Tecniche Diagnostiche per Reattori a Fusione Termonucleare

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Nuclear Structure

$^{A}_{Z}X$

Nucleon: The name given to the particles of the nucleus.

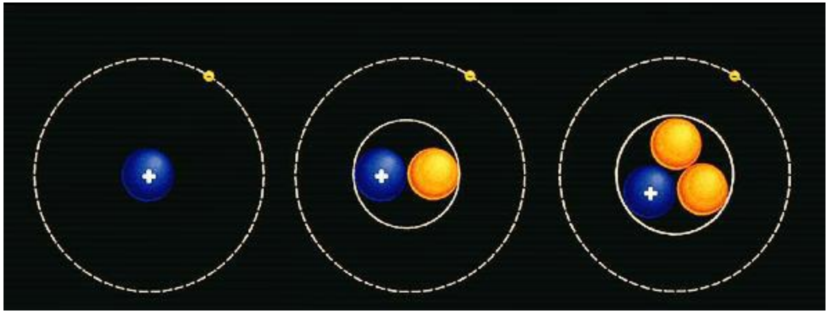
Nuclide: A particular combination of protons and neutrons that form a nucleus. It is used to distinguish isotopes among nuclei.

Nucleon number (mass number) – A: The number of protons plus neutrons in the nucleus.
The nucleon mass is measured in atomic mass units u, slightly less than the mass of the proton:

1 u = 1.660538782(83) x 10-27 Kg

Isotopes

- Isotopes are variants of a particular chemical element: whereas all isotopes of a given element share the same number of protons and electrons (equal Z) , each isotope differs from the others in its number of neutrons (different A).
- The three naturally-occurring isotopes of hydrogen:



Protium, stable (H, Z=1, A=1)	Deuterium, stable (D or $^{2}\boldsymbol{H}$, Z=1, A=2)	Tritium, radioactive (half life 12 y) (T or $^{3}\boldsymbol{H}$, Z=1, A=3)

Binding energy

A bound system has a lower potential energy than its constituent parts; this is what keeps the system together.
The "mass defect" is therefore mass that transforms to energy according to Einstein's equation and is **released in forming the nucleus from its component particles.**
(heat, light, higher energy states of the nucleous/atom or other forms of energy).

Binding energy (BE) - is therefore either **the energy required to separate the nucleus into it individual nucleons** or **the energy that would be released in assembling a nucleus from its individual nucleons**.

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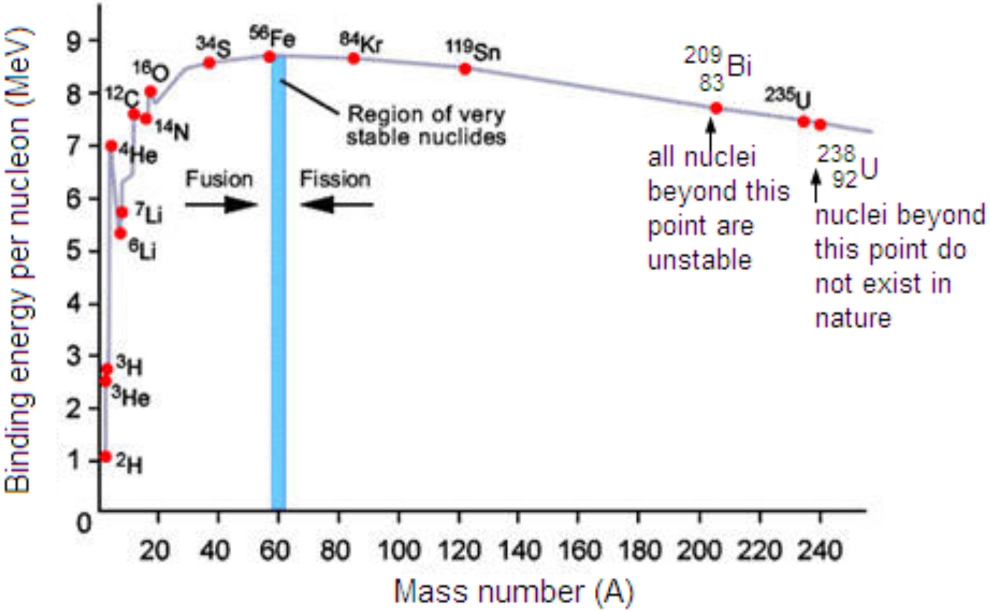
Binding energy curve

Graph of binding energy per nucleon



BE varies with mass number;

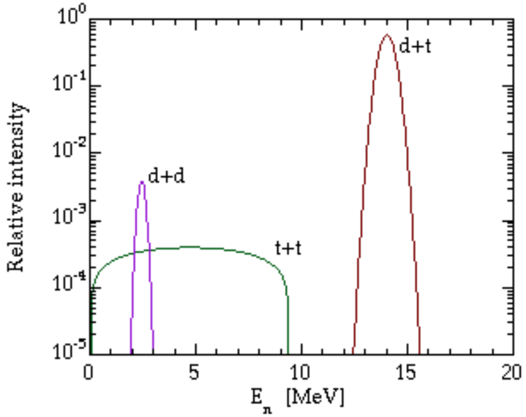
BE increase as the mass (nucleon) number increases up to Fe.

Fe is most stable.
After that it slightly decreases.

In most cases, BE is about 8 MeV per nucleon

If a nucleus has a large binding energy then it will require a lot of work to pull it apart – we say it is stable.

