

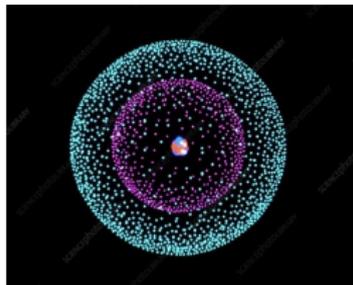
Intro-Level Nuclear Physics Concepts

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June, 2024

The Atom

- ▶ ${}^Z_A X$ → A indicates the mass number while Z indicates the atomic number. Example: ${}^2_4 He$
- ▶ We usually use the unit amu when discussing the masses of atoms and molecules. $1 \text{ amu} = \frac{1}{2}$ mass of Carbon-12. It is approximately equal to the average of the rest masses of a proton and a neutron.
- ▶ We model atoms as spherical balls in space and we estimate the radii as follow: $R = R_0 A^{\frac{1}{3}}$ while R_0 is average size of the nucleus $1.2 \times 10^{-15} \text{ m}$
- ▶ An element has a unique atomic number and its mass number might differ.



Rutherford Atomic Model

Rutherford's Gold Foil Experiment:

- ▶ Alpha particles directed at gold foil
- ▶ Most passed through, some deflected
- ▶ Conclusion: Small, dense, positively charged nucleus

Limitations:

- ▶ Could not explain stability of atoms
- ▶ Could not explain discrete spectral lines of elements

Bohr Atomic Model

Improvements on Rutherford's Model:

- ▶ Introduced quantized energy levels
- ▶ Electrons orbit nucleus in specific orbits
- ▶ Energy emitted/absorbed when electrons jump between orbits

Key Postulates:

- ▶ Electrons move in fixed orbits without radiating energy
- ▶ Energy of orbits: $E_n = -\frac{13.6 \text{ eV}}{n^2}$ (for hydrogen atom)

Mass Defect of an Atom

Concept: The difference between the mass of an atom and the sum of the masses of its constituent protons, neutrons, and electrons.

- ▶ Mass defect: $\Delta m = Zm_p + Nm_n + Zm_e - m_{\text{atom}}$
- ▶ Indicates the binding energy of the nucleus

Example: Mass Defect Calculation

Given the following data, calculate the mass defect of a carbon-12 atom:

- ▶ Mass of carbon-12 atom = 12 u
- ▶ Mass of a proton = 1.007276 u
- ▶ Mass of a neutron = 1.008665 u
- ▶ Mass of an electron = 0.000548 u

Number of protons = 6

Number of neutrons = 6

Number of electrons = 6

Total mass of protons = $6 \times 1.007276 \text{ u} = 6.043656 \text{ u}$

Total mass of neutrons = $6 \times 1.008665 \text{ u} = 6.05199 \text{ u}$

Total mass of electrons = $6 \times 0.000548 \text{ u} = 0.003288 \text{ u}$

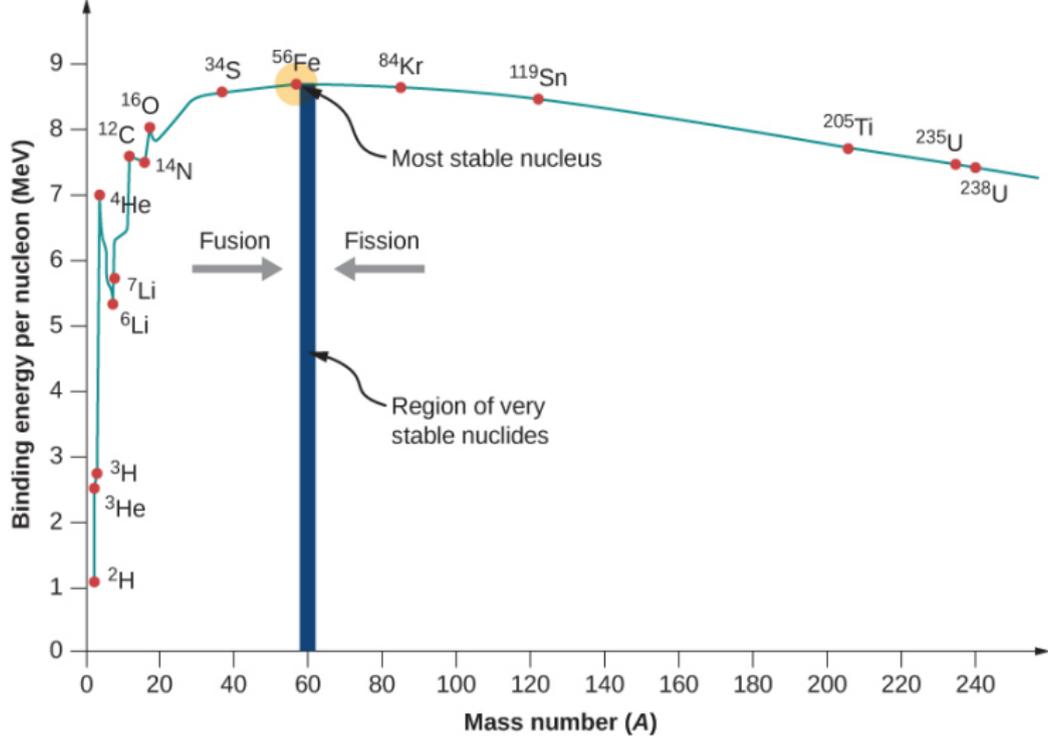
Total mass of constituents = $6.043656 \text{ u} + 6.05199 \text{ u} + 0.003288 \text{ u} = 12.098934 \text{ u}$

