Chapter 39 - Nuclear Physics

A PowerPoint Presentation by

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Objectives: After completing this module, you should be able to:

- Define and apply the concepts of mass number, atomic number, and isotopes.
- Calculate the mass defect and the binding energy per nucleon for a particular isotope.
- Define and apply concepts of radioactive decay and nuclear reactions.
- State the various conservation laws, and discuss their application for nuclear reactions.

Composition of Matter

All of matter is composed of at least three fundamental particles (approximations):

Particle	Fig.	Sym	Mass	Charge	Size
Electron	●	e^-	9.11×10^{-31} kg	-1.6×10^{-19} C	~
Proton	●	p	1.673×10^{-27} kg	$+1.6 \times 10^{-19}$ C	3 fm
Neutron	●	n	1.675×10^{-31} kg	0	3 fm

The mass of the proton and neutron are close, but they are about 1840 times the mass of an electron.

The Atomic Nucleus

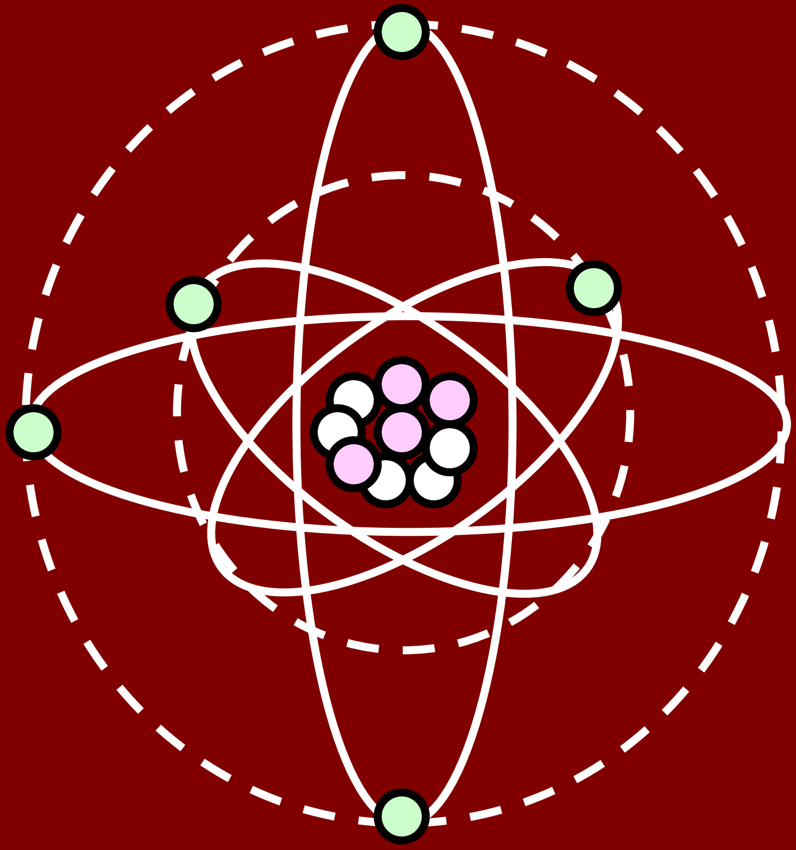
Compacted nucleus:

4 protons ○○○○

5 neutrons ○○○○○

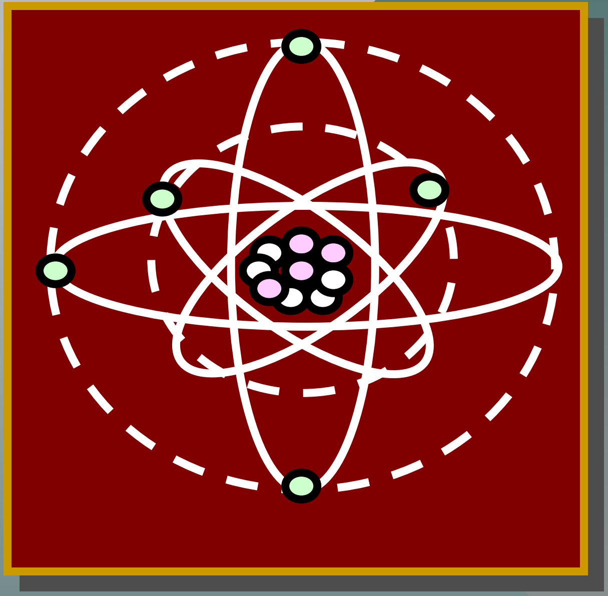
Since atom is electrically neutral, there must be 4 electrons.