Neutron energy spectra

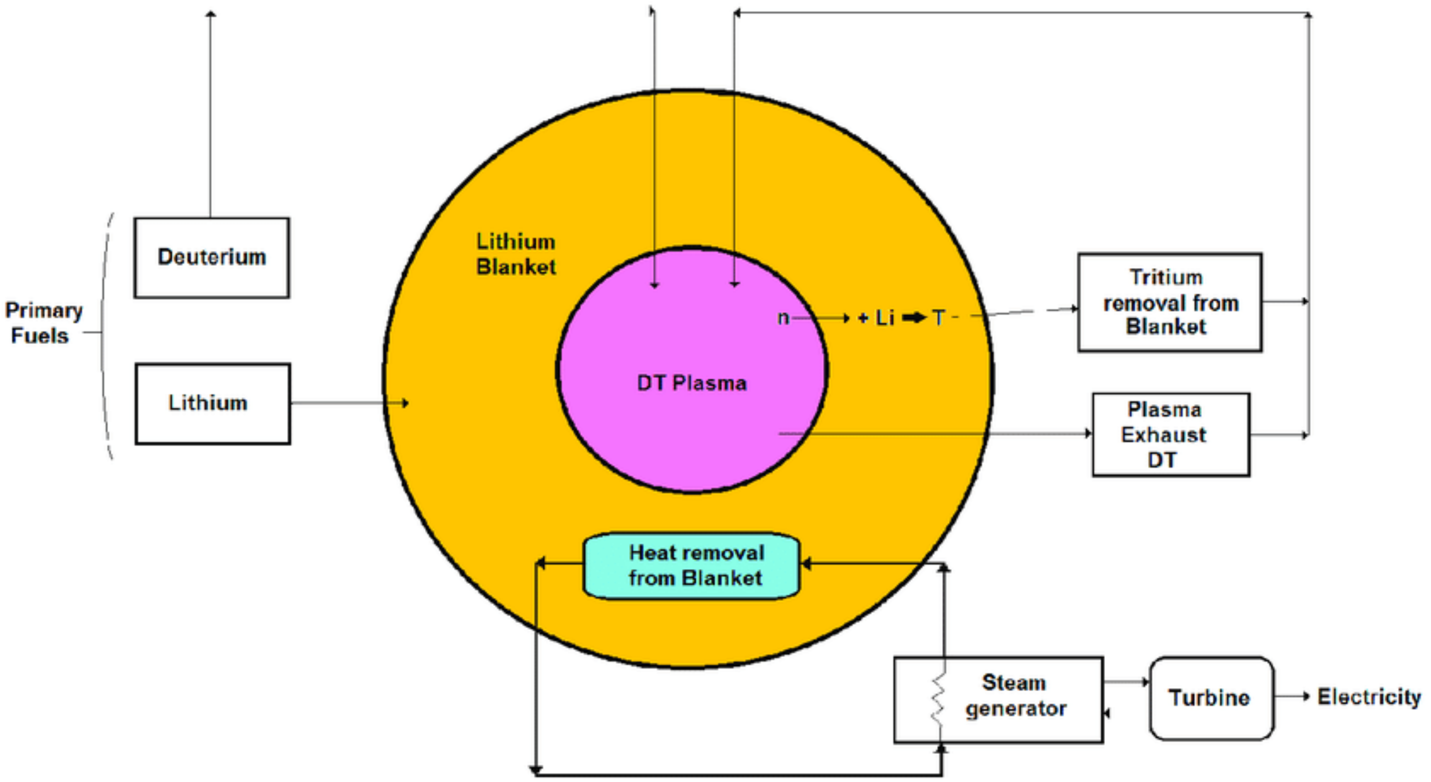


The T+T $= ^4He + 2n$ is a three-body reaction

The width of the DD and the DT neutron energy lines is due to the velocity distribution of reacting ions (K=relative kinetic energy, $v_{c.m.}$=velocity of center of mass, θ = angle between the neutron velocity and $v_{c.m}$

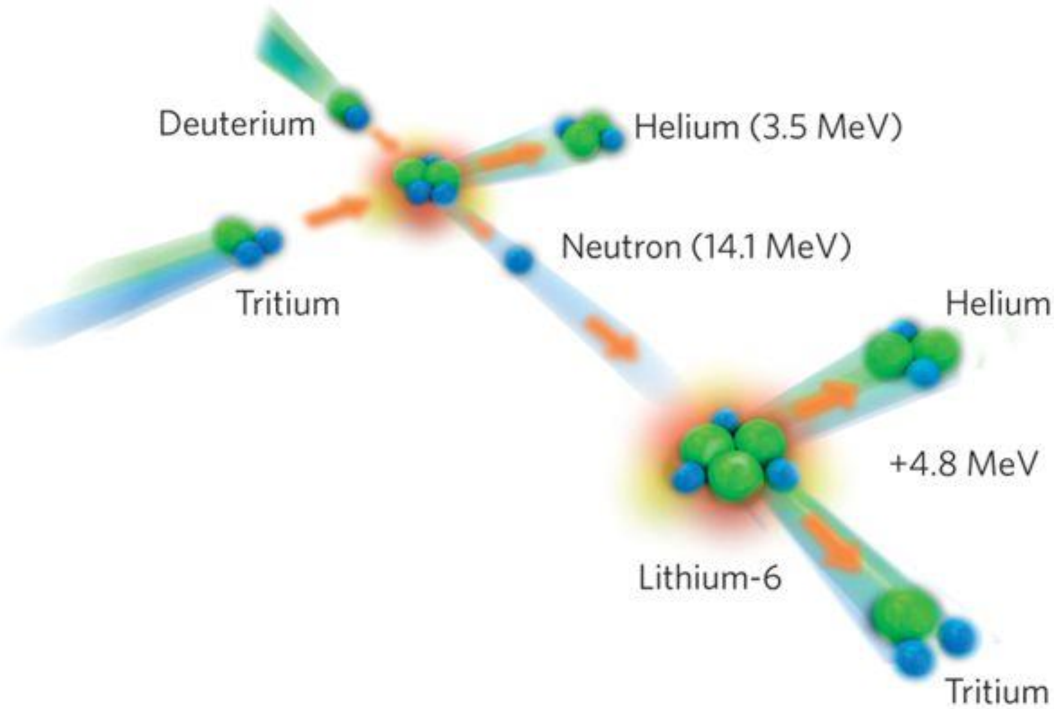
$$E_n = \frac{m_a}{m_n + m_a}(Q+K) + v_{c.m} \cos\theta \left[2\frac{m_n m_a}{m_n + m_a}(Q+K) \right]^{1/2} + \frac{1}{2} m_n v_{c.m.}^2$$

Fusion Power



Tritium production in the DT fusion cycle

$^{6}Li + n \rightarrow T + {}^{4}He$



N. Holloway, CCFE.

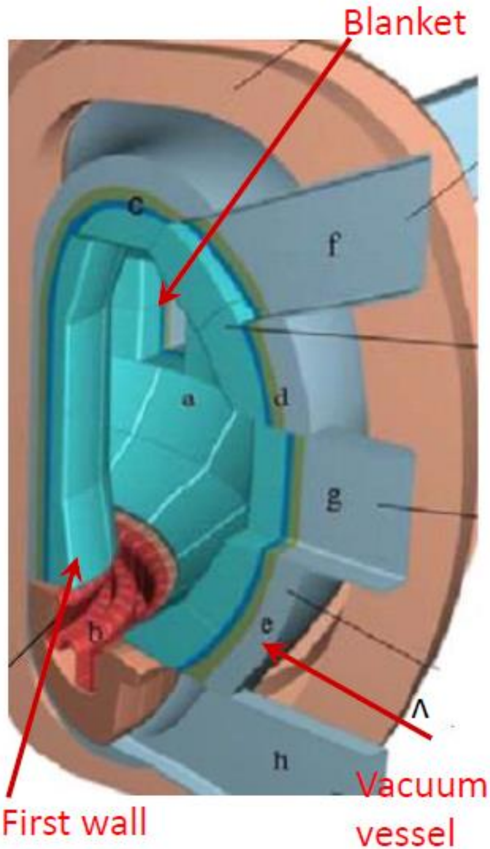
Blanket functions

The blanket surrounds the reaction chamber (vacuum vessel) and has <u>three main functions</u>:

1. Conversion of neutron energy into heat and extraction → *high efficiency> 40%*

2. Production and extraction of tritium *Tritium consumption~ 55.6 kg / GWFus / y (~154 gT/GWFus/day)* → *self-sufficiency T/n > 1.1*

3. Radiation shielding and protection of permanent components → *shielding performance* → *radiation resistant materials*



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Fusion Power

D + T fusion products:

$$P_{fus} = P_{^4He} + P_n$$

• **^{4}He nuclei (3.5 MeV)** are confined in the plasma and there deposit their energy

$$P_{^4He} = 20\%\ P_{fus}$$

• **neutrons (14.1 MeV)** escape from the reaction chamber, interact with surrounding components and there deposit their energy

$$P_n = 80\%\ P_{fus}$$

Outline

- Neutron interactions with matter
- Neutrons kinematics
- Reactions cross sections
- Activation, transmutation and damage
- Radioactive decay law

Neutron interactions with matter

Neutrons do not interact with atomic electrons, they interact with nuclei. The probabilities of interaction (cross sections) do not have a smooth dependence on A,Z of the target nuclei.

$$ {}^{A}_{Z}X + n \rightarrow {}^{A^*}_{Z^*}X + x $$

$$ {}^{A}_{Z}X(n,x){}^{A^*}_{Z^*}X $$

- Elastic scattering (n,n)
- Inelastic scattering (n,n')

Fast neutrons

- Radiative capture (n,g)
- Charged particle producing reactions (n,p), (n,a), (n,d), (n,t)
- Neutron generating reactions (n,2n), (n,3n) ......
- Fission (n,f)

Slow neutrons

(Absorbtion reactions = (n,g) + (n,a) + (n,p) + (n,f) +.............)

Neutron Interactions

- Biological effects of neutrons are strongly energy dependent.
- Neutrons are arbitrarily divided into "slow" (thermal) or "fast" (energies of 1 MeV and above)
- The chief interaction mechanisms of neutrons are scattering and capture (followed by emission of a photon or another charged particle from the absorber nucleus).

