



INTELLIGENCE LEARNING



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ENERGY SCIENCE AND ENGINEERING

UNIT 2 ONE SHOT



INTELLIGENCE LEARNING



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SYLLABUS

Unit 2 Nuclear Energy:

Fundamental forces in the universe, Quantum mechanics relevant for nuclear physics, Nuclear forces, energy scales and structure, Nuclear binding energy systematics, reactions and decays, Nuclear fusion, Nuclear fission and fission reactor physics, Nuclear fission reactor design, safety, operation and fuel cycles



Fundamental Forces in the Universe (in Simple Language)

There are four fundamental forces in the universe that govern everything from atoms to galaxies. These forces explain how matter interacts and behaves.

1. Gravitational Force:- Pulls objects with mass toward each other. And the Carrier Particle is Hypothetical graviton (not yet discovered). **Strength:** Weakest, but acts over infinite distance.

Example: Earth pulling us down; planets orbiting the sun.

2. Electromagnetic Force:- Acts between charged particles. And the Carrier Particle is Photon (light particle). **Strength:** Stronger than gravity; acts over long range.

Example: Light, magnets, electricity, atoms sticking together.

3. Strong Nuclear Force:- Binds protons and neutrons inside atomic nuclei. And the Carrier Particle is Gluon. **Strength:** Strongest of all forces, but acts over a very short range.

Example: Holds nucleus of an atom together.

4. Weak Nuclear Force:- Responsible for radioactive decay and nuclear reactions in the sun. And the Carrier Particles is W and Z bosons. **Strength:** Weaker than strong and electromagnetic forces.

Example: Beta decay in radioactive atoms.



Quantum Mechanics in Nuclear Physics

Quantum mechanics is the foundation of nuclear physics. It helps us understand how particles like protons, neutrons, and electrons behave inside atoms and nuclei — where classical physics fails.

- 1. Particles Act Like Waves:-** Tiny particles like protons and neutrons don't behave like balls — they act like waves, and we use quantum rules to understand their movement inside the nucleus.
- 2. Energy is in Steps (Not Smooth):-** Particles inside the nucleus can only have certain fixed energy levels, like steps on a ladder not just any value. This explains why some atoms are stable and others break apart (radioactive).
- 3. Quantum Tunneling (Escape Trick):-** Sometimes particles escape the nucleus even if they don't have enough energy — it's like passing through a wall! This is called tunneling, and it explains radioactive decay and fusion.
- 4. No Sharing Same Spot (Pauli Rule):-** Two similar particles can't stay in the same place with the same energy. This rule helps us understand how protons and neutrons arrange themselves inside the nucleus.
- 5. Can't Know Everything Exactly (Uncertainty):-** We can't know both where a particle is and how fast it's moving at the same time. This uncertainty helps explain how tightly particles are packed in the nucleus.

Nuclear Forces

Nuclear forces are the strong forces that hold the nucleus of an atom together, even though protons naturally repel each other due to their positive charge. These are very strong attractive forces between protons and neutrons (called nucleons) in the nucleus. Without nuclear forces, the nucleus would break apart due to the repulsion between protons.

Key Properties of Nuclear Forces:

1. **Very Strong:**- Much stronger than gravitational or electromagnetic forces — strongest in nature.
2. **Short-Range:**- Acts only inside the nucleus. If particles are too far, the force disappears.
3. **Attractive in Nature:**- Keeps the nucleus stable by pulling protons and neutrons together.
4. **Charge-Independent:**- Acts equally between proton-proton, neutron-neutron, and proton-neutron (almost the same strength).
5. **Saturating Force:**- A nucleon interacts only with its **nearest neighbors**, not with all others in the nucleus.

Types of Nuclear Forces

Type	Description
Strong Nuclear Force	Binds protons and neutrons in nucleus.
Residual Strong Force	Leftover force from strong interaction, holds nucleus together.
Weak Nuclear Force	Responsible for beta decay (radioactivity).

Energy Scales and Structure in Nuclear Physics

What is Nuclear Structure?