4 electrons ○○○○



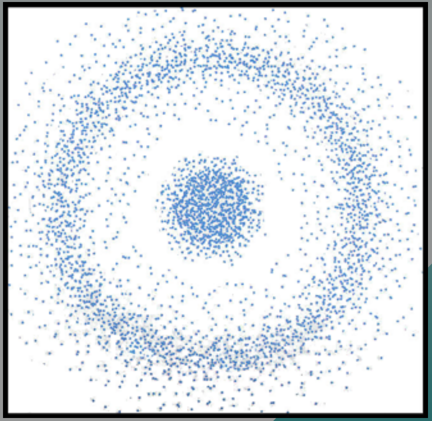
Beryllium Atom

Modern Atomic Theory



The Bohr atom, which is sometimes shown with electrons as planetary particles, is no longer a valid representation of an atom, but it is used here to simplify our discussion of energy levels.

The uncertain position of an electron is now described as a probability distribution—loosely referred to as an electron cloud.



Definitions

A nucleon is a general term to denote a nuclear particle - that is, either a proton or a neutron.

The atomic number Z of an element is equal to the number of protons in the nucleus of that element.

The mass number A of an element is equal to the total number of nucleons (protons + neutrons).

The mass number A of any element is equal to the sum of the atomic number Z and the number of neutrons N :

$$A = N + Z$$

Symbol Notation

A convenient way of describing an element is by giving its mass number and its atomic number, along with the chemical symbol for that element.

$$ {}_{Z}^{A}X = {}_{\text{Atomic number}}^{\text{Mass number}}\left[\text{Symbol}\right] $$

For example, consider beryllium (Be): ${}_{4}^{9}Be$

Example 1: Describe the nucleus of a lithium atom which has a mass number of 7 and an atomic number of 3.