Mass defect = $12.098934 \text{ u} - 12 \text{ u} = 0.098934 \text{ u}$

Binding Energy

Concept: Energy required to disassemble a nucleus into its constituent protons and neutrons.

- ▶ Calculated using mass defect: $\Delta m = Zm_p + Nm_n - m_{\text{nucleus}}$
- ▶ Binding energy: $E_b = \Delta mc^2$
- ▶ Binding energy per nucleon can be found using $E_b N = \frac{E_b}{A}$
- ▶ Binding energy per nucleon indicates stability of the nucleus



Example: Binding Energy Calculation

Calculate the binding energy per nucleon for a helium-4 nucleus (mass = 4.002603 u).

$$\text{Mass of 2 protons} = 2 \times 1.007825 \text{ u} = 2.01565 \text{ u}$$

$$\text{Mass of 2 neutrons} = 2 \times 1.008665 \text{ u} = 2.01733 \text{ u}$$

$$\text{Total mass of nucleons} = 2.01565 \text{ u} + 2.01733 \text{ u} = 4.03298 \text{ u}$$

$$\text{Mass defect} = 4.03298 \text{ u} - 4.002603 \text{ u} = 0.030377 \text{ u}$$

$$\text{Binding energy} = 0.030377 \text{ u} \times 931.5 \text{ MeV/u} = 28.299 \text{ MeV}$$

$$\text{Binding energy per nucleon} = \frac{28.299 \text{ MeV}}{4} = 7.07475 \text{ MeV/nucleon}$$

Half-Life of Radioactive Materials

Concept: The half-life of a radioactive isotope is the time it takes for half of the radioactive atoms to decay.

- ▶ Exponential decay: $N(t) = N_0 e^{-\lambda t}$
- ▶ Relationship between half-life and decay constant: $T_{1/2} = \frac{\ln 2}{\lambda}$
- ▶ Activity: $A = \lambda N$

Example on half life

Calculate the age of the Shroud of Turin given that the amount of ^{14}C found in it is 92% of that in living tissue.

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

$$0.92 = e^{-\lambda t}$$

$$\ln 0.92 = -\lambda t \implies -0.0834 = -\lambda t.$$

We can find the λ using one important fact and that is $\lambda = \frac{0.693}{t_{1/2}}$. We know the half life of Carbon and that is about 5730 years. So, t can be found

$$t = \frac{0.0834}{\frac{0.693}{5730 \text{ y}}} = 690 \text{ y}.$$

Another example

A sample of a radioactive isotope has a half-life of 8 hours. If the initial activity of the sample is 1600 Bq, what will be the activity after 24 hours?

$$A(t) = A_0 \left(\frac{1}{2}\right)^{t/T_{1/2}} = 1600 \left(\frac{1}{2}\right)^{24/8} = 1600 \left(\frac{1}{2}\right)^3 = 1600 \times \frac{1}{8} = 200 \text{ Bq}$$

Types of Radiation

Alpha Radiation:

- ▶ Helium nuclei (2 protons, 2 neutrons)
- ▶ Low penetration, can be stopped by paper

