# Nuclear Chemistry

## Introduction

- Nuclear Chemistry focuses on the reactions and properties of the atomic nucleus, distinguishing it from traditional chemistry which deals with the interactions of valence electrons.
- While chemical reactions conserve identity and mass, nuclear reactions can change one element into another (transmutation) and release energy quantities millions of times greater than chemical bonds.
- Guiding Question: What forces hold the nucleus together against the repulsion of protons, and how does the ratio of neutrons to protons determine whether an atom is stable or if it will undergo radioactive decay?

## Learning Objectives

By the end of this module, you will be able to:

- Recognize the factors determining nuclear stability, including the neutron-to-proton ratio and "magic numbers."
- Discriminate between different types of radioactive emissions (alpha, beta, gamma, positron) based on their mass, charge, penetrating power, and ionizing ability.
- Apply conservation laws of mass number and atomic number to balance nuclear equations and solve problems involving transmutation.
- Analyze the kinetics of radioactive decay and half-life to estimate the age of materials or the activity of a sample.

## Key Concepts and Definitions

| Term | Definition |
|---|---|
| **Nucleons** | The collective term for protons and neutrons found in the nucleus. |

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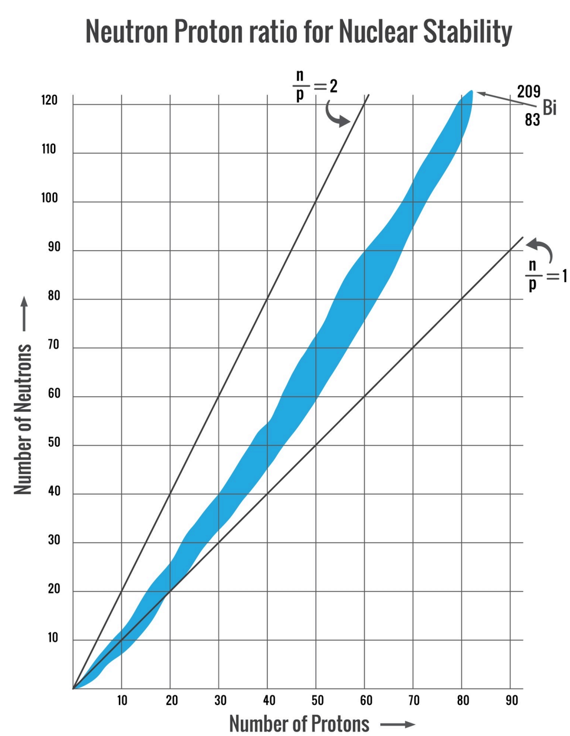
|---|---|
| **Nuclide** | A specific species of an atom characterized by its number of protons (atomic number, Z) and neutrons (neutron number, N). |
| **Mass Defect** | The difference between the mass of an atom and the sum of the masses of its constituent protons, neutrons, and electrons. This mass is converted into binding energy ($E=mc^2$). |
| **Transmutation** | The conversion of an atom of one element to an atom of another element, either naturally through decay or artificially through bombardment. |
| **Half-life (t½)** | The time required for half of the radioactive nuclei in a given sample to undergo decay. |

# Detailed Discussion

## Nuclear Stability and the Band of Stability



Not all nuclei are stable. Stability is primarily determined by the **neutron-to-proton ratio (n/p)**.

- **The Strong Nuclear Force:** Protons in the nucleus repel each other electrostatically. The nucleus is held together by the strong nuclear force, which acts over very short distances between all nucleons. Neutrons act as the "glue" that separates protons and increases the strong force without adding electrostatic repulsion.
- **The Band of Stability:** If we plot neutrons ($y-axis$) vs. protons ($x-axis$):
    - For light elements ($Z < 20$), the stable ratio is roughly **1:1** ($n/p \approx 1$).
    - As $Z$ increases, the repulsion grows, so more neutrons are needed to stabilize the nucleus. For heavy elements ($Z \approx 82$), the stable ratio rises to **1.5:1**.
    - Nuclei above the band have too many neutrons (decay via **Beta emission**).
    - Nuclei below the band have too many protons (decay via **Positron emission** or **Electron Capture**).
    - Nuclei with $Z > 83$ are always unstable and typically decay via **Alpha emission**.

