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
	$^{2}_{1}H$	Tritium - radioactive

Size of the nucleus

Radius varies as the cube root of A

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

where $r_o = 1.2x10^{-15}$ m

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

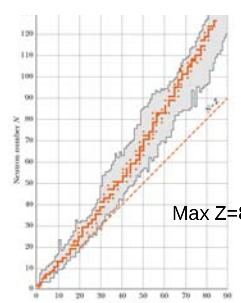
$$r = 1.2x10^{-15}(238^{1/3}) = 7.4x10^{-15}m$$

Stable Nuclei

Plot of N vs Z for all stable nuclei

N $\geq$ Z

N



Forces in the nuclei

Coulomb forces

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 (~10^{-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

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

5.1×10^5 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

$\Sigma mc^2 + \Sigma Energy$ =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

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

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)

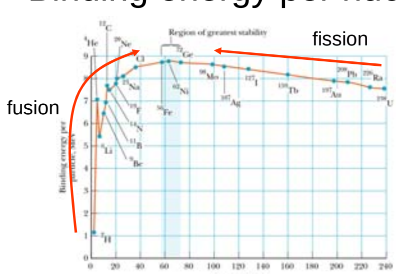
Δm = 1.007825u +1.008665u -2.014102u= 2.39×10^{-3}u

u=1.660559 $\times10^{-27}$ kg (atomic mass unit)

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

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

Binding energy per nucleon



Goes through a maxima at ^{56}Fe
Fusion – increases binding energy
Fission – increases binding energy

Radioactivity

Unstable nuclei decay releasing energy and radiation.

Three types of radiation

- alpha (α) particles - ^4_2He nuclei (+ charge)
- beta (β) particles - electrons (- charge)
- gamma (γ) particles - high frequency electromagnetic radiation. (uncharged)

Increasing penetration

Radioactive decay

Radioactive decay is a random process the amount of material remaining varies exponentially with time.

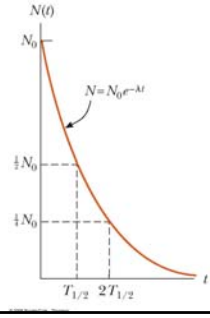
$$N = N_o e^{-\lambda t}$$

λ is the decay constant (units 1/time)

This can also be expressed as

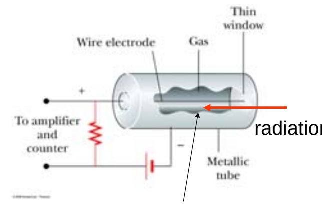
$$N = N_o \left(\frac{1}{2}\right)^{t/T_{\frac{1}{2}}}$$

where $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$



Measuring radiation

Geiger Counter



ionization of gas causes current flow.

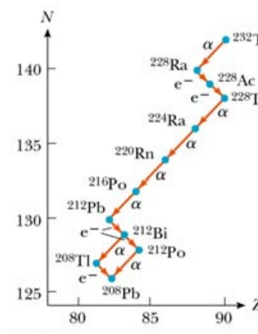
Natural radioactivity

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.



Nuclear reactions

Stable nuclei can be converted to other nuclei by undergoing nuclear reactions.

Reactions with charged nuclei require high energies (temperatures / velocities)to overcome the Coulomb repulsion.

$${}^{4}_{2}He + {}^{14}_{7}N \longrightarrow {}^{1}_{1}H + ? \quad {}^{17}_{8}O$$

Neutron reactions

Reaction with neutral neutrons can proceed at lower temperature.

$${}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2({}^{1}_{0}n)$$