8.2 Nuclear Physics

Properties of nuclei
Binding Energy
Radioactive decay
Natural radioactivity

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

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

Example $${}^{4}_{2}He$$

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

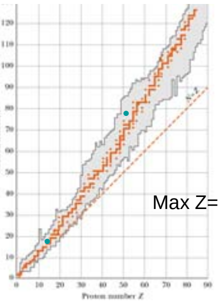
Plot of N vs Z for stable nuclei

Outline shows unstable nuclei

Some radioactive nuclei

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

N

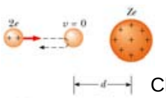


Max Z=83

Z

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 ~ 10^{-10} m

Size of the nucleus

Radius varies as the cube root of A

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

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

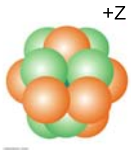
example
For Uranium 238, ${}^{238}_{92}U$
A=238

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

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

$E=mc^2= (9.1x10^{-31}kg)(3x10^8 m/s)^2 = 8.2x10^{-14} J$
$=5.1x10^5 \text{ eV}= 0.51 \text{MeV}$

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 + kinetic energy (heat)

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

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

$E=\Delta mc^2$

CO_2 + water is lighter.

Burning 1 kg of gasoline releases $44x10^6$ J of energy.

The change in mass is

$$\Delta m = \frac{E}{c^2} = \frac{44x10^6 \text{ J}}{(3x10^8 \text{ m/s})^2} = 5x10^{-10} \text{kg}$$

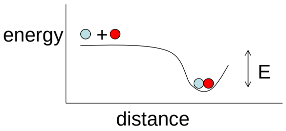
small change in mass

Binding energy

The binding energy of the nucleus can be determined by measuring the mass of the components and the final product.

$E=\Delta mc^2$

p + n -> ${}^2_1D$



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

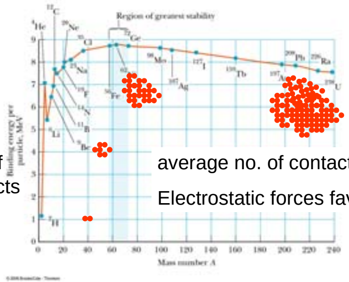
$\Delta m = 1.007825u + 1.008665u - 2.014102u = 2.39x10^{-3}u$
$u=1.660559 \text{ x}10^{-27}$ kg (atomic mass unit)

$E=\Delta mc^2= (2.39x10^{-3}u)(1.66x10^{-27}kg/u)(3x10^8 \text{ m/s})^2=3.6x10^{-13} J$

$E=2.2x10^6$ eV =2.2 MeV Binding energy of the deuteron

Binding energy per nucleon (E/A)

N neutrons+ Z protons -> Atom + energy



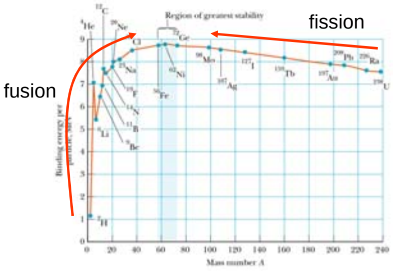
average no. of nuclear contacts increases favor higher A

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 (+2 charge)

beta (β) particles - electrons (- charge)
positrons (+ charge)

gamma (γ) particles - high frequency electromagnetic radiation. (uncharged)

Increasing
penetration

Radiation

Penetration depth

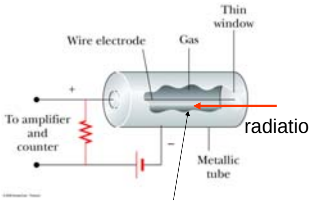
alpha particles – Stopped by a sheet of paper

beta particles - Stopped by a mm of aluminum

gamma particles - Stopped by a few cm of lead

Measuring radiation

Geiger Counter



radiation

ionization
of gas
causes current flow.

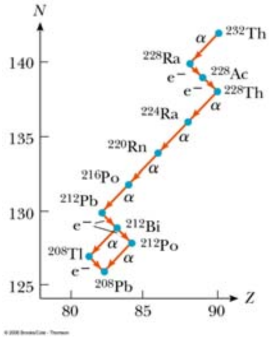
Natural radioactivity

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.



Decay rate

The rate of decay, R, for N nuclei is proportional to N

$$R = \frac{\Delta N}{\Delta t} = \lambda N$$

λ = decay constant (units time^{-1})

Activity – (measure of the rate of radioactive decay)

Units Curie,

1Ci = 3.7×10^{10} Decays/s

Radioactive decay

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

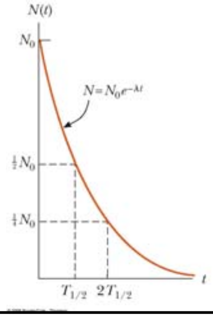
$$N = N_o e^{-\lambda t}$$

Decay constant λ (units 1/time)

This can also be expressed as

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

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



Example 29.3

The half life of radium Ra is $1.6\text{x}10^3$ yr. If the sample contains $3.00\text{x}10^{16}$ nuclei. Find the activity in curies. ($1\text{Ci}=3.7\text{x}10^{10}$ decays/s)

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

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{1.6\text{x}10^3\,\text{yr}(365\text{day}/\text{yr})(24\text{hr}/\text{day})(3600\text{s}/\text{hr})}$$

$$= 1.37\text{x}10^{-11}\text{s}^{-1}$$

$R=\lambda N$

$R=1.37\text{x}10^{-11}\text{s}^{-1}$ ($3.00\text{x}10^{16}$nuclei) $=4.12\text{x}10^5$ decays/s

$R=1.1\text{x}10^{-5}$ Ci or 11μcuries $3.7\text{x}10^{10}$decays/sCi

Example 29.3

The half life of radium Ra is $1.6\text{x}10^3$ yr. If the sample contains $3.00\text{x}10^{16}$ nuclei. Find the number of nuclei after $4.8\text{x}10^3$ yr.