Slow Neutron Interactions

Radiative Capture

$$^{1}n + {}^{1}H \rightarrow {}^{2}H + \gamma$$

$$^{1}H(n, \gamma)^{2}H$$

This reaction is important in neutron dosimetry and shielding. Hydrogen is a component of human tissue, so this reaction will produce radiation dose to humans.

Also, this reaction makes materials containing hydrogen (concrete, water, parrafin, polyethylene, etc.) good shields for neutrons.

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Slow Neutron Interactions

Radiative Capture

$$^{1}n + {}^{113}Cd \rightarrow {}^{114}Cd + \gamma$$

$$^{113}Cd(n, \gamma)\,^{114}Cd$$

This reaction is important in neutron shielding and is also used as the principal reaction for some neutron detectors.

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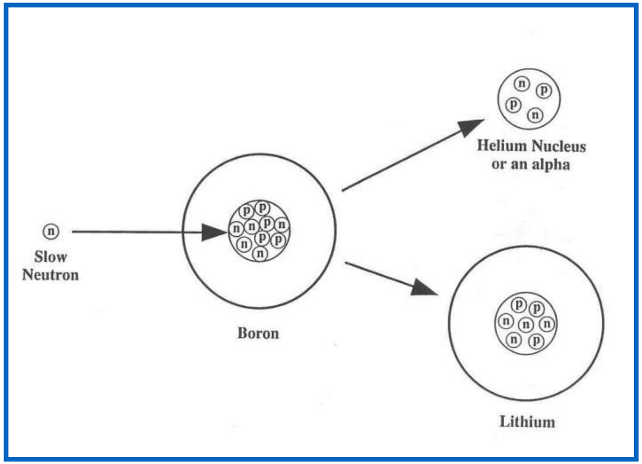
Slow Neutron Interactions

Charged Particle Emission

$$^{1}n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$$

$$^{10}B(n,\alpha)\,{}^{7}Li$$



This is why boron controls are used in nuclear power reactors, since it tends to reduce the number of neutrons present and therefore helps control the fission process.

Slow Neutron Interactions

Charged Particle Emission

$$^{1}n + {}^{14}N \rightarrow {}^{14}C + p$$

$$^{14}N(n, p)^{14}C$$

The energy of the proton released in this reaction is 0.6 MeV.

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Slow Neutron Interactions

Fission

$$^{1}n \; + \; ^{235}U \rightarrow \textbf{fission products}$$

available for more fission

The mean number of neutrons released per fission for U-235 is 2.5. This leads to a self-sustaining chain reaction or “critical mass.”

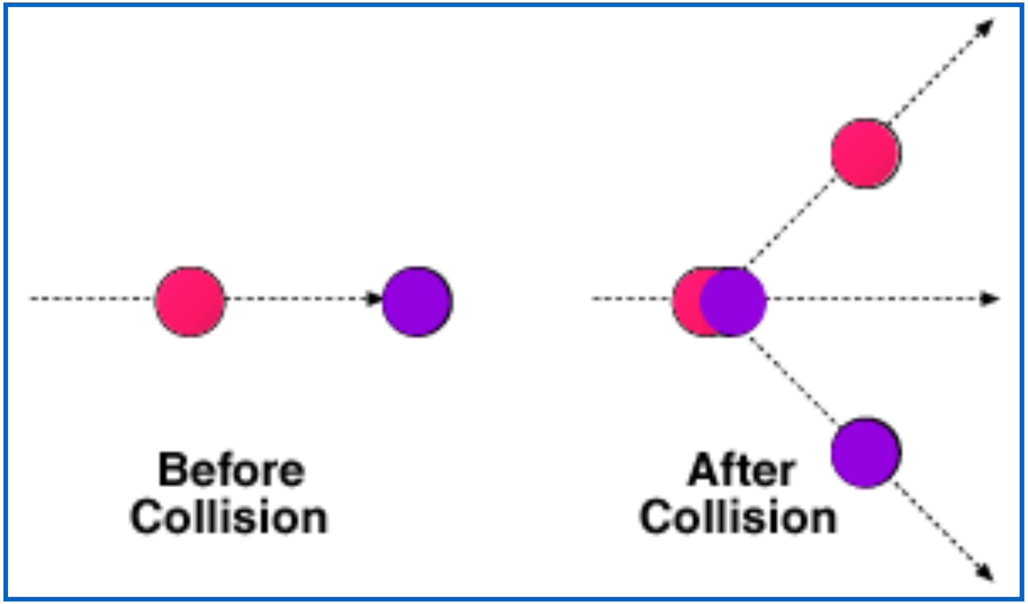
Fast Neutron Interactions

- Elastic scattering - neutrons interact with particles of approximately the same mass such as protons (billiard ball analogy)

    - Occurs in materials rich in hydrogen such as water, wax, concrete

    - Accounts for about 80% of fast neutron dose to tissue

Elastic scattering



In collision with protons, neutrons lose half their energy on average.

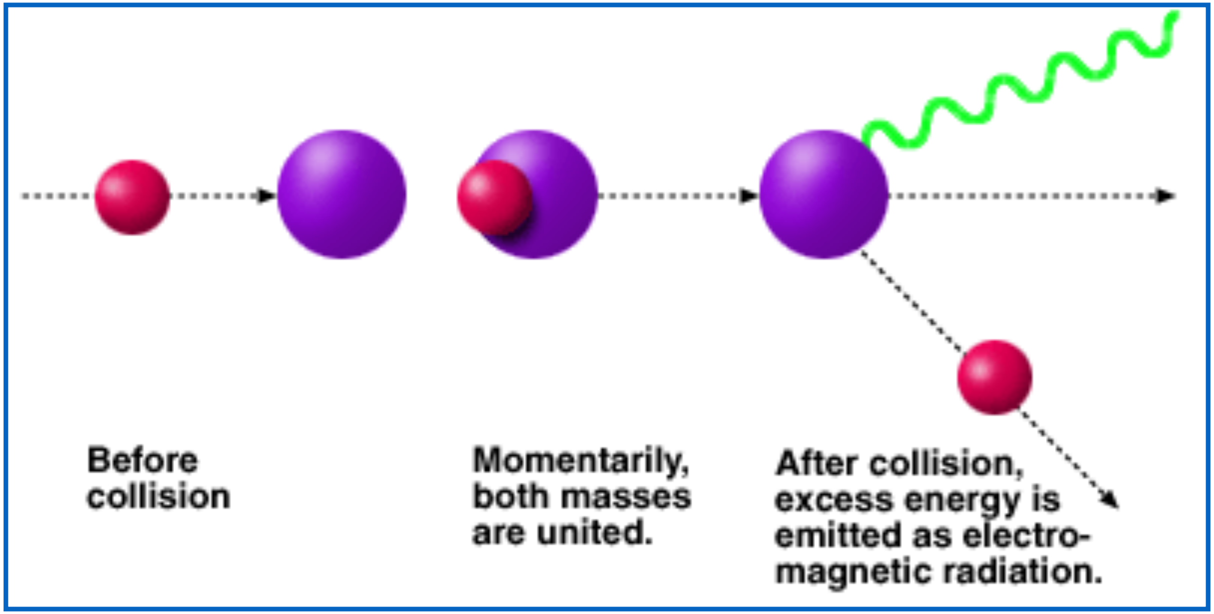
Fast Neutron Interactions

Inelastic scattering – neutrons interact with particles of much greater mass (e.g. iron)

(analogy of ping pong ball striking bowling ball)

For fast neutrons of energies of about 1 MeV, inelastic scattering can become appreciable. Inelastic scattering occurs primarily with high-Z absorbers.

Inelastic scattering



The neutron is captured, then re-emitted by the target nucleus together with the gamma photon. It has lesser energy.

