit time change with time?**
   - No, it remains constant. The decay rate depends on the number of undecayed nuclei but the probability of decay per nucleus remains constant.
7. **Compare Geiger Counter and Scintillator:**
   - **Geiger Counter**: Detects ionization from radiation; provides counts of radiation events.
   - **Scintillator**: Detects high-energy radiation by converting radiation into visible light; provides detailed information on radiation types.
8. **Ionizing Gas in Geiger-Muller Counter:**
   - Argon or other noble gases are typically used as ionizing gases.
9. **Calculate Activity:**
   - **Activity**: $A=\lambda N$

   $A=3.84\times10^{-12}\times100\times10^{6}=0.384$ Bq

10. **Plot Activity vs. Time for Technetium-99:**

    - Use the provided data to create a graph and determine the half-life from the decay pattern.

This concise note should help students understand the basics of radioactivity and its types, the implications of exposure, and methods of measurement.

the Use of Nuclear Radiation

Medical Applications of Nuclear Radiation

Nuclear medicine involves the use of radioactive materials for diagnosing and treating diseases. Here's a breakdown of its applications:

1. **Diagnosis**:
    - **Purpose**: To observe how organs or tissues are functioning.
    - **Method**: A small amount of radioactive material, called a tracer, is introduced into the body. This can be done through injection, ingestion, or inhalation.
    - **Imaging**: The tracer emits radiation that is detected by imaging devices, such as gamma cameras or PET scanners, to create images of the internal organs or tissues.
    - **Common Tracers**: Include fluorine-18, technetium-99m, and iodine-123.
    - **Example**: PET scans use tracers to provide detailed images of how organs are working and detect abnormalities like cancer.
2. **Treatment**:
    - **Purpose**: To destroy damaged or diseased tissues, such as cancer cells.
    - **Types**:
        - **External Beam Radiation**: High-energy beams (e.g., gamma rays from cobalt-60) are targeted at the cancer site from outside the body.
        - **Internal Radiation Therapy**:
            - **Brachytherapy**: Radioactive material is placed inside or near the tumor (e.g., iodine-131 for thyroid cancer).
            - **Systemic Radiation Therapy**: The patient ingests or is injected with radioactive substances that travel through the body to target cancer cells.

Radioactive Dating

Radioactive dating is a technique used to determine the age of materials using naturally occurring radioactivity.

1. **Process**:
   - **Concept**: Measures the ratio of parent isotopes (unstable) to daughter isotopes (stable) formed from decay.
   - **Formula**: $t=\frac{\ln\left(\frac{N}{N_0}\right)}{\lambda}$, where N is the number of daughter isotopes, N_0 is the initial number of parent isotopes, and λ is the decay constant.
2. **Carbon-14 Dating**:
   - **Uses**: Dates biological materials up to about 50,000 years old.
   - **Mechanism**: Carbon-14 is absorbed by living organisms. After death, it decays at a known rate (half-life of 5730 years). By comparing the remaining carbon-14 to its original amount, the age of the sample can be estimated.
3. **Limitations**:
   - **Carbon-14**: Ineffective for samples older than 50,000 years because the amount of carbon-14 becomes too small to measure accurately.

Nuclear Reactions

1. **Fission Reaction**:
   - **Process**: Splitting a heavy nucleus (e.g., uranium-235) into two smaller nuclei, releasing energy.
   - **Example**: $^{235}U+^{1}n\rightarrow^{144}Ba+^{89}Kr+3n^{1}+200MeV$.
   - **Applications**: Used in nuclear reactors to generate electricity. A chain reaction is maintained to continuously produce energy.
2. **Fusion Reaction**:
   - **Process**: Combining two light nuclei (e.g., hydrogen isotopes) to form a heavier nucleus, releasing more energy than fission.
   - **Example**: $^{2}H+^{3}H\rightarrow^{4}He+^{1}n$.
   - **Applications**: Powers the sun and other stars. Fusion reactions are also explored for potential energy production on Earth and are used in hydrogen bombs.

Summary of Key Points:

- **Medical Applications**: Nuclear medicine uses radiation for diagnosis (e.g., PET scans) and treatment (e.g., external and internal radiation therapy).
- **Radioactive Dating**: Measures the age of materials based on the decay of isotopes, with carbon-14 dating being useful for relatively recent samples.
- **Nuclear Reactions**: Include fission (splitting heavy nuclei) and fusion (combining light nuclei), with applications in energy production and, in the case of fusion, significant potential for future energy sources.

Safety Rules Against Hazards of Nuclear Radiation

1. Understanding Nuclear Safety

Nuclear safety is crucial for protecting people and the environment from the risks associated with nuclear radiation. The International Atomic Energy Agency (IAEA) defines nuclear safety as ensuring proper operating conditions and preventing or mitigating accidents. This involves protecting workers, the public, and the environment from radiation hazards. Nuclear security focuses on preventing and responding to malicious acts involving nuclear materials, such as sabotage or theft.

Key Areas of Nuclear Safety:

- Handling and disposal of fissile materials (materials that can sustain a nuclear fission chain reaction)
- Safety of nuclear power plants
- Management of nuclear weapons and radioactive materials
- Safe use of radioactive materials in industry, medicine, and research
- Disposal of nuclear waste
- Limiting radiation exposure

2. Protecting Yourself from Radiation

Radiation Protection Principles:

- **Time:** Reduce exposure time to lower radiation dose.
- **Distance:** Increase distance from the radiation source to decrease exposure significantly.
- **Shielding:** Use barriers (e.g., lead, concrete, water) to protect against radiation. For example, radioactive materials are often stored underwater or in shielded rooms.

Handling Radioactive Sources in Schools:

- Use tongs or forceps, not bare hands.
- Keep sources at arm's length and away from the body and eyes.
- Wash hands after handling and before eating.
- Store sources in sealed containers with appropriate shields.

3. What to Do in the Event of a Nuclear Accident

- **Stay Informed:** Follow instructions from authorities and emergency services.
- **Protect Yourself:** Use protective clothing if available, and avoid unnecessary exposure.
- **Evacuation:** Follow evacuation orders and seek shelter if instructed to do so.

4. Main Safety Guidelines for Nuclear Reactors

1. **Containment:** Ensure reactors are securely contained to prevent the release of radioactive materials.
2. **Redundancy:** Implement multiple safety systems to manage emergencies.
3. **Regular Maintenance:** Conduct regular inspections and maintenance to ensure all safety systems are functioning properly.

5. Radiation Detection and Measurement

- **Radiation Detectors:** Devices like scintillators, gaseous ionization detectors, and Geiger counters measure radiation levels.
- **Units of Measurement:** Radiation dose is measured in grays (Gy) and rads, while activity is measured in Becquerels (Bq) and Curie (Ci).

6. Radioactive Decay and Nuclear Reactions

- **Radioactive Decay:** Unstable atomic nuclei decay to form more stable nuclei, releasing energy.
- **Half-Life:** The time it takes for half of the radioactive nuclei to decay.
- **Fission:** Splitting of a large nucleus into smaller nuclei, releasing energy.
- **Fusion:** Combining light nuclei to form a heavier nucleus, also releasing energy.

Understanding these safety principles and guidelines is crucial for anyone working with or around nuclear materials. Always follow safety protocols and stay informed about the latest safety practices.