9.2 Nuclear Physics

Properties of nuclei

Binding Energy

Radioactive decay

Natural radioactivity

Nuclear Physics

The nucleus is the small + charged object at the center of the atom.

It is composed of protons and neutrons bound together by an enormously strong nuclear force.

Nuclei can be stable or unstable

Unstable nuclei decay to smaller particles with the release of energy, and radiation.

Nuclei can also be changed by fusion to form larger particles.

Properties of the nucleus

Consists of protons and neutrons

Z = no. of protons (Atomic number)
N = no. of neutrons (Neutron number)
A = Z+N (Mass number)

Notation :For element X with mass no. A and Atomic no. Z

$$^{A}_{Z}X$$

Isotopes

Isotopes are nuclei that have the same no. of protons but different no. of neutrons.

The chemical properties are the same but the nuclear properties are different. i.e. some isotopes may be unstable and are radioactive.

eg. $^{1}_{1}H$ Hydrogen - stable

$^{2}_{1}H$ Deuterium - stable

$^{3}_{1}H$ Tritium - radioactive

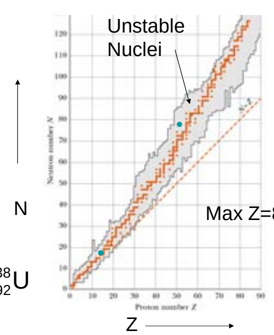
Stable Nuclei

Plot of N vs Z for stable nuclei

Outline shows unstable nuclei

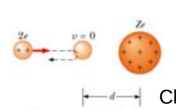
Some radioactive nuclei

$^{14}_{6}C$ $^{32}_{15}P$ $^{131}_{53}I$ $^{238}_{92}U$



Size of the nucleus

From scattering experiments with alpha particles He^{++}



Closest approach

KE — PE $=kq_1q_2/r$

For gold nuclei

closest $r < 3x10^{-14}$ m

This is smaller than the size of atoms $r \sim 10^{-10}$ m

Size of the nucleus

Radius varies as the cube root of A

$r = r_o A^{1/3}$

where $r_o = 1.2\times10^{-15}$ m

example
For Uranium 238, $^{238}_{92}U$
A=238

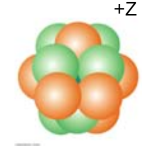
$$r = 1.2\times10^{-15}(238^{1/3}) = 7.4\times10^{-15}\,\text{m}$$

Forces in the nuclei

Coulomb forces

+Z

The protons repel each other with Coulomb forces.
These are enormously large due to the small size.



Nuclear forces

The nucleus is held together by the nuclear force.
This force acts only at short range ($\sim10^{-15}$ m) and is independent of charge (i.e. acts between proton-proton, proton-neutron and neutron-neutron).

Equivalence of mass and energy

A famous result from Einstein's Special Relativity Theory

$$E = mc^2$$

mass can be converted into energy

Energy equivalent of an electron mass

$E=mc^2= (9.1\times10^{-31}\text{kg})(3\times10^8\text{m/s})^2 = 8.2\times10^{-14}\text{J}$
$=5.1\times10^5$ eV= 0.51MeV

An electron can be annihilated (converted completely to energy). A 0.51 MeV photon is produced.

Mass changes when energy is lost or gained

Gasoline + O_2 -> CO_2 +water + energy

$\Sigma mc^2 + \Sigma\text{Energy} = \text{constant}$

The energy released is equal to the change in mass in the reaction.

$E=mc^2$

CO_2 + water is lighter.

Burning 1 kg of gasoline releases 44×10^6 J of energy.

The change in mass is

$$m = \frac{E}{c^2} = \frac{44\times10^6\,\text{J}}{(3\times10^8\,\text{m/s})^2} = 5\times10^{-10}\,\text{kg}$$

small change in mass

Binding energy

The binding energy of the nucleus can be determined by measuring the mass of the components and the final product. $E=\Delta mc^2$

For the deuterium nucleus ^2_1D formed from a proton and neutron

p + n -> ^2_1D + energy

Δm = mass (hydrogen atom) + mass (neutron) – mass (deuterium atom)