Neutron interactions with matter

- In elastic (n,n) and inelastic (n,n’) scattering neutrons loose their energy: they are slowed down or “moderated”

- In absorption reactions (n,g) + (n,a) + (n,p) + (n,t) + (n,f) + (n,...) neutrons are “absorbed” by nuclei and disappear: secondary particles are generated

- In (n,2n), (n,3n) reactions neutron are multiplied.

- Fission reactions do not occur in fusion reactors

Neutron reactions

In nuclear reactions, neutrons first combine with the target nucleus and their energy is shared among all the nucleons in the nucleus (compound nucleus).

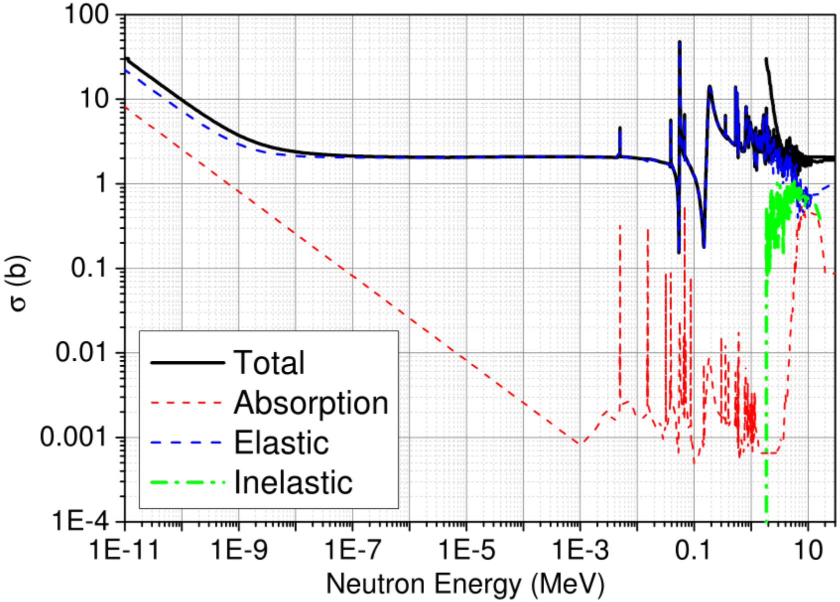
$$ {}^{A}_{Z}X + n \rightarrow \left({}^{A+1}_{Z}Y\right)^{*} $$

Because of statistical fluctuations, one or more nucleons may acquire an energy that is greater than the average energy value and that permits such particles to leave the excited nucleus.
Hence, after a relatively long period of time (typically 10^-16 s), the compound nucleus disintegrates, usually into an ejected small particle and a product nucleus.

$$ n + {}^{56}Fe \rightarrow \left({}^{57}Fe\right)^{*} \rightarrow \begin{cases} {}^{57}Fe + \gamma \\ {}^{56}Fe + n' \\ {}^{56}Mn + p \\ {}^{53}Cr + \alpha \end{cases} $$

Neutron reactions

When the energy of the incoming neutron is such that the excitation energy (neutron energy + binding energy) corresponds to a quantum state of the compound nuclei, the scattering and absorption cross sections rise sharply to high values called "resonance peaks“.



Silicon-28 elastic, absorption and total neutron cross sections (σ) against neutron energy (En), taken from NIST neutron scattering lengths and cross sections database

Outline

- Neutron interactions with matter
- Neutrons kinematics
- Reactions cross sections
- Activation, transmutation and damage
- Radioactive decay law

Neutron reactions: kinematics

Consider the reaction: $x + X \rightarrow y + Y$.

- For a target X at rest, conservation of energy is

$$M_x c^2 + K_x + M_X c^2 = M_y c^2 + K_y + M_Y c^2 + K_Y$$

- Rearranging this by separating mass from energy yields a quantity similar to the disintegration energy:

$$Q = M_x c^2 + M_X c^2 - (M_y c^2 + M_Y c^2) = K_y + K_Y - K_x$$

- The difference between the final and initial kinetic energies is the difference between the initial and final mass energies. This is called the ***Q* value**.

Neutron reactions: kinematics

The energy released when Q > 0 is from an exoergic (or exothermic) reaction. When Q < 0, kinetic energy is converted to mass energy in an endoergic (or endothermic) reaction. Collisions in this reaction are inelastic. Elastic collisions have Q = 0.

Threshold energy for an endoergic reaction (the minimum kinetic energy needed to initiate the reaction is called the threshold energy) :

$$E_{thres} = -\left(1 + \frac{M_x}{M_X}\right) Q$$

Neutron reactions: elastic collision

Conservation of energy and of momentum in the lab system

Momentum conservation:

$$\boxed{m_1\vec{v}_1 + m_2\vec{v}_2 = m_1\vec{v}_1' + m_2\vec{v}_2'}$$

Energy conservation:

$$\boxed{\frac{1}{2}m_1\vec{v}_1^{\,2} + \frac{1}{2}m_2\vec{v}_2^{\,2} = \frac{1}{2}m_1\vec{v}_1'^{\,2} + \frac{1}{2}m_2\vec{v}_2'^{\,2}}$$

(Elastic collision)

Neutron reactions: inelastic collision

Momentum conservation:

$$\boxed{m_1\vec{v}_1 + m_2\vec{v}_2 = (m_1 + m_2)\vec{v}\,'}$$

Energy conservation:

$$\boxed{\frac{1}{2}m_1\vec{v}_1^{\,2} + \frac{1}{2}m_2\vec{v}_2^{\,2} = \frac{1}{2}(m_1 + m_2)\vec{v}\,'^2 + E_{heating+deformation}}$$

(inelastic collision)

Neutron reactions: energy lost

Energy lost by neutron in the scattering process, ε:

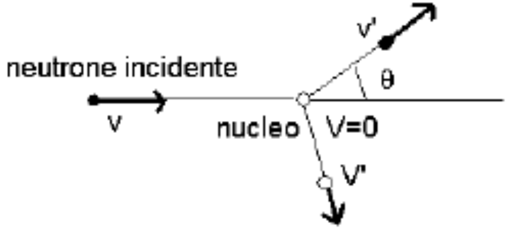
$$\varepsilon_{inel} = \overline{E - E'} = \frac{1}{2}(1-\alpha)E\left(1 - \frac{Q(A+1)}{2E}\right)$$

$$\frac{1}{2}mv^2 = \frac{1}{2}mv'^2 + \frac{1}{2}MV'^2 - Q$$
$$m\mathbf{v} = m\mathbf{v}' + M\mathbf{V}'$$

$$\alpha = \frac{(A-1)^2}{(A+1)^2}$$

$$\varepsilon_{elas} = \frac{1}{2}(1-\alpha)E = \frac{2A}{(A+1)^2}E$$

Inelastic diffusion **Q < 0**
A=M/m, $E=1/2mv^2$ e $E'=1/2mv'^2$
(isotropic diffusion in the c.m)



Elastic diffusion **Q = 0**
The maximum energy transfer occurs in scattering on H (A=1)
Hydrogen is the best neutron moderator for E < ~1 MeV

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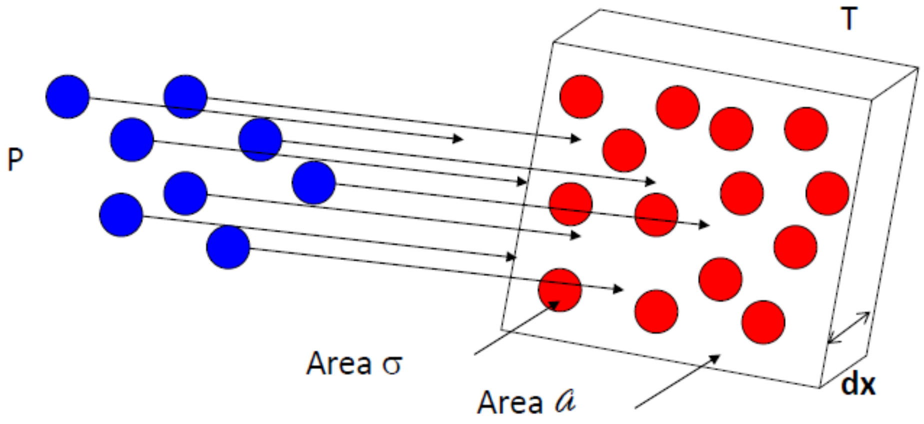
Reaction cross sections