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

$$N = 3.00\text{x}10^{16} \left(\frac{1}{2}\right)^{4.8\text{x}10^3/1.6\text{x}10^3}$$

$N=3.00\text{x}10^{16}$ (1/8)$=3.75\text{x}10^{15}$ nuclei

Example 29.3

The half life of radium Ra is $1.6\text{x}10^3$ yr. If the sample contains $3.00\text{x}10^{16}$ nuclei. Find the activity after $4.8\text{x}10^3$ yr.

$R=\lambda N$

After this time since the no. of nuclei is reduced by a factor of 8
the decay rate will also be reduced by a factor of 8.

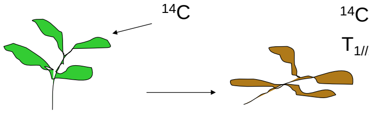
R = 11 μCi/8 =1.4 μCi

Radioactive dating

^{14}C is continually formed by cosmic rays in the upper atmosphere.

n + ^{14}N -> ^{14}C + p

so that the concentration of ^{14}C is relatively constant over long times (longer than the half life).



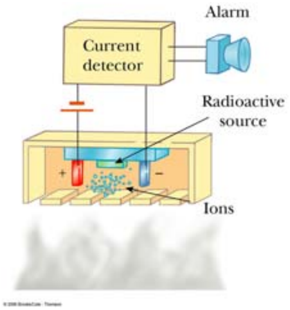
^{14}C decays

$T_{1//2}$= 5730 years

The fraction of ^{14}C decays exponentially with time.

Smoke Detector

Ionization of air by a radioactive source produces a current. Smoke traps the electrons and reduces the current. setting off the alarm.



Medical Applications.

Radiation Damage.

- Nuclear particles have much higher energies than chemical bonds.
- Radiation breaks chemical bonds – forming reactive chemical species – radicals.
- Reactive chemicals cause radiation damage to biological systems – often reaction with DNA

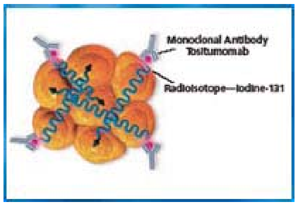
Radiation Therapy

Radiation is often used in treating cancer.

external radiation

Radioimmunotherapy

New methods for can deliver radiation more specifically to target cells



Treatment of non-Hodgkins lymphoma with radioimmunotherapy

Properties of ^{131}I

Iodine 131

Half-life – 8.07 days

Beta particle
  maximum energy- 807 keV
  average energy - 182 keV

Range in tissue -2.4 mm

Common clinical applications
  Radioimmunotherapy, thyroid ablation for benign and malignant disease

Medical Imaging

- X-ray Computer axial tomography (CAT)
- Positron emission tomography (PET)
- Magnetic resonance imaging (MRI)

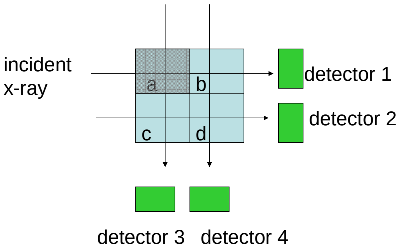
- Contrast
- Resolution.

CAT scan

Contrast – x-ray absorption
 may use heavy elements to increase contrast i.e I, Ba

A three- dimensional image is reconstructed from many two dimensional pictures.

Computer tomography



incident x-ray

a	b
c	d

detector 1

detector 2

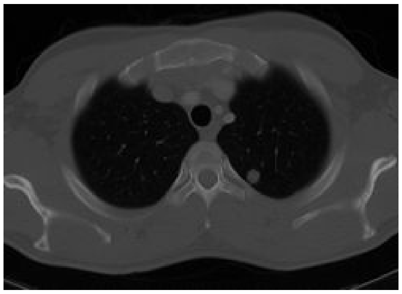
detector 3 detector 4

at each detector absorbance is due to the sum of the absorptions from each segment.

$A \text{ (detector)} = A_i + A_j$

For 4 detectors -> 4 linear equations and 4 segment - > 4 unknowns ⇨ Solve for each absorbance

CAT scan of a chest



Positron Emission Tomography

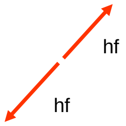
- Emission of 2 gamma ray photons traveling in opposite direction by Positron-Electron annihilation. (conservation of momentum)
- Positrons are produced by decay of short lived radioactive nuclei such as

^{18}F ($T_{1/2}$=110 min)

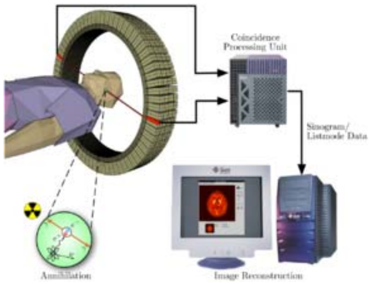
$$^{18}_{9}F \rightarrow {}^{18}_{8}O + e^{+} + \nu$$

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

Annihilation produces 2 0.51 MeV photons

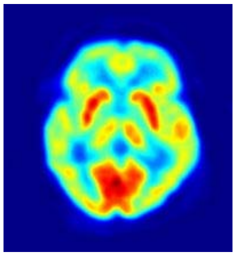


PET imaging system



Two coincident detectors are used to detect the gamma rays. The source is in a line directly between the two detectors.

PET scan of the human brain



^{15}O ($T_{1/2}$ =2 min) marks the consumption of O_2 due to brain activity.