$A = 7$; $Z = 3$; $N = ?$

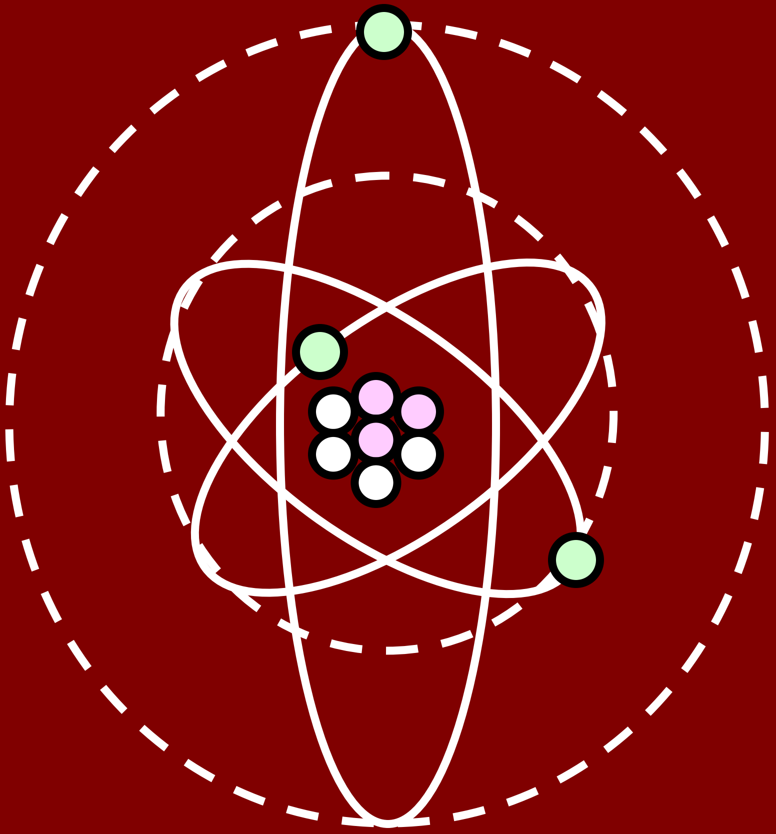
$N = A - Z = 7 - 3$

neutrons: $N = 4$

Protons: $Z = 3$

Electrons: *Same as Z*

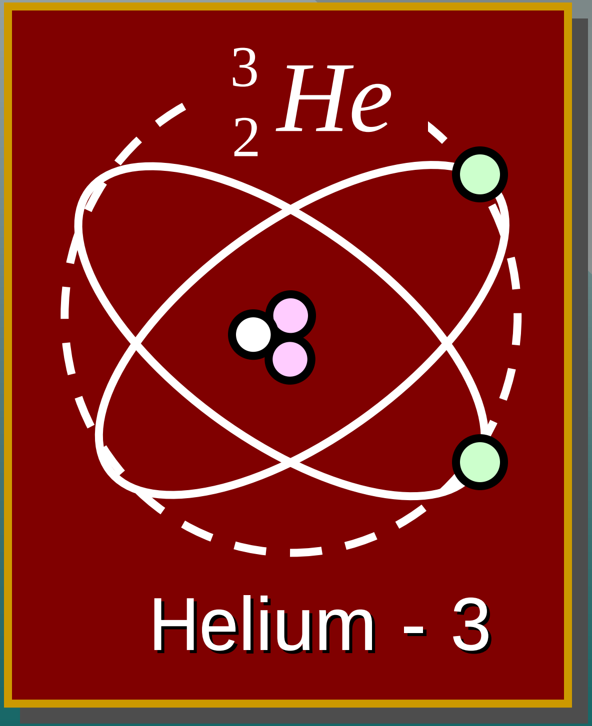
$${}^{7}_{3}Li$$



Lithium Atom

Isotopes of Elements

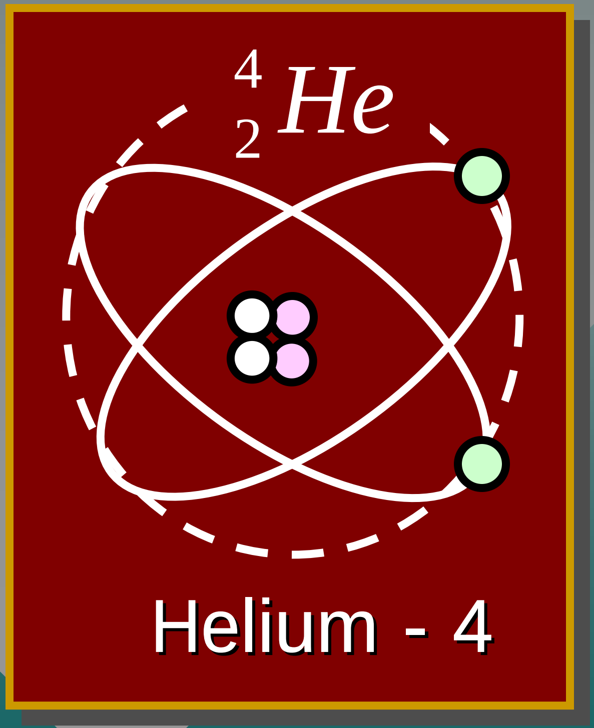
Isotopes are atoms that have the same number of protons ($Z_1 = Z_2$), but a different number of neutrons (N). ($A_1 \neq A_2$)



$^{3}_{2}He$

Helium - 3

Isotopes of helium



$^{4}_{2}He$

Helium - 4

Nuclides

Because of the existence of so many isotopes, the term element is sometimes confusing. The term nuclide is better.

A nuclide is an atom that has a definite mass number *A* and *Z*-number. A list of nuclides will include isotopes.

The following are best described as nuclides:

$${}^{3}_{2}He \quad {}^{4}_{2}He \quad {}^{12}_{6}C \quad {}^{13}_{6}C$$

Atomic Mass Unit, u

One atomic mass unit (1 u) is equal to one-twelfth of the mass of the most abundant form of the carbon atom--carbon-12.

Atomic mass unit: 1 u = 1.6606×10^{-27} kg

Common atomic masses:

○ Proton: 1.007276 u ○ Neutron: 1.008665 u

○ Electron: 0.00055 u Hydrogen: 1.007825 u

Exampe 2: The average atomic mass of Boron-11 is 11.009305 u. What is the mass of the nucleus of one boron atom in kg?

$^{11}_{5}B$ = 11.009305

○ Electron: 0.00055 u

The mass of the nucleus is the atomic mass less the mass of Z = 5 electrons:

Mass = 11.009305 u – 5(0.00055 u)

1 boron nucleus = 11.00656 u

$$m = 11.00656\text{ u}\left(\frac{1.6606 \text{ x } 10^{-27}\text{kg}}{1\text{ u}}\right)$$

$$\boxed{m = 1.83 \text{ x } 10^{-26}\text{ kg}}$$

Mass and Energy

Recall Einstein's equivalency formula for m and E:

$$\boxed{E = mc^2; \quad c = 3 \text{ x } 10^8 \text{m/s}}$$

The energy of a mass of 1 u can be found:

$$E = (1 \text{ u})c^2 = (1.66 \text{ x } 10^{-27} \text{ kg})(3 \text{ x } 10^8 \text{ m/s})^2$$

$$\boxed{E = 1.49 \text{ x } 10^{-10} \text{ J}}$$

Or

$$\boxed{E = 931.5 \text{ MeV}}$$

When converting amu to energy:

$$\boxed{c^2 = 931.5 \ \frac{\text{MeV}}{\text{u}}}$$

Example 3: What is the rest mass energy of a proton (1.007276 u)?