Let's consider a beam of particles P (neutrons) impinging on a target T of volume V= $\mathcal{A}\cdot$ dx

I = Beam intensity = number of particles entering the target surface per unit time and area

$\mathbf{N_B}$ = density of particles (nuclei) in the target



Reaction cross sections

The beam attenuation in passing through the target is given by

$$dI = -I\underbrace{(N_B\, \mathcal{A}\, dx)}_{\text{Number of target nuclei in volume Adx}}\, \sigma/\mathcal{A} = -I\, N_B\, \sigma\, dx$$

Fraction of area occupied by target nuclei

$$I(x) = I(0)\exp(-N_B\, \sigma\, x)$$

σ = microscopic cross section – reaction probability

It is a function of the beam energy

It is measured in barns: 1 barn = 10^{-28} m^2

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Macroscopic cross section and mean free path

Σ = M**acroscopic cross section**
Reaction probability per unit path

$$\Sigma = N_B \sigma$$

λ = **Mean free path** : average distance travelled by a neutron between successive collisions which modify its direction or energy or other particle properties

$$\lambda = 1/N_B \sigma$$

$N_B = \rho N_0/A$ = target nuclei density
(nuclei per unità di volume)

N_0 Avogadro Number = $6.022 \cdot 10^{23}$ mole^{-1}

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Neutron cross section

Light nuclei A < 25 : The total cross section σ_{tot} at low energy (E< 1 MeV) is given by the sum of the elastic scattering and the radiative capture cross sections

$$\sigma_{tot} \approx 4\pi R^2 + \frac{\kappa}{\sqrt{E}}$$

At E ~ 1 MeV resonances appear (not in H).

Hydrogen is a good moderator of neutrons with E < ~1 MeV

Neutron cross section

Intermediate and heavy nuclei 25 < A < 80 and A > 80

The total cross section σ_{tot} at low energy (E< 1 MeV) is given by the sum of the elastic scattering and the radiative capture cross sections
Resonances appear at :

1. E > 100 eV for intermediate nuclei,
2. E > 1 eV for heavy nuclei

For some isotopes resonances may have very high values

Neutron moderation and absorption

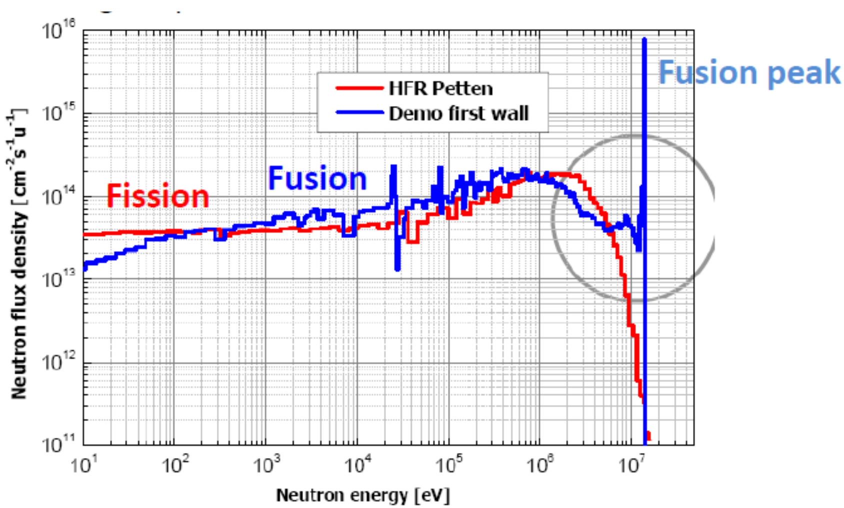
E_n > ~ 1 MeV : inelastic scattering on nuclei with medium-high A values provides the most effective mechanism for slowing down neutrons with energy higher than the first excited state of such nuclei (this holds also if $s_{el} > s_{in}$). This is no longer true when the neutron energy falls below the energy of the first excited state of such nuclei
Iron (Q= -0.847 MeV), Tungsten (Q= -0.1 MeV)

E_n < ~ 1 MeV : Low A materials are the best neutron moderators through elastic scattering
Water, graphite, beryllium, polyethylene

E_n < ~ 1 eV : Materials with high neutron capture cross combined with low A materials provide effective neutron absorption
Cadmium, Boron, Litihium

Neutron energy spectra

The energy spectrum of neutrons on the first wall of a fusion reactor is the result of all reactions of neutrons with the nuclei of materials in the blanket and in the surrounding components.



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- Activation, transmutation and damage
- Radioactive decay

Activation, transmutation and damage

Neutron reactions cause transmutation of nuclei, induce radioactivity and causes damage in the material lattice.

$$^{A}_{Z}X(n,x)^{A^*}_{Z^*}X$$

Generation of transmutation and activation products:

- Burn-up of initial constituents, build-up of new elements
- Chemical composition of materials changes
- Gas production (H, He)
- Material degradation (transmutation, displacement damage)

• Radiation hazard due to activity and afterheat production
  - Plant safety under normal & off-normal conditions
  - Radioactive waste disposal, material recycling

Activation, transmutation and damage

An isotope is an atom of the same element with the same number of protons and a different number of neutrons.

- Some isotopes are *naturally unstable* and *spontaneously change* to another isotope of a different element
- This change from one element to another is called *TRANSMUTATION*.

Activation, transmutation and damage

- Chemical reactions involve atoms rearranging by breaking and forming bonds involving electrons
- *TRANSMUTATION* involves changes in the nucleus that change the actual identity of the element
- These reactions are called *NUCLEAR* because they involve the atom's *nucleus*

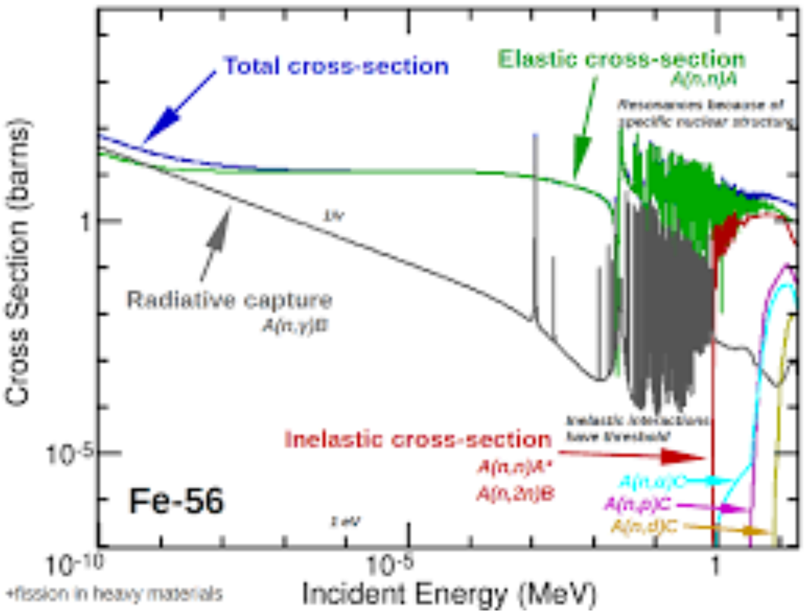
NUCLEAR TRANSMUTATION (natural)

Original Radioisotope → *New Isotope* + *Radiation*

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

Activation, transmutation and damage

Fusion neutrons are more energetic (14 MeV) than fission (<2- 3 MeV)
→ high threshold reactions can occur with higher probability
→ More H, He can be produced through (n,p) , (n,a) reactions



Activation, transmutation and damage

Transmutation of nuclei accompanied by radiation emissions was observed - **radioactivity.** Discovery of radioactivity was made by H. Becquerel (1896).