The nuclear structure refers to:

How protons and neutrons (called nucleons) are arranged inside the nucleus. It includes their energy levels, spins, interactions, and motion. Just like electrons have energy levels in atoms, nucleons have energy levels inside the nucleus but much stronger and tighter.

Energy Scales in Nuclear Physics

These are the amounts of energy involved in nuclear processes. Nuclear energy is much higher than in regular chemical reactions.

Process	Energy Scale (approx.)
Atomic (chemical)	~ 1 eV
Nuclear binding energy	~ MeV (million eV)
Radioactive decay	~ keV to MeV
Fission/fusion	~ 100s of MeV
Particle collisions	~ GeV (billion eV)

Key Energy Terms:

- 1. Binding Energy:-** Energy required to break the nucleus into protons and neutrons.
- 2. Excitation Energy:-** Energy needed to raise nucleons to higher energy levels in the nucleus.
- 3. Mass-Energy Equivalence:-** Einstein's formula $E=mc^2$ shows mass can be converted to energy, which is the basis of nuclear energy.

Nuclear Binding Energy

The energy required to break a nucleus into its individual protons and neutrons. It also represents the energy released when the nucleus is formed. Shows how tightly the nucleons are held together.

Formula: Binding Energy = $(Zm_p + Nm_n - M) \times c^2$

Where:

Z = protons, N = neutrons

m_p , m_n = masses of proton, neutron

M = mass of the nucleus

c = speed of light

Nuclear Reactions:

Reactions that involve changing the structure of a nucleus, either naturally or by collision.

Types:

1. **Fission:** Heavy nucleus splits into smaller ones (e.g., uranium in reactors).
2. **Fusion:** Light nuclei combine (e.g., hydrogen fusion in the sun).
3. **Transmutation:** Changing one element into another (e.g., in labs or stars).
4. **Elastic/Inelastic Scattering:** Used in experiments to study nuclear structure.

Conservation Laws:

In all reactions, energy, charge, and nucleon number are conserved.

Radioactive Decays:

Nuclei that are unstable release particles or radiation to become stable.

Decay Type	Description	Emitted Particle
Alpha (α)	Nucleus emits 2 protons + 2 neutrons (He nucleus)	Alpha particle (${}^4_2\text{He}$)
Beta (β^-)	Neutron \rightarrow proton + electron + antineutrino	Electron
Beta (β^+)	Proton \rightarrow neutron + positron + neutrino	Positron
Gamma (γ)	Nucleus drops to lower energy state	Gamma photon

Summary

1. **Binding energy** tells how stable a nucleus is.
2. **Fission and fusion** release energy based on mass differences.
3. **Radioactive decay** helps unstable nuclei become stable.
4. **Energy is released** because of mass converted to energy $E=mc^2$

Nuclear Fusion:- Fusion is when two light nuclei combine to form a heavier nucleus, releasing a large amount of energy.

Nuclear Fission:- Fission is when a heavy nucleus splits into two lighter nuclei, along with free neutrons and energy.

Fission Reactor Physics:- A fission reactor is a system that controls nuclear fission to safely generate heat, which is then used to produce electricity.

Fission Reactor Working Process:

1. **Fission** releases energy in the reactor core.
2. **Heat** is carried by the coolant to a **heat exchanger**.
3. **Steam** is generated to drive a **turbine**.
4. Turbine turns a **generator** to produce electricity.
5. **Control rods** adjust the reaction rate by absorbing neutrons.

Feature	Nuclear Fission	Nuclear Fusion
Fuel Used	Uranium-235, Plutonium-239	Deuterium, Tritium (Hydrogen)
Energy Output	High	Higher than fission
Waste	Radioactive	Minimal waste
Control	Easier (in reactors)	Difficult (requires extreme conditions)
Application	Nuclear power plants	Experimental (ITER, future tech)

Summary

- 1. Fission:** Heavy nucleus splits \rightarrow energy + neutrons \rightarrow controlled in reactors.
- 2. Fusion:** Light nuclei merge \rightarrow huge energy \rightarrow cleaner, but harder to achieve.
- 3. Fission reactors** use this energy to generate electricity through heat and turbines.