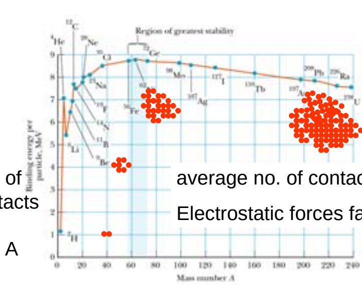
$\Delta m = 1.007825\text{u} + 1.008665\text{u} - 2.014102\text{u} = 2.39\times10^{-3}\text{u}$
$\text{u}=1.660559\times10^{-27}$ kg (atomic mass unit)

$E=\Delta mc^2= (2.39\times10^{-3}\text{u})(1.66\times10^{-27}\text{kg/u})(3\times10^8\text{ m/s})^2=3.6\times10^{-13}\text{J}$

$E=2.2\times10^6$ eV =2.2 MeV Binding energy of the deuteron

Binding energy per nucleon (E/A)

N neutrons+ Z protons -> Atom + energy



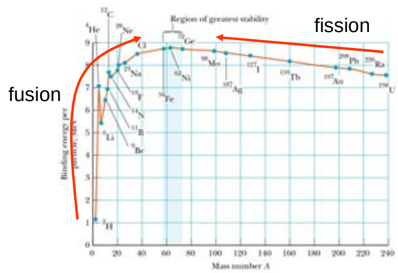
average no. of nuclear contacts increases favor higher A

average no. of contacts constant.

Electrostatic forces favor lower A

Goes through a maxima at ^{56}Fe

Binding energy per nucleon (E/A)



Goes through a maxima at ^{56}Fe

Fusion (combine small nuclei)– increases binding energy

Fission (break large nuclei)– increases binding energy

Radioactivity

Unstable nuclei decay releasing energy and radiation.

Three types of radiation

- alpha (α) particles - $^{4}_{2}He$ nuclei (+ charge)
- beta (β) particles - electrons (- charge)
- gamma (γ) particles - high frequency electromagnetic radiation. (uncharged)

Increasing penetration

Decay process

Alpha decay

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$$

Uranium decay

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

Beta Decay

electron e^-

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^- + \bar{\gamma}$$

positron e^+

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^+ + \gamma$$

e^+ positron has the same mass as an electron but a positive charge. the antiparticle of the electron

γ neutrino, no charge, low mass particle –carries of some momentum and energy

$\bar{\gamma}$ anti-neutrino, antiparticle of the neutrino

Beta decay

electron

$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^- + \bar{\gamma}$$

positron

$$^{12}_{7}N \rightarrow ^{12}_{6}N + e^+ + \gamma$$

Gamma Decay

Many nuclear reaction produce nuclear excited states that decay giving of high energy electromagnetic radiation-gamma rays.

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + e^- + \bar{\gamma} + gamma(1.17Mev,1.33Mev)$$

Radiation

Penetration depth

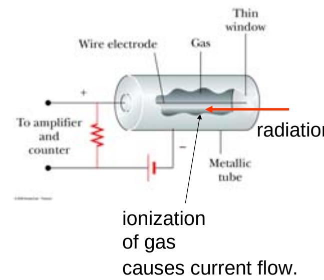
alpha particles – Stopped by a sheet of paper

beta particles - Stopped by a mm of aluminum

gamma particles - Stopped by a few cm of lead

Measuring radiation

Geiger Counter



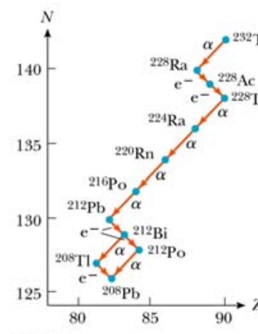
Natural radioactivity

Many elements found in nature are unstable and decay emitting radioactivity.

These include Uranium, ^{238}U , Radon ^{224}Ra and Potassium ^{40}K. Carbon ^{14}C,

Natural radioactive decay

Thorium decay gives a variety of unstable products.



Cosmic rays

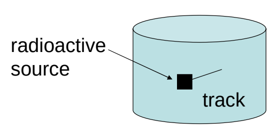
Cosmic rays –High energy particles (protons, alpha particles, atomic nuclei) from distant stars collide with atoms in the atmosphere and break them apart to sub atomic particles.

Some particles e.g. muons rain down to the earth's surface and are a source of background radiation.

Cloud chamber

A cloud chamber can be used to visualize radioactive particles.

The chamber contains a supersaturated vapor



The radioactive particle causes ionization of atoms The charge initiates the condensation of the vapor, Leaving a visible track.

Cloud chamber demo

http://www.youtube.com/watch?v=kuzWNOUqLmQ