Three basic types of radioactivity and nuclear decay:

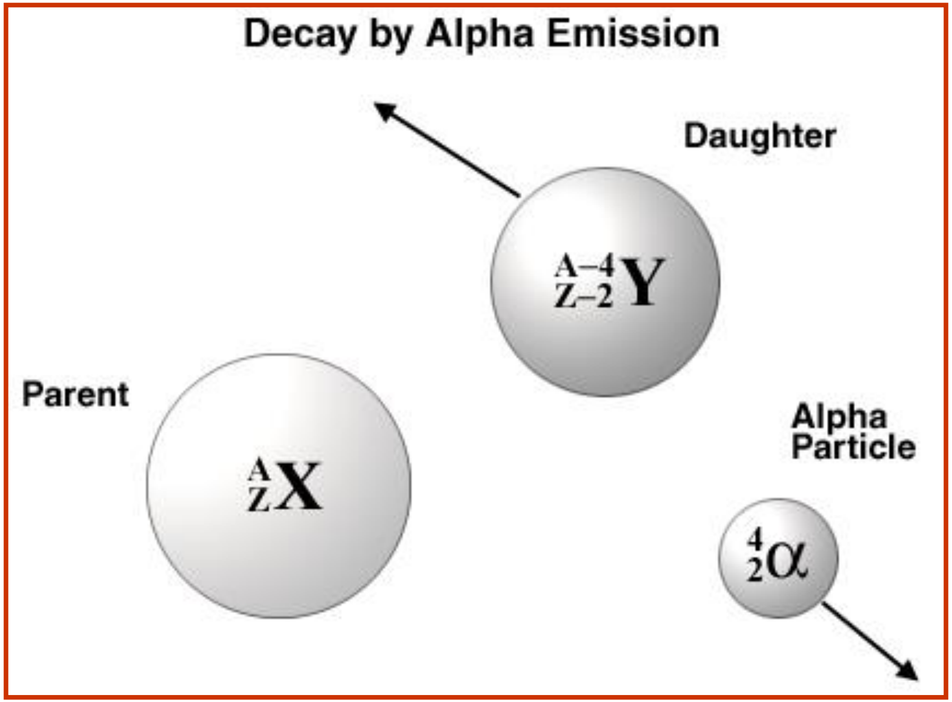
1) **Alpha decay**
2) **Beta decay**
3) **Gamma decay**

and nuclear fission (spontaneous or induced) and further, more exotic types of decay.

Alpha decay

- Emission of a highly energetic helium nucleus from the nucleus of a radioactive atom
- Occurs when neutron to proton ratio is too low
- Results in a decay product whose atomic number is 2 less than the parent and whose atomic mass is 4 less than the parent
- Alpha particles are monoenergetic

Alpha particle decay



Alpha particle decay: example

^{226}Ra decays by alpha emission

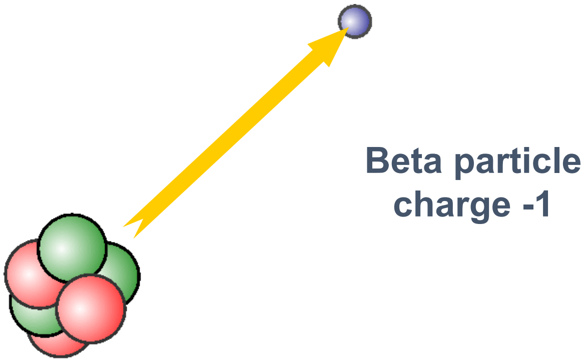
When ^{226}Ra decays, the atomic mass decreases by 4 and the atomic number decreases by 2

The atomic number defines the element, so the element changes from radium to radon

$$^{226}_{88}Ra \rightarrow \, ^{222}_{86}Rn + \, ^{4}_{2}He$$

Beta emission

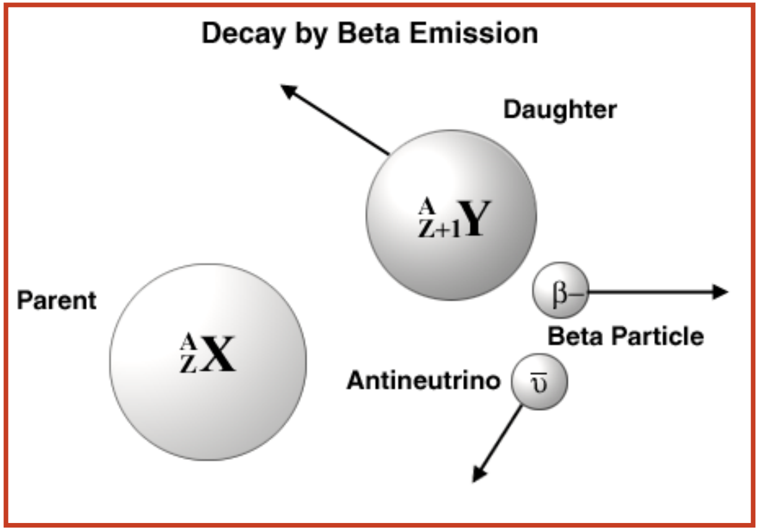
- Emission of an electron from the nucleus of a radioactive atom (n $\rightarrow$ p+ + e-1)
- Occurs when neutron to proton ratio is too high (i.e., a surplus of neutrons)
- Beta particles are emitted with a whole spectrum of energies (unlike alpha particles)



Beta (-) particle decay

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p \rightarrow {}^{0}_{-1}\beta + \overline{\nu} $$

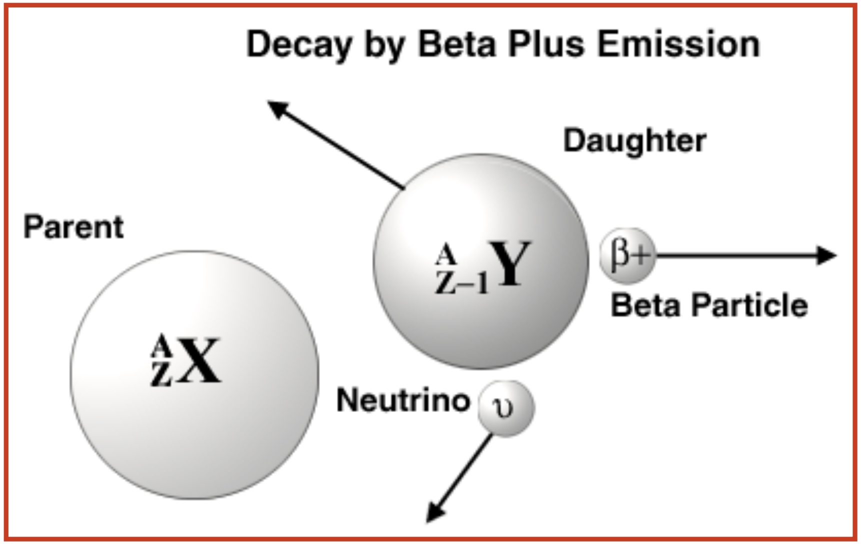
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + \beta^{-} + \bar{\nu} $$



Positron (Beta+) emission

$$p^+ \rightarrow n + \beta^+ + \nu$$

$$\boxed{{}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + \beta^+ + \nu}$$



$$\boxed{{}^{23}_{12}Mg \longrightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + {}^{0}_{0}\nu}$$