$E = mc^2 = (1.00726\text{ u})(931.5\text{ MeV/u})$

Proton: $E = 938.3$ MeV

Similar conversions show other rest mass energies:

Neutron: $E = 939.6$ MeV

Electron: $E = 0.511$ MeV

The Mass Defect

The mass defect is the difference between the rest mass of a nucleus and the sum of the rest masses of its constituent nucleons.

The whole is less than the sum of the parts!

Consider the carbon-12 atom (12.00000 u):

Nuclear mass = Mass of atom – Electron masses
= 12.00000 u – 6(0.00055 u)
= 11.996706 u

The nucleus of the carbon-12 atom has this mass.

(Continued . . .)

Mass Defect (Continued)

Mass of carbon-12 nucleus: 11.996706

○ Proton: 1.007276 u

○ Neutron: 1.008665 u

The nucleus contains 6 protons and 6 neutrons:

6 p = 6(1.007276 u) = 6.043656 u

6 n = 6(1.008665 u) = 6.051990 u

Total mass of parts: = 12.095646 u

Mass defect m_D = 12.095646 u – 11.996706 u

$$\boxed{m_D = 0.098940 \text{ u}}$$

The Binding Energy

The **binding energy** E_B of a nucleus is the energy required to separate a nucleus into its constituent parts.

$$E_B = m_D c^2 \quad \text{where} \quad c^2 = 931.5\ \text{MeV/u}$$

The binding energy for the carbon-12 example is:

$$E_B = (0.098940\ \text{u})(931.5\ \text{MeV/u})$$

Binding E_B for C-12: $E_B = 92.2\ \text{MeV}$

Binding Energy per Nucleon

An important way of comparing the nuclei of atoms is finding their binding energy per nucleon:

Binding energy per nucleon $\frac{E_B}{A} = \left(\frac{\text{MeV}}{\text{nucleon}}\right)$

For our C-12 example A = 12 and:

$$\frac{E_B}{A} = \frac{92.2\ \text{MeV}}{12} = 7.68\ \frac{\text{MeV}}{\text{nucleon}}$$

Formula for Mass Defect

The following formula is useful for mass defect:

Mass defect

m_D

$$\boxed{m_D = \left[\left(Zm_H + Nm_n \right) - M \right]}$$

m_H = 1.007825 u; m_n = 1.008665 u

Z is atomic number; N is neutron number;
M is mass of atom (including electrons).

By using the mass of the hydrogen atom, you avoid the necessity of subtracting electron masses.

Example 4: Find the mass defect for the $^{4}_{2}He$ nucleus of helium-4. (M = 4.002603 u)

Mass defect

m_D

$$\boxed{m_D = \left[\left(Zm_H + Nm_n \right) - M \right]}$$

Zm_H = (2)(1.007825 u) = 2.015650 u

Nm_n = (2)(1.008665 u) = 2.017330 u

M = 4.002603 u (From nuclide tables)

m_D = (2.015650 u + 2.017330 u) - 4.002603 u

$$\boxed{m_D = 0.030377 \text{ u}}$$

Example 4 (Cont.) Find the binding energy per nucleon for helium-4. (m_D = 0.030377 u)

$$E_B = m_D c^2 \text{ where } c^2 = 931.5 \text{ MeV/u}$$

$$E_B = (0.030377 \text{ u})(931.5 \text{ MeV/u}) = 28.3 \text{ MeV}$$

A total of 28.3 MeV is required To tear apart the nucleons from the He-4 atom.