Beta Radiation:

- ▶ Electrons (beta-minus) or positrons (beta-plus)
- ▶ Moderate penetration, can be stopped by aluminum

Gamma Radiation:

- ▶ High-energy electromagnetic radiation
- ▶ High penetration, can be stopped by thick lead or concrete

Conservation Laws in Radioactive Decay

Key Conservation Laws:

- ▶ Conservation of mass-energy: Total mass and energy remain constant
- ▶ Conservation of charge: Total charge remains constant
- ▶ Conservation of momentum: Total momentum remains constant
- ▶ Conservation of nucleon number: Total number of protons and neutrons remains constant

Applications of Research Reactors

Medicine:

- ▶ Production of medical isotopes (e.g., Technetium-99m for diagnostic imaging)
- ▶ Treatment of cancer using neutron therapy

Industry:

- ▶ Neutron activation analysis for material composition
- ▶ Isotopes for radiography to inspect welding joints and structural integrity

Research:

- ▶ Study of neutron scattering to understand material properties
- ▶ Development of new materials and nuclear technologies

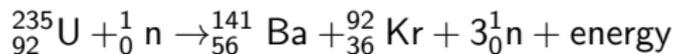
Nuclear Energy

Concept: Nuclear fission and chain reactions.

- ▶ Fission: Splitting of a heavy nucleus into lighter nuclei, releasing energy
- ▶ Chain reaction: Neutrons produced in fission cause further fission reactions
- ▶ Application: Nuclear power plants generate electricity using controlled fission reactions

Example: Nuclear Fission

Example: Fission of Uranium-235



- ▶ Each fission event releases approximately 200 MeV of energy
- ▶ Energy used to produce steam and drive turbines for electricity generation

Neutron Activation Analysis (NAA)

Concept: Irradiation of a sample with neutrons.

- ▶ Formation of radioactive isotopes
- ▶ Emission of characteristic gamma rays
- ▶ Determination of composition and concentration of elements

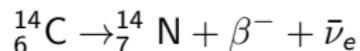
Example: Application in Archaeology

Analysis of ancient pottery to determine composition and origin, providing insights into trade routes and cultural exchanges.

- ▶ Sample is irradiated in a research reactor
- ▶ Induced radioactivity measured and analyzed
- ▶ Elemental composition deduced from gamma-ray spectra

Beta-minus Decay of Carbon-14

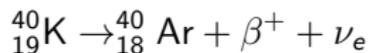
Carbon-14 (^{14}C) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Nitrogen-14 (${}^1_7\text{N}$).

Beta-plus Decay of Potassium-40

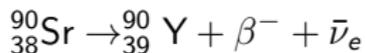
Potassium-40 (^{40}K) can undergo beta-plus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Argon-40 ($^{40}_{18}\text{Ar}$).

Beta-minus Decay of Strontium-90

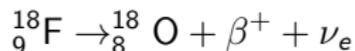
Strontium-90 (^{90}Sr) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Yttrium-90 ($^{90}_{39}\text{Y}$).

Beta-plus Decay of Fluorine-18

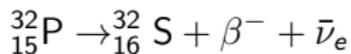
Fluorine-18 (^{18}F) undergoes beta-plus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Oxygen-18 (^{18}O).

Beta-minus Decay of Phosphorus-32

Phosphorus-32 (^{32}P) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Sulfur-32 (${}_{16}^{32}\text{S}$).

Beta-minus Decay of Iodine-131

Iodine-131 (^{131}I) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Xenon-131 (${}_{54}^{131}\text{Xe}$).

Beta-plus Decay of Sodium-22

Sodium-22 (^{22}Na) undergoes beta-plus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Neon-22 ($^{22}_{10}\text{Ne}$).

Beta-minus Decay of Technetium-99

Technetium-99 (^{99}Tc) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Ruthenium-99 (${}_{44}^{99}\text{Ru}$).

Beta-minus Decay of Cesium-137

Cesium-137 (^{137}Cs) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Barium-137 (${}_{56}^{137}\text{Ba}$).

Beta-minus Decay of Thallium-204

Thallium-204 (^{204}Tl) undergoes beta-minus decay. Write the balanced nuclear equation for this decay process and identify the resulting daughter nucleus.



The daughter nucleus is Lead-204 (${}_{82}^{204}\text{Pb}$).