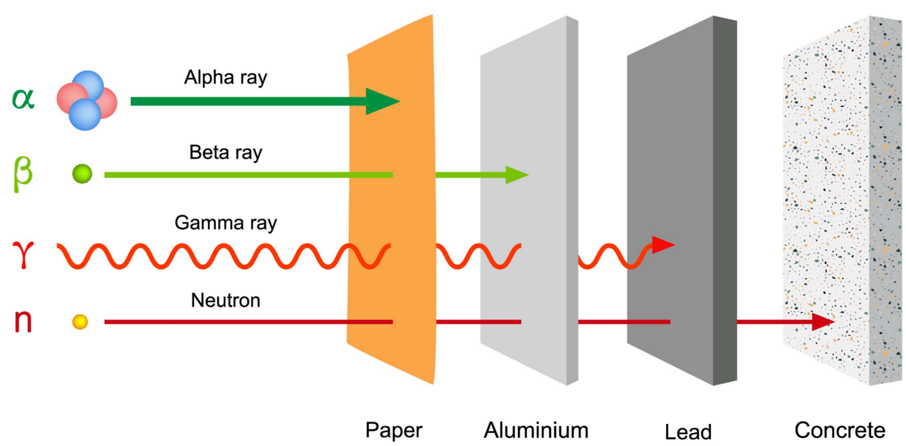
Example

Predicting Stability:

- **Carbon-12 ($^{6}_{6}C$):** Has 6 protons and 6 neutrons. Ratio = 1.0. **Stable.**
- **Carbon-14 ($^{14}_{6}C$):** Has 6 protons and 8 neutrons. Ratio = 1.33. This is too high for a light element. It is **unstable** and will undergo beta decay to turn a neutron into a proton.

## Modes of Radioactive Decay

Penetrating power of Alpha, Beta and Gamma ray through Paper, Aluminium, Led and Concrete



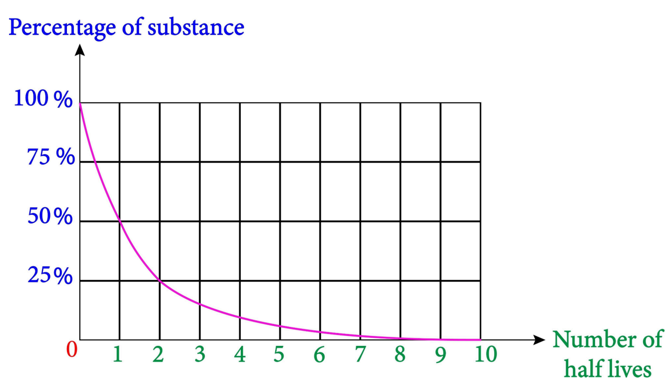
Unstable nuclei spontaneously emit particles or energy to reach a lower energy state.

- **Alpha Decay (α):** Emission of a Helium nucleus ($^{4}_{2}He$).
  - *Nature:* Heavy, positively charged (+2).
  - *Penetration:* Very low (stopped by paper or skin).
  - *Equation:* Mass number drops by 4; Atomic number drops by 2.
- **Beta Decay ($\beta^-$):** Emission of a high-speed electron ($^{0}_{-1}e$). occurs when a neutron turns into a proton.
  - *Nature:* Light, negatively charged (-1).
  - *Penetration:* Moderate (stopped by wood or aluminum foil).
  - *Equation:* Mass number stays same; Atomic number increases by 1.
- **Gamma Decay (γ):** Emission of high-energy photons.
  - *Nature:* Electromagnetic radiation, no mass, no charge. Often accompanies other decay types.
  - *Penetration:* Very high (requires thick lead or concrete to block).
- **Positron Emission ($\beta^+$):** Emission of the antimatter counterpart to the electron ($^{0}_{1}e$). Occurs when a proton turns into a neutron.

**Example Balancing Nuclear Equations:**

- **Alpha Decay of Uranium-238:** $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$ *(Note: 238 = 234 + 4 and 92 = 90 + 2)*
- **Beta Decay of Thorium-234:** $^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta$ *(Note: 234 = 234 + 0 and 90 = 91 + (-1))*