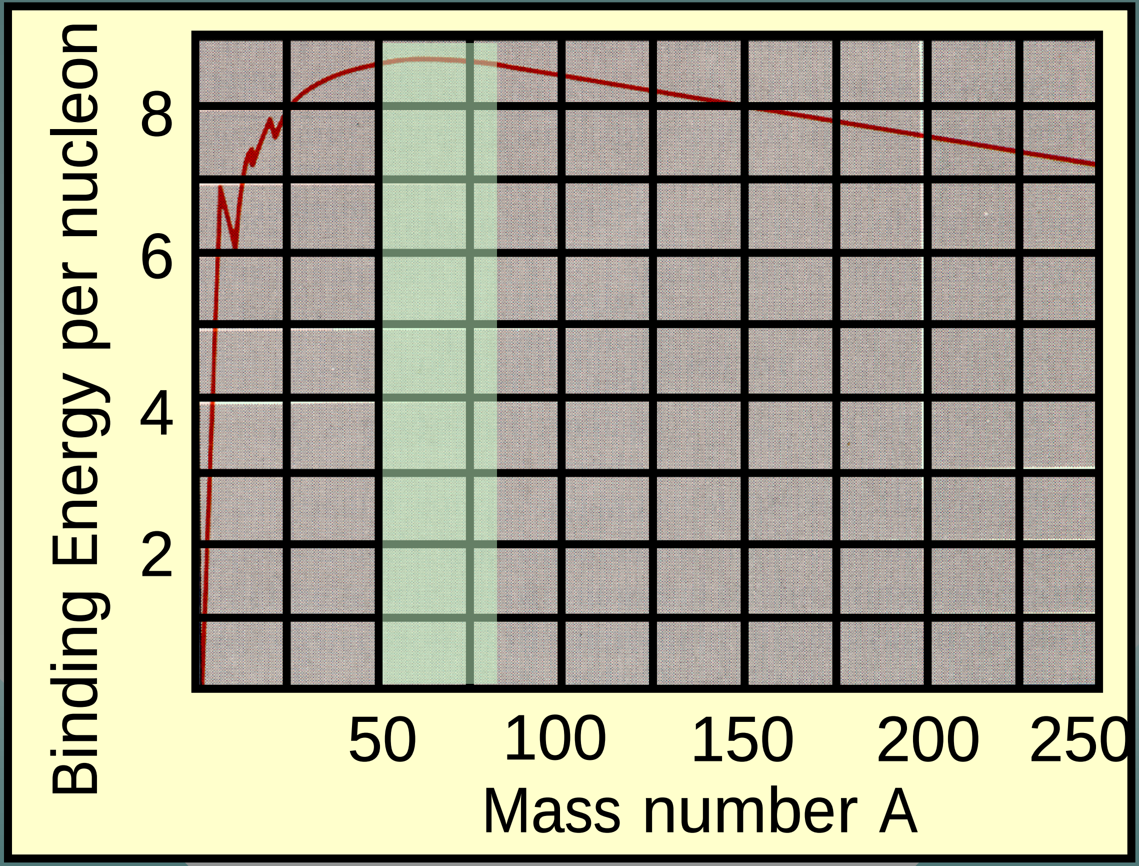
Since there are four nucleons, we find that

$$\frac{E_B}{A} = \frac{28.3 \text{ MeV}}{4} = 7.07 \frac{\text{MeV}}{\text{nucleon}}$$

Binding Energy Vs. Mass Number

Curve shows that E_B increases with A and peaks at $A = 60$. Heavier nuclei are less stable.

Green region is for most stable atoms.



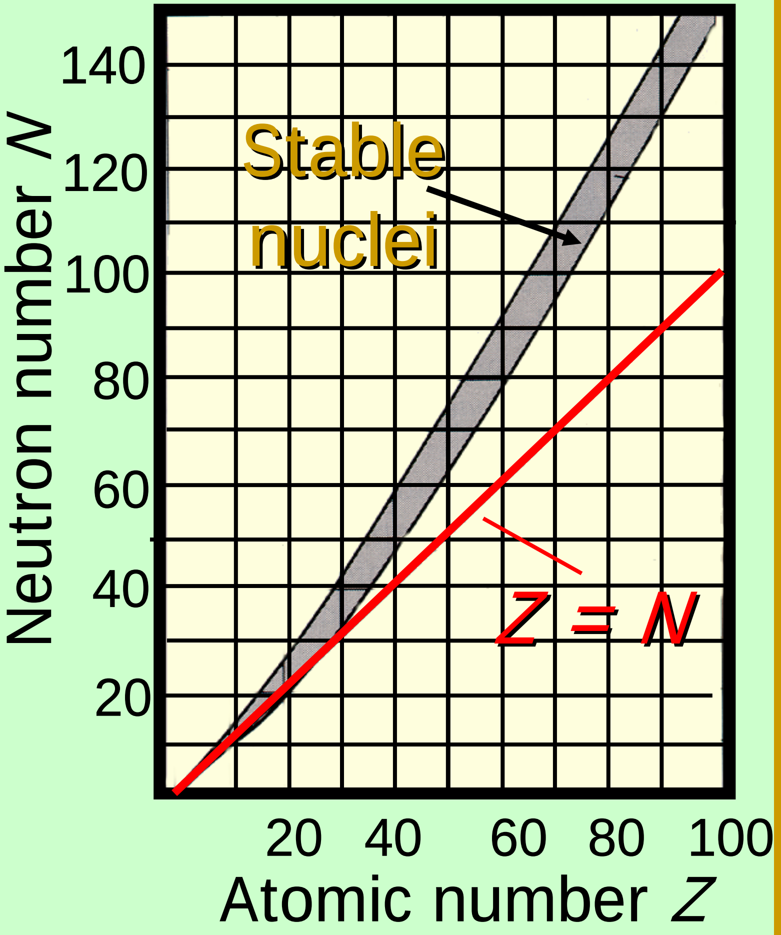
For heavier nuclei, energy is released when they break up (fission). For lighter nuclei, energy is released when they fuse together (fusion).