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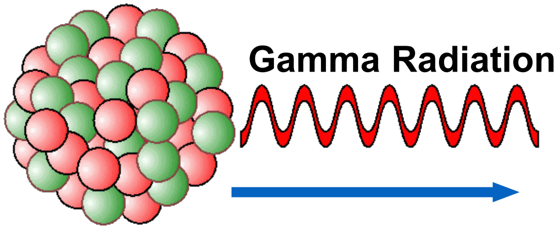
Gamma ray emission

- Monoenergetic radiations emitted from nucleus of an excited atom following radioactive decay
- Rid nucleus of excess energy
- Have characteristic energies which can be used to identify the radionuclide
- Excited forms of radionuclides often referred to as "metastable", e.g., 99mTc. Also called "isomers"



Summary of radioactive decay mechanisms

Decay Mode	Characteristics of Parent Radionuclide	Change in Atomic Number (Z)	Change in Atomic Mass	Comments
Alpha	Neutron Poor	-2	-4	Alphas Monoenergetic
Beta	Neutron Rich	+1	0	Beta Energy Spectrum
Positron	Neutron Poor	-1	0	Positron Energy Spectrum
Gamma	Excited Energy State	None	None	Gammas Monoenergetic

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Radioactive decay

- Neutron reactions may produce radioactive nuclei (radionuclides or radioisotopes) that are unstable and decay to a different state or nucleus
- Radioactive decay: spontaneous transformation of a nucleus with the emission of particles or radiation, causing a change of A, Z
- Decay modes: alpha (emission of an a particle), beta (emission of e_+, e_- particles), gamma (emission of g rays)
- The **Activity** of a radioactive nuclei is defined as the number of decays per second.
- The activity is measured in *Becquerel (SI)*

1 Bq = 1 decay/second

(1 curie =$3.7 \times 10_{10}$ Bq***,*** attivity of 1g di $_{226}$Ra***)***

The radioactive decay law

The decay law states that: *the number of nuclei that will decay per second is proportional to the number of atoms present that have not yet decayed*

$$\frac{dN}{dt} = -\lambda N$$

Here λ is a constant, known as the decay constant. Its physical meaning is that it represents the probability of decay per unit time.

If the **number of nuclei originally present** (at **t=0**) is $\mathbf{N_0}$, by integrating the previous equations it can be seen that the number of nuclei of the decaying element present at time **t** is

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

The radioactive decay law

- As expected the number of nuclei of the decaying element is decreasing exponentially as time goes on.

- If after a certain time t (lets call it $t_{1/2}$), the number of decaying nuclei is reduced by half **$N=N_0/2$**. So,

$$N = N_0 e^{-\lambda t} \Leftrightarrow \frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \Leftrightarrow \frac{1}{2} = e^{-\lambda t_{1/2}}$$

Using the logarithms:

$$\ln\left(\frac{1}{2}\right) = \ln\left(e^{-\lambda t_{1/2}}\right) \Leftrightarrow \ln\left(\frac{1}{2}\right) = -\lambda t_{1/2} \Leftrightarrow$$

$$\Leftrightarrow \ln 1 - \ln 2 = -\lambda t_{1/2} \Leftrightarrow \ln 2 = \lambda t_{1/2} \Leftrightarrow \boxed{t_{1/2} = \frac{\ln 2}{\lambda}}$$

The radioactive decay law

$$t_{1/2} = \frac{\ln 2}{\lambda} \Leftrightarrow t_{1/2} = \frac{0.693}{\lambda}$$

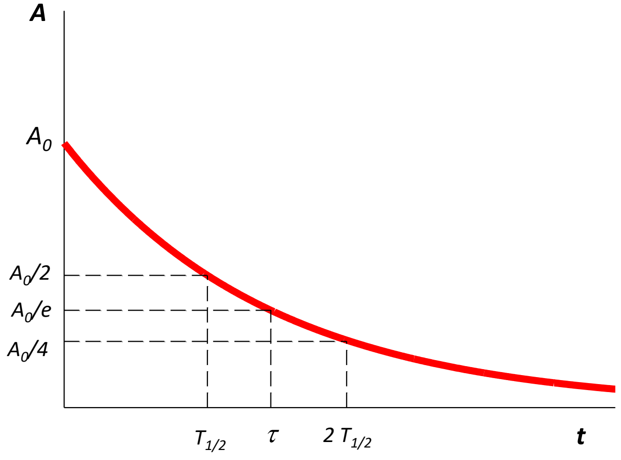
This is the relationship between the decay constant and the half-life.

This also means that we can have an equivalent formula for the decay equation:

$$N = N_0 \left(\frac{1}{2}\right)^{t/t_{1/2}}$$

The **number of decays per second** is called **activity** where $A_0=N_0\lambda$. So:

$$A = N_0 \lambda e^{-\lambda t}$$



Why the decay constant is the probability of decay per unit time

Since $$\frac{dN}{dt} = -\lambda N$$

we know that in a short time interval **dt** the number of nuclei that will decay is **dN=λNdt**.

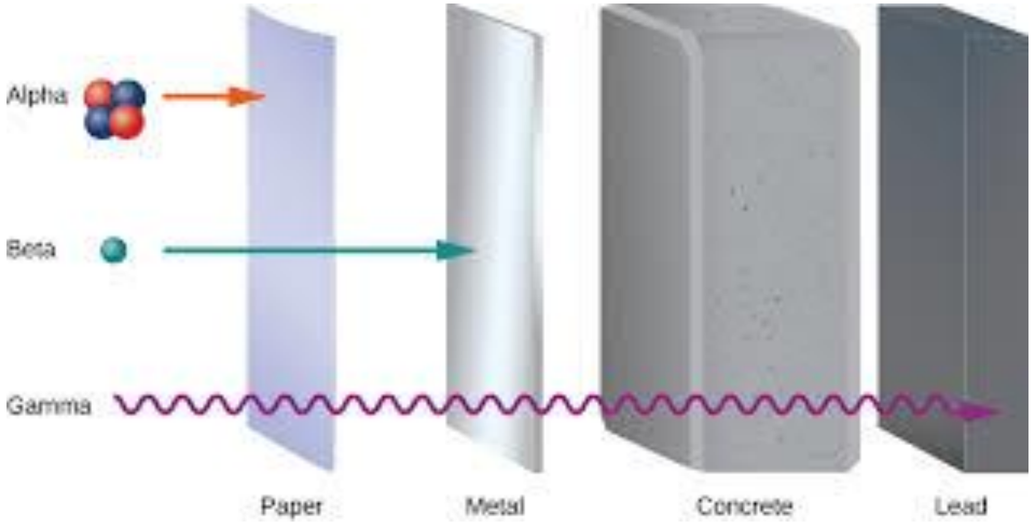
The probability that any one nucleus will decay within the time interval **dt** is thus:

$$\text{probability} = \frac{dN}{N} = \lambda dt$$

and so the probability of decay per unit time is equal to the **decay constant:**

$$\frac{\text{probability}}{dt} = \lambda$$

Penetration of ionised radiation



In neutron reactions generation of secondary particles occurs:

- neutrons and g-rays deep penetrating radiation → transport
- charged particles (n,a),(n,p),(n,d),(n,t)..