Reactor Design

A nuclear fission reactor is a system built to control the fission reaction and generate electricity efficiently and safely.

Main Parts of a Reactor

Component	Function
Fuel Rods	Contain fissionable material (U-235 or Pu-239).
Moderator	Slows down neutrons (commonly water or graphite).
Control Rods	Absorb excess neutrons to control reaction (made of cadmium/boron).
Coolant	Transfers heat from the reactor core (water, gas, or liquid metal).
Pressure Vessel	Contains the core and maintains high pressure.
Steam Generator	Produces steam to drive turbines.
Containment Building	Concrete/steel structure for radiation protection.

Reactor Operation (Step-by-Step)

1. **Fission begins** in fuel rods, releasing heat and neutrons.
2. **Moderator slows** the neutrons to increase the chance of further fission.
3. **Control rods regulate** the reaction by absorbing extra neutrons.
4. **Coolant absorbs heat** from the core and transfers it to a steam generator.
5. **Steam drives turbines**, which rotate the generator to produce electricity.
6. **Used coolant is cooled**, and the cycle repeats.

Types of Nuclear Fission Reactors

1. **Pressurized Water Reactor (PWR)** (Most common type worldwide)

Coolant & Moderator: Pressurized water

Key Feature: Water in the reactor core doesn't boil due to high pressure. Steam is produced in a separate loop and it is Used in USA, France, India.

2. **Boiling Water Reactor (BWR)** (Simpler design)

Coolant & Moderator: Water

Key Feature: Water boils directly in the reactor core to produce steam and it is Used in Japan, USA

3. **Pressurized Heavy Water Reactor (PHW)** (Also called **CANDU reactor**)

Coolant: Heavy water (D_2O) and **Moderator:** Heavy water

Key Feature: Can use natural uranium (no enrichment needed) and it is Used in India (e.g., Kakrapar, Rajasthan)

4. Gas-Cooled Reactor (GCR) (High-temperature design)

Coolant: Carbon dioxide or helium gas

Moderator: Graphite

Key Feature: Operates at high temperatures, good for electricity & hydrogen production and it is Used in UK, earlier European designs

5. Fast Breeder Reactor (FBR) (Produces more fuel than it consumes)

Coolant: Liquid metal (usually sodium)

Moderator: None (fast neutrons used)

Key Feature: Converts U-238 into Pu-239 (usable fuel) and it is Used in Russia, India (e.g., Kalpakkam prototype)

6. Small Modular Reactors (SMRs) (*New tech*)

Compact, factory-built, safer design.

Ideal for remote areas and quick deployment.

Under development globally.

Nuclear Fuel Cycle

The **fuel cycle** is the entire process of **creating, using, and disposing of** nuclear fuel.

Fuel Cycle Stages:

Stage	Description
1. Mining & Milling	Uranium ore is mined and purified.
2. Enrichment	Increases % of U-235 (fissionable isotope).
3. Fuel Fabrication	Fuel is made into rods/pellets for reactor use.
4. Reactor Use	Fission occurs in reactor; fuel gets "spent."
5. Spent Fuel Storage	Used fuel is stored safely (wet pools or dry casks).
6. Reprocessing (Optional)	Extracts reusable material like U-235 or Pu-239.
7. Waste Disposal	Final disposal of non-reusable radioactive waste.

Reactor Safety Features

Safety is extremely important in reactor design to prevent accidents.

Key Safety Systems:

1. **Control Rods:** Instantly inserted to stop reaction in emergencies.
2. **Cooling System:** Prevents overheating of the reactor core.
3. **Containment Structure:** Prevents radioactive leakage.
4. **Redundant Systems:** Multiple backups for pumps, power, and cooling.
5. **Automatic Shutdown (SCRAM):** Emergency system that stops the chain reaction instantly.
6. **Monitoring & Alarms:** For radiation levels, temperature, and pressure.

Summary

1. Nuclear fission reactors use controlled chain reactions to produce energy.
2. Reactor design focuses on efficiency and safety (using fuel rods, control rods, coolant, etc.).
3. Fuel cycles cover from uranium mining to waste management.
4. Safety systems are designed to prevent accidents and radiation leaks.



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