Stability Curve

Nuclear particles are held together by a nuclear strong force.

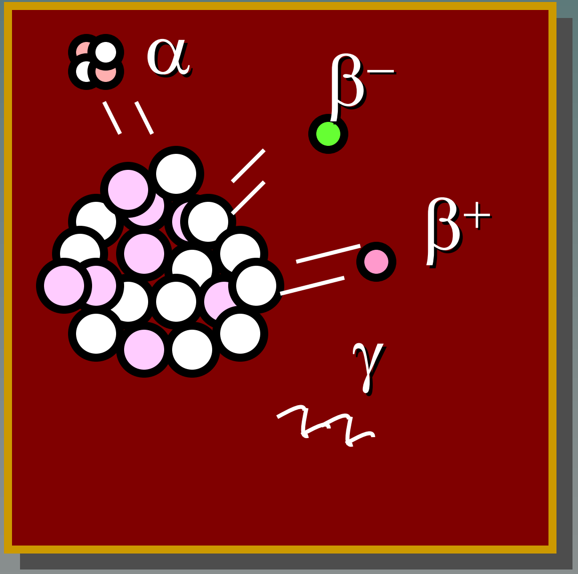
A stable nucleus remains forever, but as the ratio of N/Z gets larger, the atoms decay.

Elements with Z > 82 are all unstable.



Radioactivity

As the heavier atoms become more unstable, particles and photons are emitted from the nucleus and it is said to be radioactive. All elements with A > 82 are radioactive.



Examples are:

Alpha particles α

Gamma rays γ

β^- particles (electrons)

β^+ particles (positrons)

The Alpha Particle

An alpha particle α is the nucleus of a helium atom consisting of two protons and two neutrons tightly bound.

- Charge = $+2e^{-} = 3.2 \text{ x } 10^{-19}$ C
- Mass = 4.001506 u
- Relatively low speeds ($\approx 0.1c$)
- Not very penetrating

The Beta-minus Particle

A beta-minus particle β^- is simply an electron that has been expelled from the nucleus.

- Charge = e^- = -1.6×10^{-19} C
- Mass = 0.00055 u
- High speeds (near *c*)
- Very penetrating

The Positron

A beta positive particle β^+ is essentially an electron with positive charge. The mass and speeds are similar.

- Charge = $+e^- = 1.6 \times 10^{-19}$ C
- Mass = 0.00055 u
- High speeds (near *c*)
- Very penetrating

The Gamma Photon

A **gamma ray** γ has very high electromagnetic radiation carrying energy away from the nucleus.

- Charge = Zero (0)
- Mass = zero (0)
- Speed = c (3 x 10^8 m/s)
- Most penetrating radiation

Radioactive Decay

As discussed, when the ratio of N/Z gets very large, the nucleus becomes unstable and often particles and/or photons are emitted.

Alpha decay ${}^{4}_{2}\alpha$ results in the loss of two protons and two neutrons from the nucleus.

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + energy}$$

X is parent atom and *Y* is daughter atom

The energy is carried away primarily by the K.E. of the alpha particle.

Example 5: Write the reaction that occurs when radium-226 decays by alpha emission.

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + energy}$$

$${}^{226}_{88}Ra \rightarrow {}^{226-4}_{88-2}Y + {}^{4}_{2}\alpha + energy$$

From tables, we find Z and A for nuclides.
The daughter atom: Z = 86, A = 222

$$\boxed{{}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha + energy}$$

Radium-226 decays into radon-222.

Beta-minus Decay

Beta-minus β^- decay results when a neutron decays into a proton and an electron. Thus, the Z-number increases by one.

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + energy}$$

X is parent atom and *Y* is daughter atom

The energy is carried away primarily by the K.E. of the electron.

Beta-plus Decay

Beta-plus β^+ decay results when a proton decays into a neutron and a positron. Thus, the Z-number decreases by one.

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + energy}$$

X is parent atom and *Y* is daughter atom

The energy is carried away primarily by the K.E. of the positron.

Radioactive Materials

The rate of decay for radioactive substances is expressed in terms of the activity *R*, given by:

Activity $$R = \frac{-\Delta N}{\Delta t}$$

N = Number of undecayed nuclei

One **becquerel (Bq)** is an activity equal to one disintegration per second ($1\ s^{-1}$).