## Kinetics of Radioactive Decay



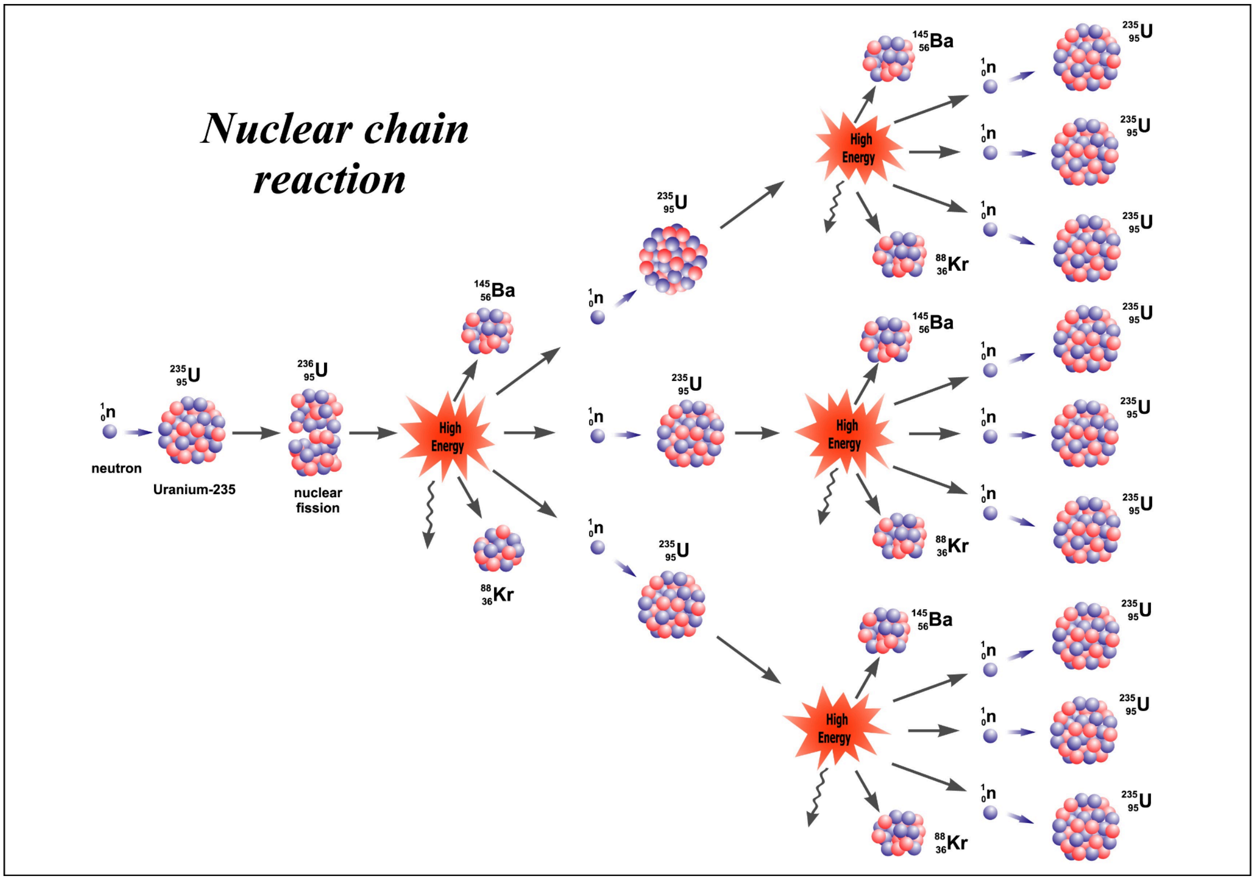
Radioactive decay follows **First-Order Kinetics**, meaning the rate of decay is proportional only to the amount of nuclide present.

- **Half-Life ($t_{1/2}$):** This is a constant value for a specific isotope and is independent of temperature, pressure, or chemical state. Whether you have 1 gram or 1 kilogram, it takes the same amount of time for half of it to decay.
- **Radiometric Dating:** By measuring the ratio of parent isotope to daughter isotope (e.g., Uranium-238 to Lead-206, or Carbon-14 to Nitrogen-14), scientists can calculate the age of rocks or organic artifacts. Carbon-14 dating is effective for objects up to ~50,000 years old.

**Example Calculations:** If a sample of Iodine-131 (used in thyroid treatment) has a half-life of 8 days, how much of a 100 mg sample remains after 24 days?

- Number of half-lives = 24 days / 8 days = 3 half-lives.
- Amount remaining = Initial Amount × $(1/2)^n$
- Calculation: 100 mg → 50 mg → 25 mg → **12.5 mg**.

## Nuclear Transmutation and Energy




**Artificial Transmutation:** Elements can be transformed by bombarding nuclei with high-speed particles (protons, alpha particles, or neutrons) in particle accelerators. This is how "synthetic" elements (like Technetium and transuranium elements) are made.

- **Nuclear Fission:** The splitting of a heavy nucleus (like Uranium-235) into lighter nuclei. This releases massive energy because the products have a higher "binding energy per nucleon" than the parent. Fission releases neutrons, which can strike other uranium nuclei, causing a **chain reaction**.
- **Nuclear Fusion:** The combining of light nuclei (like Hydrogen isotopes) to form a heavier nucleus (Helium). This powers the sun. It releases even more energy per gram than fission but requires temperatures of millions of degrees to overcome the electrostatic repulsion between protons.

**Example Bombardment Reaction (Discovery of Proton):** Rutherford bombarded Nitrogen gas with alpha particles to produce Oxygen and a proton. $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$

**Fission Reaction:** $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$ + Energy *(Notice the 3 neutrons produced can trigger 3 more reactions).*

## References


1. Choppin, G., Liljenzin, J. O., & Rydberg, J. (2013). *Radiochemistry and Nuclear Chemistry*. Academic Press.
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3. Petrucci, R. H., et al. (2017). *General Chemistry: Principles and Modern Applications*. Pearson.