short propagation range ≤~mm → local absorption generation of gas H, He

Transmuations

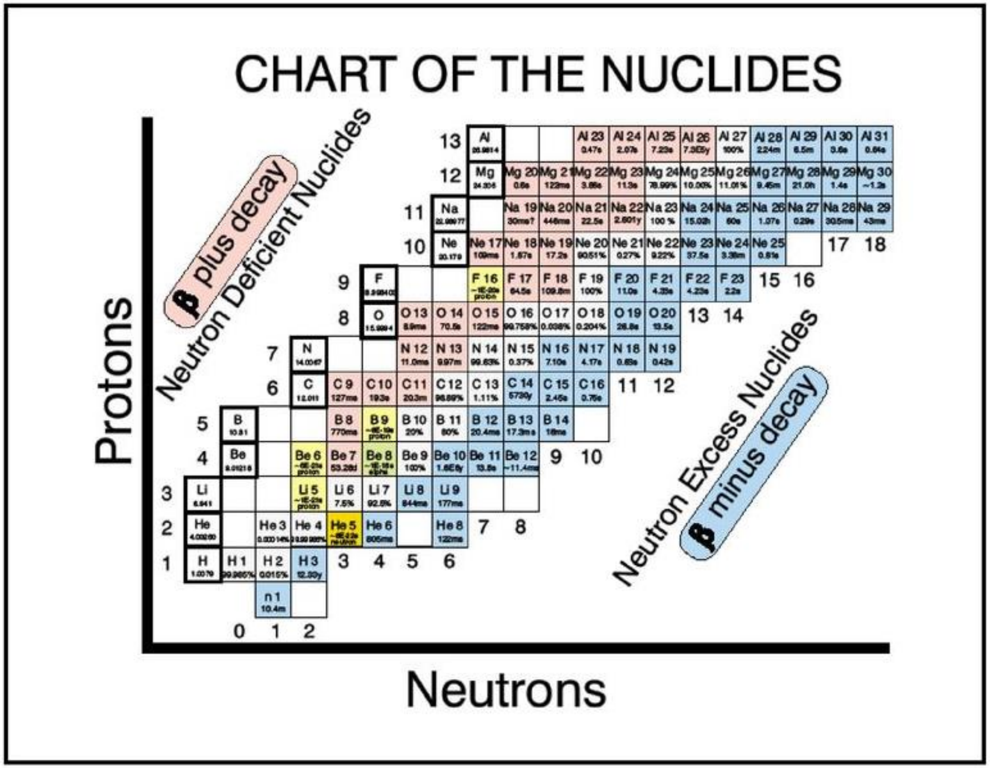
Production of i-nuclides through transmutations and decay of j-nuclides

$$\frac{dN_i(t)}{dt} = -(\sigma\Phi + \lambda_i)N_i(t) + \sum_j (\sigma_{ij}\Phi + \lambda_{ij})N_j(t)$$

Loss of i-nuclides through transmutation (burn-up) and decay

N_i, N_j Number of i,j nuclides at time t
λ_i decay constant of i-nuclide [s^{-1}]
λ_{ij} decay costant of j-nuclides that decay in i-nuclide [s^{-1}]
σ_j cross section of i-nuclide [cm^2]
σ_{ij} cross section of j-nuclides for reactions that produce i-nuclide [cm^2]
Φ neutron flux density [$cm^{-2}s^{-1}$]

Chart of nuclides



Transmuations

Z+2			(^{3}He,n)	(α,n)
Z+1		(p,n) (d,2n)	(d,n) (t,2n)	(t,n)
Z	(n,3n)	(n,2n)	Target	(n,γ)
Z-1	(n,n′t)	(n,t) (n,n′d)	(n,d) (n,n′p)	(n,p)
Z-2	(n,n′α)	(n, α) (n,n′^{3}He)	(n, ^{3}He) (n,pd)	(n,2p)
	N-2	N-1	N	N+1

Reactions by secondary particles produced in primary reactions by neutrons

Primary reactions by neutrons

Energy deposition

Neutrons deposit their energy in the blanket through nuclear reactions in the blanket materials (structural and functional ones)

- ✓ elastic, inelastic (recoil nuclei)
- ✓ Tritium breeding and neutron multiplying reactions

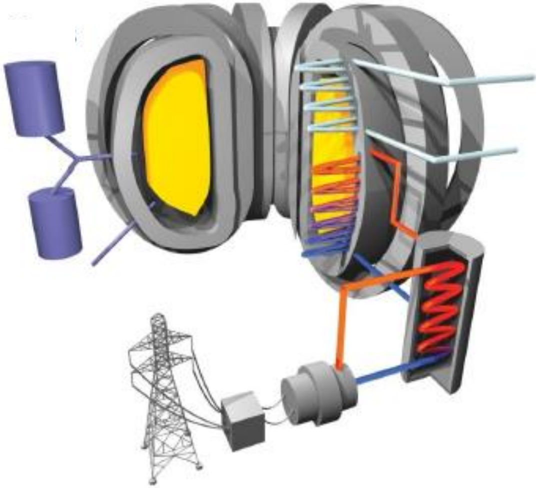
  $_{6}Li(n, T)\ _{4}He$ + 4.8 MeV

  $_{7}Li(n, n'T)\ _{4}He$ - 2.46 MeV

  $_{9}Be(n,2n)\ _{8}Be$ - 1.67 MeV

  $_{8}Pb(n,2n)\ _{7}Pb$ - 7.4 MeV
- ✓ radiative capture

  Es. : $_{56}Fe$ (n, g) $_{57}Fe$ + 7.64 MeV



Neutron energy is amplified by a factor ~1.15 – 1.4 and converted into heat

Example: transmuations in Be

$$\frac{dN_{9Be}(t)}{dt} = -\left(\sigma_{(n,2n)} + \sigma_{(n,\alpha)} + \sigma_{(n,t)}\right)\Phi N_{9Be}(t)$$

$$N_{9Be}(t) = N_{9Be}(0)e^{-\left(\sigma_{(n,2n)}+\sigma_{(n,\alpha)}+\sigma_{(n,t)}\right)\Phi t}$$

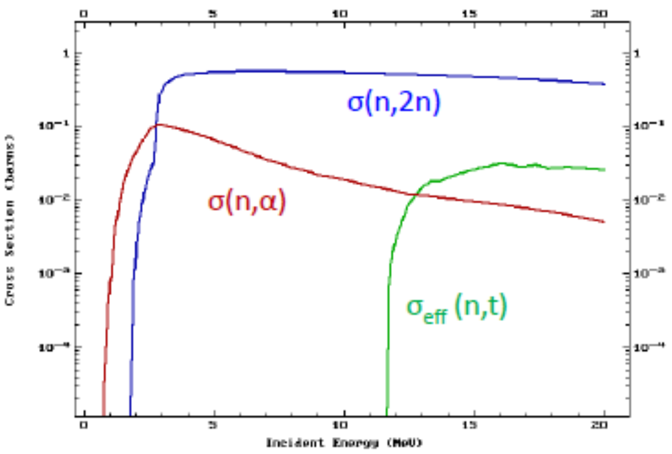
Beryllium is used in tritium breeding blankets
Let's calculate the transmutation rate of Be through
- Reactions producing He: $^{9}Be(n,2n)2\alpha$, $^{9}Be(n,\alpha)\,^{6}He \rightarrow {}^{6}Li$ (β^-, 0.8s)
- Reactions producing Tritium: $^{9}Be\,(n,t)_7Li$, $^{9}Be(n,\alpha)\,^{6}He \rightarrow {}^{6}Li$, $^{6}Li \rightarrow {}^{6}Li(n,\alpha)t$

$\Rightarrow$ cross sections: s(n,2n), s(n, α), σ(n,t)

Example: transmuations in Be

Typical neutron flux density in a fusion reactor blanket:
$\Phi \approx 10^{15}\ cm^{-2}S^{-1}$ ($\approx 2 \times 10^{14}\ cm^{-2}S^{-1}$ con E > 1 MeV)

$\sigma_{eff}(n,2n) \sim 0.54\mathrm{x}10^{-24}\ cm^{2}$
$\sigma_{eff}\ (n,\alpha) \sim 0.02\mathrm{x}10^{-24}\ cm^{2}$
$\sigma_{eff}\ (n,t) \sim 0.01\mathrm{x}10^{-24}\ cm^{2}$



- Transmutations of ^{9}Be (burn-up) : 0.5 % per year
- Production of He : 7670 ppm per year
- Production of T : 80 ppm per year