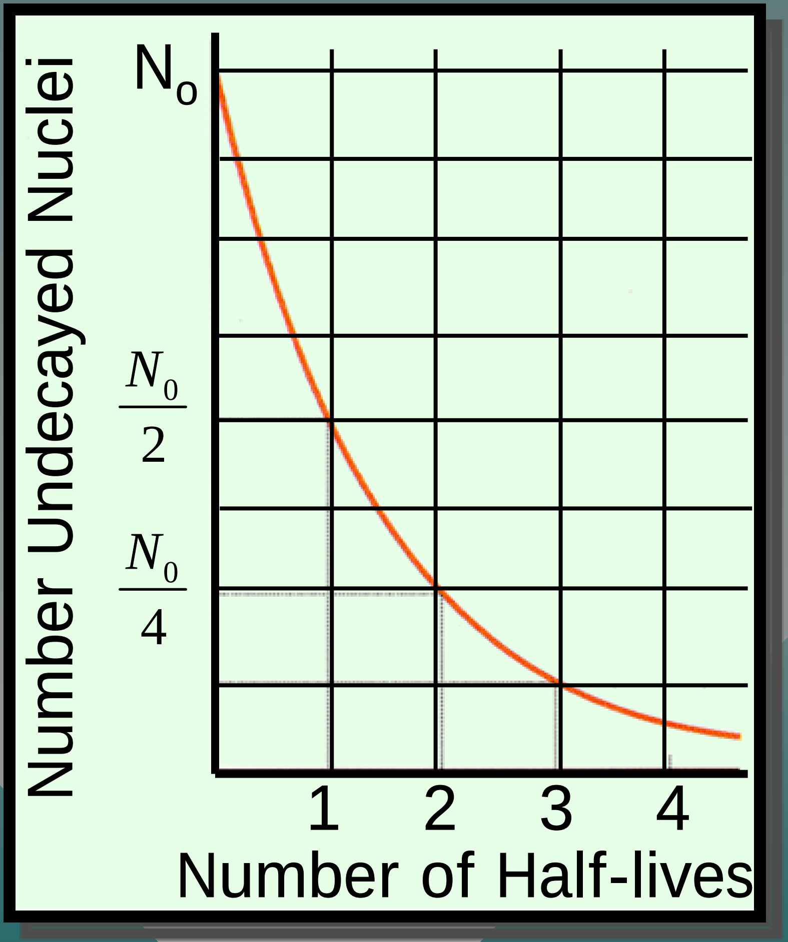
One curie (Ci) is the activity of a radioactive material that decays at the rate of 3.7×10^{10} Bq or 3.7×10^{10} disintegrations per second.

The Half-Life

The **half-life $T_{1/2}$** of an isotope is the time in which one-half of its unstable nuclei will decay.

$$N = N_0 \left(\frac{1}{2}\right)^n$$

Where *n* is number of half-lives



Half-Life (Cont.)

The same reasoning will apply to activity R or to amount of material. In general, the following three equations can be applied to radioactivity:

Nuclei Remaining

$$N = N_0 \left(\frac{1}{2}\right)^n$$

Activity R

$$R = R_0 \left(\frac{1}{2}\right)^n$$

Mass Remaining

$$m = m_0 \left(\frac{1}{2}\right)^n$$

Number of Half-lives:

$$n = \frac{t}{T_{1/2}}$$

Example 6: A sample of iodine-131 has an initial activity of 5 mCi. The half-life of I-131 is 8 days. What is the activity of the sample 32 days later?

First we determine the number of half-lives:

$$n = \frac{t}{T_{1/2}} = \frac{32\text{ d}}{8\text{ d}}$$

n = 4 half-lives

$$R = R_0\left(\frac{1}{2}\right)^n = 5\text{ mCi}\left(\frac{1}{2}\right)^4$$

R = 0.313 mCi

There would also be 1/16 remaining of the mass and 1/16 of the number of nuclei.

Nuclear Reactions

It is possible to alter the structure of a nucleus by bombarding it with small particles. Such events are called nuclear reactions:

General Reaction: $x + X \rightarrow Y + y$

For example, if an alpha particle bombards a nitrogen-14 nucleus it produces a hydrogen atom and oxygen-17:

$${}^{4}_{2}\alpha + {}^{14}_{7}N \rightarrow {}^{1}_{1}H + {}^{17}_{8}O$$

Conservation Laws

For any nuclear reaction, there are three conservation laws which must be obeyed:

Conservation of Charge: The total charge of a system can neither be increased nor decreased.

Conservation of Nucleons: The total number of nucleons in a reaction must be unchanged.

Conservation of Mass Energy: The total mass-energy of a system must not change in a nuclear reaction.

Example 7: Use conservation criteria to determine the unknown element in the following nuclear reaction:

$$_{1}^{1}H + _{3}^{7}Li \rightarrow _{2}^{4}He + _{Z}^{A}X + energy$$

Charge before = +1 + 3 = +4

Charge after = +2 + Z = +4

Z = 4 – 2 = 2 (Helium has Z = 2)

Nucleons before = 1 + 7 = 8

Nucleons after = 4 + A = 8 (Thus, A = 4)

$$\boxed{_{1}^{1}H + _{3}^{7}Li \rightarrow _{2}^{4}He + _{2}^{4}He + energy}$$

Conservation of Mass-Energy

There is always mass-energy associated with any nuclear reaction. The energy released or absorbed is called the Q-value and can be found if the atomic masses are known before and after.

$$\boxed{{}_{1}^{1}H + {}_{3}^{7}Li \rightarrow {}_{2}^{4}He + {}_{2}^{4}He + Q}$$

$$Q = \left({}_{1}^{1}H + {}_{3}^{7}Li\right) - \left({}_{2}^{4}He + {}_{2}^{4}He\right)$$

Q is the energy released in the reaction. If Q is positive, it is exothermic. If Q is negative, it is endothermic.

Example 8: Calculate the energy released in the bombardment of lithium-7 with hydrogen-1.

$$\boxed{{}^{1}_{1}H + {}^{7}_{3}Li \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + Q}$$

$$Q = \left({}^{1}_{1}H + {}^{7}_{3}Li\right) - \left({}^{4}_{2}He + {}^{4}_{2}He\right)$$

$${}^{1}_{1}H = 1.007825\text{ u}$$

$${}^{7}_{3}Li = 7.016003\text{ u}$$

$${}^{4}_{2}He = 4.002603\text{ u}$$

$${}^{4}_{2}He = 4.002603\text{ u}$$

Substitution of these masses gives:

Q = 0.018622 u(931.5 MeV/u)

$$\boxed{Q = 17.3\text{ MeV}}$$

The positive Q means the reaction is exothermic.

Summary

Fundamental atomic and nuclear particles

Particle	Fig.	Sym	Mass	Charge	Size
Electron	●	e	9.11×10^{-31} kg	-1.6×10^{-19} C	~
Proton	●	p	1.673×10^{-27} kg	$+1.6 \times 10^{-19}$ C	3 fm
Neutron	○	n	1.675×10^{-31} kg	0	3 fm

The mass number A of any element is equal to the sum of the protons (atomic number Z) and the number of neutrons N : $A = N + Z$

Summary Definitions:

A nucleon is a general term to denote a nuclear particle - that is, either a proton or a neutron.

The mass number *A* of an element is equal to the total number of nucleons (protons + neutrons).

Isotopes are atoms that have the same number of protons ($Z_1 = Z_2$), but a different number of neutrons (N). ($A_1 \neq A_2$)

A nuclide is an atom that has a definite mass number *A* and *Z*-number. A list of nuclides will include isotopes.

Summary (Cont.)

Symbolic notation for atoms

$$ {}_{Z}^{A}X = {}_{\text{Atomic number}}^{\text{Mass number}}\left[Symbol \right] $$

Mass defect m_D

$$ m_D = \left[\left(Zm_H + Nm_n \right) - M \right] $$

Binding energy

$$ E_B = m_D c^2 \text{ where } c^2 = 931.5 \text{ MeV/u} $$

Binding Energy per nucleon

$$ \frac{E_B}{A} = \left(\frac{\text{MeV}}{\text{nucleon}} \right) $$

Summary (Decay Particles)

An alpha particle α is the nucleus of a helium atom consisting of two protons and two tightly bound neutrons.

A beta-minus particle β^- is simply an electron that has been expelled from the nucleus.

A beta positive particle β^+ is essentially an electron with positive charge. The mass and speeds are similar.

A gamma ray γ has very high electromagnetic radiation carrying energy away from the nucleus.

Summary (Cont.)

Alpha Decay:

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + energy}$$

Beta-minus Decay:

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + energy}$$

Beta-plus Decay:

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + energy}$$

Summary (Radioactivity)

The **half-life $T_{1/2}$** of an isotope is the time in which one-half of its unstable nuclei will decay.

Nuclei Remaining

$$N = N_0 \left(\frac{1}{2}\right)^n$$

Activity R

$$R = R_0 \left(\frac{1}{2}\right)^n$$

Mass Remaining

$$m = m_0 \left(\frac{1}{2}\right)^n$$

Number of Half-lives:

$$n = \frac{t}{T_{1/2}}$$

Summary (Cont.)

Nuclear Reaction: $x + X \rightarrow Y + y + Q$

Conservation of Charge: The total charge of a system can neither be increased nor decreased.

Conservation of Nucleons: The total number of nucleons in a reaction must be unchanged.

Conservation of Mass Energy: The total mass-energy of a system must not change in a nuclear reaction. (Q-value = energy released)

CONCLUSION: Chapter 39
Nuclear Physics